Author’s response to RC1

Westerlund, A., Miettunen, E., Tuomi, L., and Alenius, P.: Refined estimates of water transport through the Åland Sea, Baltic Sea, Ocean Sci. Discuss. [preprint], https://doi.org/10.5194/os-2021-56, in review, 2021

Below, reviewer comments are displayed with a gray background, while author responses are without highlighting.

RC1: Anonymous Referee #1, 28 Jun 2021

> Review of submission os-2021-56

> Title: Refined estimates of water transport through the Aland Sea, Baltic Sea

> Authors: A. Westerlund, E. Miettunen, L. Tuomi, P. Alenius

> General:

> The study by Westerlund et al. investigates main pathways of water transport through the Aland Sea by means of a high-resolution regional model application. Previous observational and model approaches provided limited understanding of the transport and circulation structure in that area because of the strong seasonality of the regional atmospheric forcing as well as the complex bottom topography which requires high-resolution data coverage both in space and time to adequately capture the main transport characteristics. The aim of the study, as I understand it, is to gain insight into exchange dynamics between the Baltic Proper and the Bothnian Sea at interannual and seasonal scales of the recent past. To this end, the authors constructed a bathymetric representation of the Aland Sea with an unprecedented resolution of 500m horizontally and 200 vertical layers. The applied hindcast simulation with NEMO provided hourly to daily model output for the period 2013-2017.

> While the model setup has been evaluated against available station data and seems to perform sufficiently well, my main concern is related to the rather limited use of the comprehensive model output. Substantial parts of the ms are dedicated to the discussion of the model biases and their possible origins. The transport dynamics as being the main focus of the study, by contrast, are presented in a rather descriptive way whithout analyzing and discussing any driving mechanisms or broader context that would finally gain our process understanding of the Aland Sea circulation. Apart from the shown figures, the transport rates are not even quanitfied. In this way, the only new finding of the study seems to be that about 25% of the transport entering the Aland Sea from the south does not follow the main strait at 20.5°E but rather happens through a topographic depression at 19.6°E. Of course, it is valuable to reflect on the model biases. But if the focus on the analysis and discussion of the model results is underrepresented, it conveys a rather defensive and repetitive flavor.

> Nevertheless, I do see great potential to use the performed simulation for further analysis that, in my opinion, would substantially increase the depth, relevance and impact of this

study. For instance, questions that naturally arise while reading the present version of the ms and could well be addressed, are: What drives the occasional northward turn of the surface flow? Is it exceptional wind conditions? Does the northward surface flow lead to SSH and pressure anomalies in the Aland and Bothnian Sea? Do these anomalies temporally weaken the more steady sub-halocline northward flow? What drives the sub-halocline gyre in the Aland Sea Proper? Why is the surface circulation strongest in summer? Is this related to melt water discharge from land? What are the transport budgets of the individual basins of the Aland Sea? Is the sub-halocline northward transport a continuous steady flow or is part of the inflow returned and exported southward horizontally or temporally or via mixing with the surface flow? Are there regionalized future projections for wind and freshwater discharge available that could be utilized to hypothesize on potential climate change impacts (e.g. those used by Meier et al. 2021, https://doi.org/10.1038/s43247-021-00115-9)? Could one also hypothesize/extrapolate from your results on the water mass exchange to the nutrient supply into the Bothnian Sea?

> The conclusions could then follow a more explanatory line, if supported by the model results, such as: Continuous northward transport into the Bothnian Sea is dominated almost entirely by sub-halocline water masses. Northward flow potentially occurs in any area where the bathymetry exceeds the local depth of the halocline. If these areas are wide enough (with respect to the deformation radius?) the Coriolis force aligns the northward flow to the eastern side of the passages, which leads to a shoaling of the halocline at the eastern side and a deepening at the western side. Wind conditions can drive the predominantly southward surface flow of the estuarine-type general circulation towards the north on monthly to seasonal scales, causing significant anomalies in SSH and halocline structure. Further conclusions could be drawn from addressing some of the questions given above.

> I therefore would like to encourage the authors to dive deeper into the subject, provide more detailed analysis of the simulation already available, and from this derive more comprehensive and thoughtful conclusions.

We would like to thank the reviewer for providing this insightful and encouraging commentary of our manuscript. It is highly appreciated.

The suggestions made by the referee regarding additional questions for analysis are excellent. We have carefully considered them and implemented a number of changes to the manuscript. We have expanded the analysis of wind conditions. We have revised how model biases are analyzed. We also added more information about the transport rates, as requested. We hope these modifications improve the depth and relevance of this study.

We have revised the introduction so that it answers questions about the scope and the objectives of the study better and more clearly. We have also clarified how this study sits in the larger research plan we have for the coming years. We think that these changes based on reviewer suggestions were beneficial and that the introduction has improved.

As far as we understand, the main criticism the referee is offering here is that the referee feels the manuscript falls short of the potential it could have. We find this point of view understandable. We are planning several further studies where this modelling setup is used and had to limit the scope of the already rather extensive current study somehow. We note

that the main focus of the paper, as set out in the title for example, is to provide refined estimates of transports through the Åland Sea, and this is done in the manuscript.

