

# Author response to Referee Comments

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Thanks to the two anonymous referees for their useful comments. We will go over each point in the following. The equations, pages and lines we refer to in our responses are from the revised manuscript. Supplement material: LaTeX difference of the old and new manuscript.

## 1 Referee 1

1) While the authors suggest that the "dividing salinity method" is preferred to the "sign method" but the former requires a algorithm to find extrema of  $Q$ . While they provide a detailed description of the algorithm they: "came up with", that particular working ("that we came up with") made me wonder if they feel there are shortcomings in this method. If so, please elaborate. If not, perhaps they could change the wording to something like..." We provide a detailed description of an algorithm to obtain extrema of  $Q$  which is required to determining the dividing salinity values" ...

In principle, any algorithm dedicated to finding extrema should be suitable for the first step of finding the extrema of  $Q$ . It is then important that the final extrema are alternating minima and maxima and to reduce the extrema to the relevant ones.

We don't see any shortcomings of using the provided algorithm as it should find any minimum and maximum by using the 3 point window. The key to lower the number of relevant extrema is the threshold transport which filters out the physically unimportant ones.

We agree to rephrase to: "We provide a detailed description of a robust algorithm to obtain extrema of  $Q$  which is required to determine the dividing salinities in Appendix B." (P16 L4f)

2) Section 4.1 line 25. "The bulk values change considerably", I assume they mean  $s, Q$ . While they do show more variability than the dividing salinity method, they only vary by a few percent. . . so referring to it as considerable change seems a bit severe. Also, shouldn't the bulk quantities be noted as  $Q_{\text{in}}, s_{\text{in}}, Q_{\text{out}}$  and  $s_{\text{out}}$ ?

We just recognized that in the pdf provided by Ocean Science all labels from the pdf figures are not displayed correctly. In the original upload they are denoted by  $Q_{\text{in}}$  etc.. We rephrased to: "The bulk values still change with increasing  $N$ ." and deleted "and causes the sign method to converge towards the absolute exchange values.", because we don't provide the absolute values.

- 3) The map does not include the indicating the locations of places mentioned in the text (Gotland Island, Gotland Basin, Bothnian Bay).

Indications are also lost due to the pdf error.

## 2 Referee 2

- 1) [...] Selection criteria of the number of bins are well known for histograms. Drawing parallels between traditional histogram bins and TEF salinity bins would hopefully improve readability of the paper for wider audience.

Thanks for this very good comment. We incorporated this in the introduction by rephrasing or adding sentences:

- P3L7ff: "Comparable to a histogram, the transport data are binned into salinity classes according to their associated salinities. As discussed by MacCready et al. (2018), the resulting TEF profiles can become noisy, [...]"
- P3L16ff: "In order to obtain robust bulk values, which are less sensitive to the number of salinity bins, MacCready et al. (2018) suggested an alternative to the sign method. Instead of finding an optimal number of bins (a problem well known for histograms (Knuth, 2006)), they suggested to find a *dividing salinity*  $S_{\text{div}}$  which separates the inflow and outflow of a classical two-layer estuary with inflow at high and outflow at low salinity classes, i.e.  $q^c(S_{\text{div}}) = 0$  and  $Q^c(S_{\text{div}}) = \max(Q^c(S))$ ."

- 2a) The central finding in the MS is that one of the TEF calculation methods, the sign method, does not converge to the analytically determined exchange flow when the number of data points and the number of salinity bins both increase. The other method, the dividing salinity method, reveals nice convergence and therefore is the preferred TEF calculation method. This result is mentioned in several places, but proof is presented only very shortly in Section 2 P4 L25 to P5 L7 based on Fig. 3. This figure contains many curves and is not easy to read. Alternative or complementary figures reflecting the conclusion should be welcome.

We took  $s_{\text{in}}$  out from Fig. 3 and separated the dividing salinity method and the sign method into a and b subplots which makes the figure hopefully more clear and readable, see Fig. below.

