- **RC2**: 'Comment on egusphere-2023-920', Anonymous Referee #2, 26 Aug 2023 reply

In the paper by Muchowski et al. new observations around a sill in the Southern Quark region (Baltic Sea), i.e. the area connecting the Northern Baltic Proper with the Bothnian Sea, are presented. The new dataset is massive and comprehensive as it includes velocity and hydrographic data but also microstructure measurements as well as high-res acoustic observations of turbulent mixing. Results show that turbulent diffusivities, dissipation and vertical flux rates are very large and about 3-4 orders of magnitude bigger near the sill with respect to reference unperturbed stations. Such a strong mixing is thought to result from hydraulic jumps and stationary lee waves and shown to affect also oxygen values, impacting the ventilation and residence times of the deep layers in the region.

The paper is well written and organized and fits well the scope of the journal. I have only a major concern related to the large diffusivity values shown in Figure 8 which are reported to reach 10^{⁻1}-1 m2/sec in the deeper layers and even be larger than 1 at about 160-m of depth. I urge the authors to discuss these large values and compare with those observed in other areas. Can this be related to the choice of a constant mixing efficiency?

This is a very good point and was indeed misleading. The high diffusivities were related to the bottom boundary layer where assumptions of isotropy and a constant mixing efficiency break down. To avoid the problem, we removed the lowermost 10 m of data in all MSS profiles and we entirely removed two MSS profiles (MSS 131 from EL19 and MSS 143 from EL20) which have outliers in dissipation rates slightly above 10 m from the seafloor. We updated the corresponding information in the Supplementary material tables ST3-ST4, updated Fig. 8 (which now became Fig. 9) including the figure caption, and added this information on LL491 of the tracked changes version: "For the calculation of dissipation rates, vertical turbulent diffusivities and salt fluxes, we removed the lowest 10 m of data close to the seafloor."

A process of revisions is suggested to address also the following minor concerns:

1. L24-25: the large values of mixing should be reported in the abstract

We included the values in the abstract on LL 28 of the tracked changes version which now reads: "Dissipation rates of turbulent kinetic energy, vertical turbulent diffusivities and vertical salt flux rates were increased by 3-4 orders of magnitude in the entire water column in the vicinity of the sill compared to reference stations not directly influenced by the overflow with average dissipation rates near the sill between 10^{-7} and 10^{-6} W kg^{-1}, average vertical diffusivities of 0.001 m^2 s^{-1} in the halocline and up to 0.1 m^2 s^{-1} below the halocline, and average vertical salt flux rates around 0.01 g m^{-2} s^{-1} in the halocline and between 0.1 and 1 g m^{-2} s^{-1} below the halocline."

2. Fig1: please add a rectangle in panel a to show the close-up of panel b like it is done in b with the yellow rectangle for panel c.

We added a yellow rectangle in (a).

Many dots in panel c are barely visible also for the color choices (green and turquoise over a blue or light-blue bathymetry). I suggest to have panel c and its inset (panel d) way larger and below panels a and b

We incorporated the suggested changes and updated Figure 1.

3. L135-141: Not sure these lines are relevant. Why is the bedrock geology important for this study?

It simply explains why we have such a dramatic seafloor topography in the first place, which is a premise for the mixing we address. We have removed some details from the paragraph and added a sentence, putting it better into context. The paragraph on LL 146 reads now:

"The dramatic seafloor morphology of the Southern Quark is to a large extent inherited from the underlying bedrock geology. The Southern Åland Sea basin and Lågskär Deep were formed from a tectonic depression underlain by 1.0-1.6 Ga old sandstone, while the rough seafloor areas surrounding Åland as well as the islands themselves, are predominantly comprised of even older crystalline bedrock, i.e. to a large extent the famous Rapakivi granite (EMODnet Geology) (Beckholmen and Tiren, 2009). The steep ridge in the Southern Quark mentioned above is proposed to be composed of dolerite, which is a resistant magmatic rock (Beckholmen and Tirén, 2009). The Southern Quark is a typical example of how the underlying geology often serves as the foundation for the rough seafloor, implying that the general geology may provide valuable insights into identifying critical regions for turbulent mixing, in the Baltic Sea or elsewhere."

4. L151-152: very true but also consider that ocean models need to have enough horizontal resolution to fully resolve the bathymetric features present in the DBM dataset and that it is usual practice in some ocean models (e.g. sigma models) to smooth bathymetry

Yes, this is true. It underlines the importance of high-resolution bathymetry data to parametrize mixing based on bathymetry roughness. The influence of the bathymetry on mixing and drag should, ideally, still be included.

5. L161: what kind of mixing values (i.e. diffusivity values) are expected to sustain such an estuarine-type circulation? How do they compare with those observed in this study?