We agree with the reviewer that the discussion of model biases in the manuscript is somewhat more extensive than would have been the bare minimum. The reason behind this is that this manuscript is the first one where this particular model setup has been used. We felt it was important to discuss the quality of the model results in detail here to build confidence in further studies we have planned to conduct with this modelling setup. We are glad that the referee feels that this setup is performing sufficiently well.

We would like to thank the reviewer especially for raising in this review a number of interesting unanswered questions about water transport in the area. For example, the question regarding nutrient supply to the Bothnian Sea is certainly something that motivated our efforts as a long term goal and that warrants further study in upcoming years. Deeper analysis of transport dynamics is planned for further studies. While it is not possible to address all of these questions here given the time and scope constraints, we hope to continue on this line of research for many years to come, and to be able to resolve most of these questions. We highly appreciate the encouragement the referee is offering for further analysis of the data in this manuscript.

We hope the changes we have implemented address the concerns raised by the referee. We believe the manuscript has notably improved in this process. Please also find below our detailed answers to the specific comments made by the reviewer.

Some minor specific comments:

> L21: What are these changes in the eutrophication status? Would be helpful information to better understand the context of the study.

We have modified the introduction to more clearly discuss how eutrophication relates to this study.

> Fig.1: Would be helpful to have an additional (small) inlet that shows the entire Baltic Sea and marks the location of the Aland Sea.

We understand the point and in fact experimented with this modification already before initial submission. This Figure is somewhat challenging, as it needs to convey a lot of information regarding the main focus area, its location, geographical references and the area of the model domain. Also important are the readability of the map as well as that it is appropriate for the context. After a lot of experimentation, the decision was made to leave the Baltic Sea map out, as it was difficult to combine it with the two other maps in a readable style. We understand that this is a compromise, and while we would prefer to keep this map as it is, we are willing to experiment with different solutions, if it is considered important. Perhaps a new Figure for the Baltic Sea map on another page might be the most feasible solution.

> L24-35: This paragraph would be better structured if it was split between the Aland Sea and the Archipelago Sea.

Done.

> L40: Maybe extend the last sentence by: " ... as the Archipelago Sea is too shallow to establish significant sub-halocline fluxes."

We would prefer not to state this so categorically in this paper. Although the Archipelago Sea is very shallow, there still are relatively deep canyons and pathways there. While their role might be relatively minor in this respect, it would require further study to quantify it in sufficient detail.

> L46/47: It is stated that there are 'no clearly defined water masses' in the Aland Sea but in the next sentence, 'the existence of a deep water type' is mentioned. Isn´t this contradictory?

We agree with the reviewer, this is a bit confusing. Hela (1958) seems to agree as well. He described the use of a TS diagram here "schematic and more or less arbitrary" and stated: "The word 'water type' is used instead of the more traditional one of 'water mass' in order to emphasize their more or less varying character." We have modified the paragraph, hopefully clarifying what Hela meant.

> L55: The unit [g kg-1] is used to refer to a change in salintiy. The cited study by Palosuo, however, dates back to the year 1964, where probably [psu] was used.

The reviewer is of course correct that Palosuo did not use [g kg-1]. He used per mille as the unit of salinity, which in this case corresponds to the same value in g/kg. We used [g kg-1] for the benefit of the reader in this indirect reference to make this paragraph easier to read. It may be interesting to note here that psu was not yet defined in the 1960's. In 1960's "the salinity was determined by titration with silver nitrate solution according to the method by Knudsen, and using Copenhagen Normal Water as the standard."

> L62-66: This paragraph can be condensed to: "... More recently, numerical modelling allows us to investigate intra- and inter-annual variability with much richer detail than we could with observations alone."

The paragraph has been condensed. We kept the reference to spatial and temporal coverage, as this is discussed later on in the manuscript. Hopefully the paragraph is acceptable now.

> L82: "... in this topographically complex and irregular area."

Fixed.

> L83: "... information about the bottom topography and related dynamics of different exchange pathways."

We would like to keep the mention of sill depth here to emphasize its importance. We modified the sentence, hopefully it is more clear now.

> L88: "... represents realistic bathymetric features in the investigated area."

This change would slightly alter the intention of the sentence, but we did try to clarify the sentence. Hopefully it is better now.

> L89/90: The aim of the study is not well outlined. I assume, the aim is at least to provide a detailled understanding of the present-day water mass exchange dynamics in the Aland Sea. And maybe some more such as to draw conclusions on the nutrient fluxes in the area or generally to provide information for the development of a science-based marine management strategy?

We agree that the aim and scope of the study needed clarification. Hopefully our modifications have improved the situation.

> L96: You may refer to the flushing times of the Aland Sea to justify the comparatively short spinup time of 6-7 months.

We have added information about the water renewal time in our model to section 3.3.

> L110: Why does the use of a sea ice model with thermodynamic formulation reduce computational demands?

