

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

### **Anonymous Referee #2**

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The submitted manuscript presents a comprehensive update of the Arctic Mediterranean (AM) oceanic volume fluxes based on the long-term observational efforts in the different branches of Atlantic inflows, and surface and deep outflows (overflows). Based on available transport estimates, the authors aim to construct a physically consistent volume budget within the estimated uncertainties of discussed AM exchanges and, where possible, to evaluate the seasonal variations of volume transport in individual branches (and in the integrated Atlantic inflow). The long-term trends in the AW exchange branches are discussed in the context of the recently widely debated weakening of the AMOC with reaching the important conclusion about a lack of observational evidence thereof. The manuscript not only provides the most comprehensive

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and up-to-date overview of the AM exchanges, but also addresses the limitations of existing observational arrays/activities in different inflow and outflow branches, and discusses uncertainties introduced by their imperfect coverage by long-term measurements. The submitted paper is clearly structured and divided into the sections focused on individual AM exchange branches, followed by the chapters integrating the partial results towards the overall budget and its seasonal and long-term variability. The final conclusions are well justified by presented results and discussion. The comprehensive table summarizes the details of volume transports in all addressed branches while a complex spatial structure of AM exchanges is illustrated with detailed maps, including a conceptual scheme of two circulation loops representing the whole budget. The submitted paper offers a much-needed synthesis of the current knowledge about volume exchanges between the AM and the World Ocean that have a profound impact both on regional circulation and global climate-relevant processes. The scientific content is sound, the results solid, and the manuscript is generally well written, so the suggested modifications/additions are not critical but intended to improve readability and clarify the details. Therefore, I would like to recommend the manuscript for publication in the Ocean Science journal after a minor revision.

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) – 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. Danialt et al., 2016, Prog. Oceanogr., or Gary et al., 2018, J. Geophys. Res. Oceans) or along the other lines,

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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.

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

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'.

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

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'

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

I suggest 'The overflow water is mainly produced...'

Page 1 line 35: '...is fed from the Pacific inflow and freshwater'

I suggest adding the origin of freshwater in this sentence.

Page 1 line 35: '...is ~2/3rds from modified Atlantic water.'

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I would suggest '...is ~2/3rds of modified Atlantic water'.

Page 1 line 38: 'At the 95% level...'

It should be 'At the 95% confidence level...'

Page 2 line 16: '...transporting heat, salt and other substances.'

As above – what other substances?

Page 2 line 27: '...as "overflow" waters.'

Why to use the quotation marks here? Overflow water is well-accepted name for this water mass.

Page 2 line 29: '...entrain on route...'

Either 'en route' or 'on the way'.

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?

Page 3 line 22: '...expected to be qualitatively different...'

This statement sounds 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.

Page 4 line 7: 'without any yielding any information...'

One 'any' too many... (without yielding any information).

Page 4 line 9: 'the variability in physical aspects...'

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This sounds somehow cryptic. What are the differences between individual branches that make them difficult to be described in a consistent manner?

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?

Page 4 lines 25-26: 'Over the deepest part. . . . towards the Irminger Sea'.

This sentence does not belong here as it describes the outflow (DSOW flowing 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.

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

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

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?

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...'

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

Either 'on the Greenland shelf' or 'in the Greenland shelf region...'

Page 9 line 19: '...uncertainty (estimated from their figures)...'

How was the uncertainty estimated from the figures?

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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?

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

Page 11 line 9 and following: 'Canadian Archipelago...'

The commonly accepted name is the Canadian Arctic Archipelago (CAA).

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'.

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

Page 14 line 22: '...without taking serial correlations into account...'

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Please explain more precisely how would accounting for autocorrelation increase the confidence intervals for calculation of trends in volume transports.

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.

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.

Page 18 lines 1-8: I would be more careful about downplaying the uncertainties related to different criteria used to distinguishing 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.

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'.

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.

Page 19 line 5: 'Combining the uncertainties. . . . quadratically, as commonly done...'

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'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?

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.

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)?

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

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)?

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

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.

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'

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

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.)

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.

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.

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