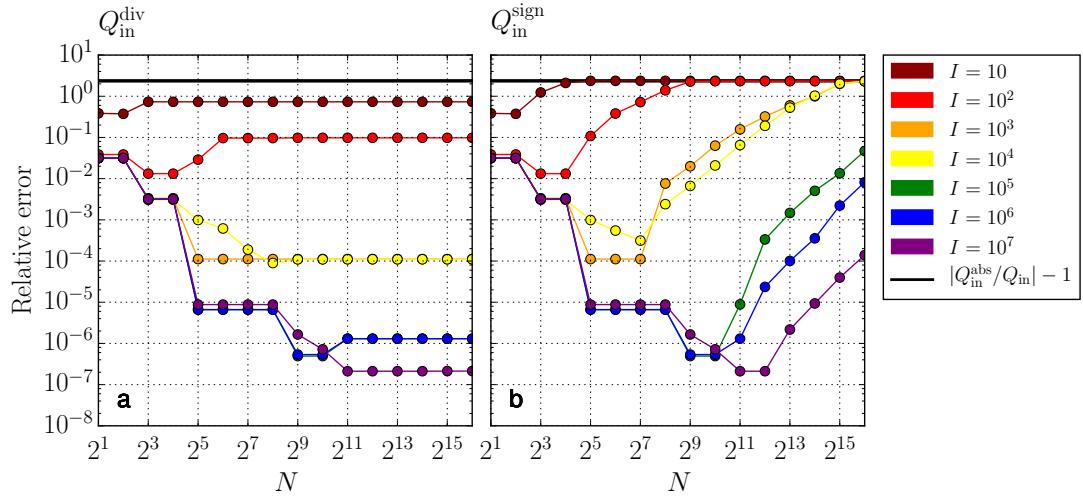


Figure 1: Oscillating exchange flow (see Section 2): relative error of  $Q_{\text{in}}$  computed with a) the dividing salinity method and b) the sign method in dependency of the number of time steps  $I$  (color) and salinity classes  $N$ . The sign method, (5) and the dividing salinity method, (7) coincide for a small number of salinity classes, but the error of the sign method converges in the limit of large  $N$  towards the error of the absolute bulk values (black line, (6)). In contrast, the error of the dividing salinity method converges towards a constant value. The errors of both methods decrease with increasing number of time steps  $I$ .

2b) Another issue with convergence presentation appears in the introduction on P3 L5-9 and L14-18 with infinite number of salinity bins. It remains unclear if eq (5) is mathematically derived or guessed from numerical experiments. The detailed parts could be moved to Section 2 in order to support analysis of the convergence of numerical results to analytical findings.

We removed the limit against infinity equation and replaced it with a more detailed explanation of why the sign method cannot converge towards the desired bulk values on P3L9-15, but will rather converge towards the absolute values.

”For data sets with pairwise disjunct salinities the number of transport values assigned to a single salinity bin decreases with the number of the salinity bins. After exceeding a threshold number of salinity classes, the bins will be sufficiently small to hold at most one transport value. In this case  $Q_{\text{in}}^{\text{sign}}$  is equal to  $Q_{\text{in}}^{\text{abs}}$ , with

$$Q_{\text{in}}^{\text{abs}} = \left\langle \int_A u^+ dA \right\rangle. \quad (6)$$

In most practical applications the salinity data are neither constant in space nor time and in the limit of an infinite number of salinity classes  $Q_{\text{in}}^{\text{sign}}$  will converge to  $Q_{\text{in}}^{\text{abs}}$  which is not the desired result for  $Q_{\text{in}}$ .”

3) [...] The 3-hourly output values were averaged using a special method that description is not available at the moment. At the end of the section it is written ”12- hourly model output is enough to resolve the exchange flow properly”. The conclusions say on the same matter ”Ideally, either results for all baroclinic time steps would be stored or the numerical model should do the binning into salinity classes of a chosen transect itself and save profiles of qc for desired tracers c”. It is not clear, how the conclusions match the findings in the previous chapters.

The ”special method” is thickness-weighted averaging (TWA) and is available as accepted JPO manuscript (JOR; doi: 10.1175/JPO-D-18-0083.1).

The comparison of the different methods is valid for any number of time steps. But we wanted to investigate also the influence of the temporal resolution. The results in Section 2 show that the bulk values only match the analytical values, if the temporal resolution is sufficiently high enough,  $\sim I = 1000$ . We added on P5L2-L5:

”The convergence analysis for different numbers of time steps is done to gain experience in the impact of temporal resolution of the oscillating flow on the final bulk values. With the time step here being the equivalent to the output interval of a hydrodynamic model which provides data for TEF, the findings can directly be transferred to the analysis of model data.”