In our profiling of model code we have found that when a fully coupled ocean-sea ice model is in use, the dynamic solver in the current model code for sea ice dynamics can take several tens of percents of computational power required by the model. We think that in a study like the present one, the tradeoff of turning off the full dynamics of the sea ice field in favour of a longer run makes sense. As the modelling system is updated and developed in the future, we will continue to do profiling to investigate any changes.

> L110-114: Would you expect that the water mass exchange is different during years/winters with large ice cover?

We expect that if there was a severe ice winter during the modelling period, this might introduce additional and unnecessary uncertainties to the analysis.

> L116-119: The calculation of volume transports does not have to be explained. These sentences could be condensed to: "We analyze volume transports across several transects to investigate the pathways of water exchange more closely."

We in principle agree that this paragraph is perhaps almost overly detailed. However, based on our discussions with our colleagues before and during this study, we expect that this article will be of interest to relatively many oceanographers whose primary interest does not lie in physical oceanography. Based on these discussions, we believe it might be beneficial for these readers if we define here what we mean by volume transport. We would therefore prefer to keep this paragraph in the manuscript.

> L128-133: Suggest to condense this paragraph to: "To mitigate artificial interpolation issues we checked and edited ... to ensure that it accurately represents the coastline and depth variations in the 0.25 NM resolution model domain."

This modification would, in our opinion, make the paragraph somewhat incomplete, as then the reader would not be informed of the kinds of issues that typically result from the bathymetry compilation process. We believe it is important also to openly discuss challenges encountered during the study. We have, however, tried to condense the paragraph to address this comment. Hopefully it has improved.

> L134-140: Suggest to delte this paragraph as it does not contain important information.

We respectfully would prefer to keep this information. Our reasoning is that this is relevant for the reader so that they are able to evaluate and reflect which areas in the model domain are most challenging from the bathymetric point of view.

> L141: Why is it advantagous or necessary to smooth the steepest bathymetry gradients?

The matter of model tuning involves a compromise where the model is tuned to perform as realistically as possible, while at the same time keeping the model numerically stable enough so that the model runs are able to complete successfully. We modified this sentence to clarify this.

> L182: What are these processes? Would be helpful to name a few examples: "... other processes such as ..."

This sentence was somewhat incomplete in the submitted version. We have now clarified it.

> Fig.3: Have you compared the station data also with the ocean reanalysis product you use to drive the model? As you are mentioning in L457, might be that the S biases are related to the boundary conditions.

Good idea. We added the reanalysis product mean to Fig. 3 to illustrate the biases.

> L209ff: Suggest to delete the first sentence and start with "We evaluate modelled current magnitudes and ...". Also suggest to delete L211-213 (While time ... ADCP was located.)

We included this information on how ADCP validation was performed to inform the reader of the challenges involved with validating currents and to establish why this section was included. We believe this is not common knowledge with all of the intended audience of this manuscript. For this reason, we would prefer to keep this information.

> L261: Why can the stronger surface flow at the western side be expected? Would be interesting to elaborate more on the dynamics.

This fragment at the end of the sentence was likely a reference to earlier results in the literature concerning currents in the Åland Sea, which are not really relevant for this analysis. It seems that we have left this fragment in the submitted manuscript by mistake. We have therefore removed it. Thank you for pointing this out.

> L264: Why is the persistency of surface currents lower in autumn? Due to stronger or more frequent south-westerly wind conditions?

We have expanded the analysis of wind conditions in the manuscript. Hopefully it now addresses this comment.

> L267: What driving mechanism turned the surface flow northward during winter 2013/2014?

Hopefully the expanded wind analysis also addresses this comment.

> Fig.8: Why is the surface circulation strongest in summer? Due to melt water discharge and export?

This is likely related to the wind distribution in summer having a large percentage of relatively strong northerly winds supporting the transport of excess fresh water southward from the Bothnian Sea, but lower percentage of relatively strong S and SW winds than spring. Comprehensive analysis of this would require more time that was available at this point, so we left out this still somewhat speculative explanation from the manuscript. Recent analysis of Ferrybox data by Äijälä (2019), however, supports this assumption, showing lower salinities in the Bothnian Sea during summer months (their Fig. 3.10).

Reference: Äijälä, C. (2019). Suolaisuuden ja lämpötilan vaihtelu Pohjanlahdella perustuen FerryBox-dataan. http://urn.fi/URN:NBN:fi:hulib-201910083600. Master's thesis, University of Helsinki. In Finnish.

> L296: At least give correlation coefficients to support this statement.

Thank you for pointing this out, this comment made us realize our sentence was quite badly written and could be understood in English differently than was intended. The purpose of this sentence was only to say that quantitatively the values at different transects are of the same order, rather than make statements of time series correlation. However, we have now added more information about the other transects. Hopefully this paragraph is more clear now.

> L316: "... through the Northern Aland Sill."?

Exactly, over the sill to the strait. We rephrased it to make it more clear.

> L326: What are 'the issues discoverd by Tuomi et al. and Miettunen et al.'?

Unfortunately, we had written this sentence in a way that did not make it clear that the improvement meant here is the inclusion of Åland Sea into the configuration. We have rephrased this to be more clear.