

## ***Interactive comment on “Arctic Mediterranean Exchanges: A consistent volume budget and trends in transports from two decades of observations” by Svein Østerhus et al.***

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Reply to Referee # 2

Please find our answer to Referee #2 below (a more reader friendly PDF file is included as supplement).

General comments: While the manuscript provides a wealth of detailed information on available measurements in the discussed branches of AM exchanges, little attempt has been made to compare the obtained budget and variability to other existing estimates, based on numerical models, reanalyses or other observations (e.g. satellite altimetry)

C1

– or a combination thereof. Two recent publications with a similar focus but different approach would be the obvious candidates for such comparison: Bringedal et al. (2018, Journal of Climate) for time series of volume transports and seasonal variability, and Rossby et al. (2018, J. Geophys. Res. Oceans) for volume exchanges across the across the Greenland-Iceland-Faroe-Scotland Ridge. How do volume transports and their seasonal variations presented in the manuscript compare to the estimates obtained farther south, at the Ovide or OSNAP sections (e.g. Daniault et al., 2016, Prog. Oceanogr., or Gary et al., 2018, J. Geophys. Res. Oceans) or along the other lines, closing the passage between Greenland and Scotland (e.g. Chafik et al., 2014, J. Geophys. Res. Oceans). It would be very interesting to consider the presented fluxes in a wider context. Another interesting question would be how well the proposed budget concur with the constraints for exchanges in the Arctic Mediterranean as elaborated by Rudels (2010, Tellus A). While the simplified concept of a double estuary with two circulatory loops serves as a good representation of the overall budget, I would appreciate a more thorough discussion of how much of the Atlantic inflow, modified along different pathways in the AM and returning to the North Atlantic, is not accounted for by the measured combination of surface outflows on both sides of Greenland and deep overflows in different branches.

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ANSWER We fully agree that comparing our direct volume transport observations with estimates build on other methods would add value to this paper, but here we have deliberately chosen to give a conscientious description and analyses of our observations. However, in future works we will compare our observations with numerical models other observations to discuss our results in wider context. We have added a sentence in sect. 4.4: “. . . but will have to await future observational efforts for confirmation. Meanwhile our time series will be combined with results from numerical models, reanalyses (Bringedal et al., 2018) and observations using other methods (Rossby et al., 2018)”

C2

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Specific comments:

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Page 1 line 23: Should be '...is modified within the AM.'

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ANSWER Changed accordingly

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Page 1 line 26: '...heat, salt and other substances. . .', '...are important for conditions in the AM' These statements sound a little vague, please be more precise about 'other substances' and 'conditions'.

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ANSWER Changed to" ... heat and salt."

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Page 1 line 31: Superscripts are not correctly typeset here (and also in many following instances in the text).

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ANSWER Changes made

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Page 1 line 31-32: '...has a seasonal variation of amplitude close to 1 Sv' I would rather suggest 'has the amplitude of the seasonal variation close to 1 Sv'

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ANSWER Changed accordingly

C3

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Page 1 line 33: 'The overflow is mainly produced. . .' I suggest 'The overflow water is mainly produced. . .'

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ANSWER Changed accordingly

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Page 1 line 35: '...is fed from the Pacific inflow and freshwater' I suggest adding the origin of freshwater in this sentence.

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ANSWER Added: (runoff and precipitation)

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Page 1 line 35: '...is  $\frac{2}{3}$ rds from modified Atlantic water.' I would suggest '...is  $\frac{2}{3}$ rds of modified Atlantic water'.

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ANSWER Changed accordingly

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Page 1 line 38: 'At the 95% level. . .' It should be 'At the 95% confidence level. . .'

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ANSWER Changed accordingly

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Page 2 line 16: '...transporting heat, salt and other substances.' As above – what other substances?

C4

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ANSWER Changed to” . . . heat and salt.”

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Page 2 line 27: ‘. . .as “overflow” waters.’ Why to use the quotation marks here? Overflow water is well-accepted name for this water mass.

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ANSWER Quotation marks removed

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Page 2 line 29: ‘. . .entrain on route. . .’ Either ‘en route’ or ‘on the way’.

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ANSWER Changed to “en route”

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Page 3 lines 4-6: ‘The inflowing water from the Atlantic. . .’ What about the part of Atlantic water that recirculates along different loops in the Nordic Seas and Arctic Ocean and does not return as ‘cold and fresh surface outflow’ but rather occupies the subsurface and intermediate layers when flowing to the south?

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ANSWER Rewritten to: The inflowing water from the Atlantic that does not return as overflow mixes with the Pacific inflow and leaves the AM through the Canadian Archipelago and Denmark Strait and the upper western Fram Strait as cold and relatively fresh "surface outflow" (Curry et al., 2014; de Steur et al., 2017).

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Page 3 line 22: ‘. . .expected to be qualitatively different. . .’ This statement sounds

C5

a little peculiar. If it was meant that the budget has different components (different flow branches) then it is quantitatively different. On the other hand, the volume (mass) budget should be closed both for the AM and for the Arctic Ocean thus it cannot be ‘qualitatively different’. I would suggest reformulating this sentence.