Similarly to the varying  $I$  for the analytical scenario, we decreased the number of time points for the model data of Darss Sill by thickness-weighted-averaging to emulate less temporal resolution.

By the definition of  $Q$  in (1) the temporal average is outside of the integral which ensures that all physical, small or large temporal or spatial scales of currents are included. In

reality, the model output is saved i.e. 3-hourly which is in itself a conservative mean value (for our model), resulting that the  $c$  and  $u$  in (1) are mean values. Therefore,  $Q$  only approximates the "real"  $Q$  of all time steps. If one would save  $q$  and  $q^s$  online during the model run, there was no need to discuss the frequency of model output and all processes of small timescales were included. The offline analysis adds therefore additional errors. To make this point clearer, we rephrased P16L7-P16L15 in the best-practice section:

"Once a transect for the TEF analysis has been identified, the frequency for storing the output along that transect has to be chosen. For analytical correctness, the binning of data into salinity classes should be done online within the hydrodynamic model at every model time step. Time-averaged model output of these binned data can directly be used for the TEF-analysis. If the model only provides output within the model layers, the binning and averaging must be done offline during postprocessing. This would induce different kind of errors: (i) instantaneous data snapshots which skip intermediate model time steps do not conserve fluxes and do not consider intermediate salinity variations; (ii) model data obtained by thickness-weighted averaging over model time steps conserve fluxes, but merge data of different salinities. Both types of errors can be reduced with a sufficiently high output frequency, such that the output data still resolve the dynamics of the flow."

4) P1 L11-12: The sentence "Since inflow and outflow occurring at the same salinity compensate, TEF characterises the net exchange flow with the ambient ocean" should be reformulated. The first part of the sentence could be understood that the net exchange flow is missing since inflow and outflow compensate. Perhaps it should be "Since oscillatory inflow and outflow components occurring at the same salinity compensate...".

Changed to the suggested phrasing.

5) P3 L2: "TEF profiles computed from numerical model output can be noisy", it should be useful to present some physical reasons of noisy results. Perhaps, within well-mixed space-time domains conversion from depth to salinity coordinates has errors. Other reasons may also exist.

We think the main reason actually lies in the number of salinity bins as the second part of the quoted sentence says. As each data point has probably a different numerical salinity value, although they should have the same value, for increasing  $N$  compensating inflow and outflow components do not compensate anymore. For the analytical example the sampling in discrete values did not reproduce the exact salinity values for ebb and flood period, but deviated in some decimal places, which for high enough  $N$  created the deviation from the analytical example. We don't convert from depth to salinity coordinates by doing calculations. We use the model's salinities for each cell and only sort the tracer transport of said cell into the corresponding salinity bin. No noise is added by this process.

6) P3 L19: "Obviously, this dividing salinity method only works for classical exchange flows". Please consider if this sentence is needed at this point of introduction.

We reformulated to: "Using the maximum of  $Q$  only works for classical two-layer exchange flows."

7) P4 L13: "To visualise why only the dividing salinity method is converging towards the real bulk values" is not clear, "why only" cannot be found. It is not explicitly written by which method Fig. 2a-c have been produced.

Fig. 2a-c are produced with (15) and (16). We added a reference to these equations in the Figure caption.

We deleted the clause "To visualise [...]" . The paragraph now starts with: " We created a time series [...]" .

8) P4 L24: "The differences of the noises are because of ...", it is not clear the noises of what quantities are considered. It is well known that integrating the discrete curve makes the result smoother, but taking derivatives amplifies the small-scale variations (noise).

We mean that what you said here. We rephrased the sentence to: "The integration process of the discrete  $q^c$ , see (3), smooths the resulting  $Q^c$  . "

9) P11 L23-25 : "...TEF bulk values, computed with the sign method.  $q$  becomes more noisy with increasing  $N$  and causes the sign method to converge towards the absolute exchange values.". It is not clear what the absolute exchange values are and how the convergence is proved.

Please see point 2b).