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ANSWER The word qualitative is now deleted and the sentence reformulated

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Page 4 line 7: ‘without any yielding any information. . .’ One ‘any’ too many. . . (without yielding any information).

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ANSWER Changed accordingly

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Page 4 line 9: ‘the variability in physical aspects. . .’ This sounds somehow cryptic. What are the differences between individual branches that make them difficult to be described in a consistent manner?

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ANSWER Deleted statement

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Page 4 line 17: ‘. . .for historical and logistical reasons. . .’ What are ‘logistical’ reasons? Do you mean the distribution/locations of observations or the structure of paper?

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ANSWER The word logistical has been deleted and the sentence reformulated

C6

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Page 4 lines 25-26: 'Over the deepest part. . . . towards the Irminger Sea'. This sentence does not belong here as it describes the outflow (DSOWflowing towards the Irminger Sea), not inflow. The same refers to the previous sentence where the surface outflow in the EGC is described. I would suggest keeping the description of inflows and outflows separate.

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ANSWER The discussion of the two outflows have been deleted

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Page 4 line 27 and Fig. 3: Why are these two branches not shown on Figure 3?

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ANSWER Both branches are now shown on the figure

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Page 4 line 34, page 5 line 1: This sentence is difficult to follow (in particular 'are used' at its end), please reformulate.

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ANSWER The sentence has been deleted

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Page 5 lines 25-27: Does the Faroe Current as measured at the section N include the entire flow of AW passing between Iceland and Faroe or is there any part that passes northward beyond the section and is not accounted for?

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ANSWER A sentence has been added to clarify this.

C7

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Page 6 lines 5-6: '. . .a significant fraction originally crossed. . . . bifurcated into the FSC. . .' The verb tenses are strange here. I would suggest '. . .a significant fraction that originally crossed the ridge. . . . enters the Faroe Current and bifurcates into the FSC. . .'.

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ANSWER Changed accordingly

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Page 8 line 27: '. . . on the Greenland shelf region. . .' Either 'on the Greenland shelf' or 'in the Greenland shelf region. . .'

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ANSWER Changed to: "on the Greenland shelf"

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Page 9 line 19: '. . .uncertainty (estimated from their figures). . .' How was the uncertainty estimated from the figures?

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ANSWER The text "(estimated from their figures)" has been deleted Page 10 line 9: '. . .the "kinematic overflow", has an average volume transport of. . .' What is a difference overflow and 'kinematic overflow'? Is the latter one defined not by density range but some other criteria?

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ANSWER Clarifying text has been added Page 10 line 30: 'The definition of FSCBW is denser than our criterion. . .' Is the assumed source FSCBW denser than the criterion for overflow water or the mixture between FSCBW and AW? The criterion

C8

used by Johnson et al. (2017) is on the other hand less dense therefore 0.3 Sv may be overestimated.

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ANSWER 'The definition of FSCBW is slightly denser than our criterion for overflow water (27.8 kg m<sup>-3</sup>) and thus, 0.2 Sv is a lower bound for the volume transport. Previous measurements in the region have suggested transports between 0.1 and 0.3 Sv (Hansen and Østerhus, 2000). We therefore use the timeseries of FSCBW transport based on the method of Sherwin et al. (2008) but attach an uncertainty of  $\pm 0.1$  Sv.'

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Page 11 line 9 and following: 'Canadian Archipelago. . .' The commonly accepted name is the Canadian Arctic Archipelago (CAA).

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ANSWER Changed to Canadian Arctic Archipelago (CAA)

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Page 11 lines 16-17: '. . . carries inputs from the integrated CA outflow as well as northward inflow. . .' Perhaps it could be helpful here to mention a different origin (and characteristics) of water masses in the integrated CAA outflow and in the recirculating flow from the West Greenland shelf and slope. A more precise way to describe the outflow from the Davis Strait would be 'the integrated CAA throughflow and modified AW recirculating from the West Greenland Current'.

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ANSWER We have added more text on the origin of water masses

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Page 13 lines 22-23: 'The sum of the transport values. . . . did not, however,

C9

differ substantially from the sum based on the full periods' Even if the sum of transport values did not differ substantially, it would be helpful to be able to compare the 6-year averages of volume transport for individual branches with those based on the full periods. Perhaps one more column could be included in Table 1 to show transports averaged for the reference (overlapping) period, especially when taking into account that monthly averages over this period are later employed to analyze the seasonal variations.

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ANSWER Text changed to: The sum of the transport values for all of these branches in these months are all inside the error estimate for the sum based on the full periods (Table 1).

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Page 14 line 22: '. . . without taking serial correlations into account. . .' Please explain more precisely how would accounting for autocorrelation increase the confidence intervals for calculation of trends in volume transports.

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ANSWER This has been elaborated on

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Page 17 line 9: '. . . which supports the value of 5 cm as a maximum in the AM as a whole.' Could you elaborate more precisely how is the maximum value of 5 cm for the whole AM obtained from the sea level variations south of 82°N.

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ANSWER The sentence has been modified

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C10

Page 17 line 13: ‘. . .is not very consistent with this.’ I would not call it ‘not very consistent’ but not consistent at all since there is a difference on the order of magnitude between the seasonal amplitude estimated from the sea level variation and seasonal amplitude based on volume transport measurements.

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ANSWER “not very” has been changed to “not at all”

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Page 18 lines 1-8: I would be more careful about downplaying the uncertainties related to different criteria used to distinguish water masses in inflows and outflow/overflows. The relationship between flow (transport) and hydrographic characteristics at the section is not necessarily linear and it is unclear to me why possible differences should result in systematic biases, not the random errors.

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ANSWER This whole argument has been deleted from the text here and later

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Page 18 line 8: ‘. . .budget of the AM and data quality’ The phrase ‘Data quality’ does not reflect the core of the problem as the data quality is the most likely acceptable for this kind of large-scale estimates. The problem is in too sparse measurements, so I would rather suggest ‘. . .budget of the AM and gaps in the observational coverage’

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ANSWER Changed accordingly

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Page 18 lines 19-20: ‘. . .in the form of an unknown bias rather than a randomly varying error. . .’ As mentioned above, I am not convinced that this is necessarily the case.

C11

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ANSWER As mentioned above, this argument has been deleted from the text

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Page 19 line 5: ‘Combining the uncertainties. . . .quadratically, as commonly done. . .’ ‘Combining quadratically’ sounds a little peculiar, please reformulate into the assumption about error propagation. Why should it also be ‘a conservative estimate’ of the overall uncertainty?

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ANSWER The text has been modified to refer to error propagation and the word “conservative” has been removed

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Page 19 lines 18-19: ‘. . .most of this seasonality would have to come from the DS-outflow, i.e. the estuarine loop. . .’ The meaning of the estuarine and thermohaline loops should be introduced before discussing their roles in the seasonal variability.

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ANSWER Deleted “, i.e., the estuarine loop”

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Page 19 lines 21-22: ‘. . .if the monitoring of the various import and export branches in the Greenland-Scotland region had been better coordinate with identical monitoring sections for import and export branches.’ The meaning of this sentence is entirely incomprehensible to me. Do you mean coordination in time (concurrent monitoring)?

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ANSWER The text has been modified and the meaning hopefully clearer

C12

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Page 19 line 34: Should be 'in some years. . .'

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ANSWER Changed accordingly

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Page 20 line 3: 'in a mixing rate of 99:1. . .'. Where does this estimate of mixing ratio come from (it is not clear from the given salinities for AW and OW)?

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ANSWER It is not clear to us why the referee disagrees. More accurately, the ratio is 0.9887 to 0.0113 ( $35.3 \times 0.9887 + 0 \times 0.0113 = 34.9 \times 1.0000$ ), which we round to 0.99:0.01 = 99:1. Retaining more decimals seems to us not justified taking into account the uncertainties in the basic numbers (e.g. salinities). Thus, we have not changed this text, but we have added some more text, which hopefully clarifies the argument.

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Page 20 lines 15-17: Could you provide at least rough estimates for the additional contributions from the entrainment and convection?

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ANSWER We find it difficult to quantify these contributions without considerable extra text. Instead, we have modified the text slightly and added a reference to a just-published paper emphasizing the point that we wanted to make.

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Page 21 lines 10-11: 'Perhaps, slight strengthening of both circulation loops but certainly no weakening'. This sounds as a speculative statement. Please elaborate more precisely and formulate as a full sentence.

C13

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ANSWER The sentence has been deleted

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Page 22 lines 7-8: 'We argue that the exchange branches that have been monitored for a long time most likely do give a good representation of the long-term variations'

The sentence that longer observations provide better estimates of long-term variations is a truism. I would suggest using more precise formulation here.

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ANSWER The sentence has been reformulated to be more precise

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Page 22 lines 30: '. . . a one-time effort with all exchange branches monitored over a year would help substantially.' While this is the most likely true, a concrete argument how would it help would be more convincing (e.g. elucidating relations between transports in different branches, lower uncertainties, etc.)

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ANSWER The sentence has been deleted

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Page 32 Figure 3 and page 33 Figure 4: My suggestion is to slightly enlarge Figure 3 towards the south and incorporate the arrows showing the ES inflow into it. Figure 4 is in my opinion superfluous.

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ANSWER Figure 3 has been enlarged and necessary information from the old Figure 4 has been added to Figure 3. Figure 4 has been deleted and subsequent figures

C14

re-numbered.

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Page 34 Figure 7. Why are the abbreviations of currents' names with dots (periods) on this figure (and in its caption) and without periods on other figures.

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ANSWER The dots on this figure (now Figure 6) and on old Figure 5 (now Figure 4) have been removed and figure captions modified accordingly

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Page 35 Figure 8 and page 36 Figure 10: I would suggest combining panels (a) and (b) into one plot for each of these figures and, in the first place, using one Y-scale for inflows and outflows to be able to compare their variations.

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ANSWER Has been done (now Figures 7 and 9)

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Interactive comment on Ocean Sci. Discuss., <https://doi.org/10.5194/os-2018-114>, 2018.