Thank you. That's a very good idea to include those values. We added on LL 496 "We find that energy dissipation (10^{-7} - 10^{-6} W kg^{-1}), turbulent vertical mixing (0.001 – 0.1 m^{2}s^{-1}) and vertical salt flux rates (0.01 - 1 g m^{-2}s^{-1}) are increased by two to four orders of magnitude in the entire water column near the Southern Quark Sill compared to reference stations south of the sill, during both cruises EL19 and EL20 (Fig. 9d-f)."

and added the following paragraph on LL 500: "To maintain the general estuarine-type circulation in the Baltic Sea, an estimated mean diapycnal salt transport (from the deeper water across the pycnocline into the surface water) of 30 kg m^{-2} a^{-1} is needed (Reissmann et al. 2009). This equals a vertical salt flux of approximately 0.001 g m^{-2} s^{-1}. The in this study measured vertical salt transport in the halocline is in both regions, near the sill as well as in the north-western shallow part of the study region, with around 0.01 g m^{-2} s^{-1} an order of magnitude larger than this. It is important to note that Reissmann's estimate includes vertical transport during Major Baltic Inflows as well as all other sources of mixing."

6. L264-270: really confused mainly by the text here. It looks to me that at the beginning the ship ADCP data show northward velocities and not southward as written in the text while after 1.5 hours velocities are back towards the north and not the south. Please check, clarify and rephrase

We apologize for the confusion and admit the somewhat sloppy formulation here. At the very beginning of the transect the flow was indeed already northward. We rewrote the text starting on LL 278, trying to be a bit more precise and clear: "The simultaneously collected ship ADCP data reveal that in the first half of the almost 3-h long transect, the surface layer flow in the vicinity of the sill was mostly southward, as expected for an estuarine-type circulation, while at the very beginning of the transect as well as north of the sill, during the second half of the transect (at a distance of about 4.5 km from the start of the transect), the flow direction changed towards the south (Fig. 2a,b). Corresponding wind data from SMHI station Örskär (60.5256 °N, 18.3729 °E) in the vicinity of the study region reveal a shift in wind direction and drop in wind speed during the time of the measurement that coincides with the change in surface water current direction in the second half, about 1.5 hours into the transect (Supplementary Fig. S1).

7. L271-275: confused again as ADCP data are showing northward velocities also below the halocline but above 140m. Is this consistent with an estuarine-type circulation? If yes please explain better

*The very bottom water below 140 m flows north**west**ward and the intermediate water below the halocline down to 140 m flows northward.*

Reviewer 1 commented on the sentence as well. We rewrote on LL 289 of the tracked changes version to: "The main flow direction of the intermediate water below the halocline but above 140 m depth (the near-surface layer is outside the range of this instrument) was northward, as expected for an estuarine-type circulation."

8. Figure 2, panels c-f: please explain how is interpolation performed

We manually perform a linear interpolation to interpolate all data plotted in one panel on the same z axis grid and then use Matlab function contour to plot the data - which interpolates linearly between data points in 2D.

We changed Figure caption on LL 313 of the tracked changes version to: "(c)-(f) ***Linear*** *interpolation of MSS 212-230, excluding casts 221 and 224 which were aborted. (c) Conservative temperature, (d) absolute salinity, (e) oxygen concentration, (f) energy dissipation rate. Black isopycnals* ***plotted with Matlab function contour*** *at intervals of 0.05 g kg^{-1}, grey isopycnals at 0.01 g kg^{-1}."*

9. L325: why not saying simply white arrow instead of bright grey? Initially I got lost try to find a different grey arrow

We changed the caption and text to "white arrow".

10. L334: how can you be sure to say that below 100 m the echoes are due to eddies or large overturns?

We rewrote the sentence on LL 356 of the tracked changes version to: "In the deeper regions below 100 m, however, turbulence microstructure related to large overturns, eddies, and internal-wave oscillations is ubiquitous in the echogram (Fig.4, seen as more fuzzy scattering without clear edges) as well as in the microstructure data (Fig. 2c-e), causing increased mixing all the way down to the seafloor (Fig. 2f). Further away from the sill, increased mixing rates in the deep water are likely also influenced by the steep walls on both sides of the valley."

11. L339-340: what does "where there is little temperature and salinity microstructure" mean? Do you mean gradient?

We rewrote the sentence on LL 362 of the tracked changes version to: "where temperature and salinity gradients are small,"

12. L374: the dark blue dots in Fig.5f are barely visible

We added white circles around all dots in Figure 5f to make especially the dark blue dots better visible. A revised version of Figure 5 is now included in the manuscript. We further noticed that we hadn't mentioned the positions of the moorings in the caption of Figure 5 and added it now.

13. Figure 5: what about the two relative maximum temperature values for the black line across the 50-m depth? Intrusion of intermediate waters?

We agree and added on L395: "Furthermore, MSS profiles 229 and 230 have two pronounced local temperature maxima just above and below 50 m depth. We hypothesize that those could be intrusions of intermediate waters."

14. L409-425: the first and last lines of this paragraph seem to me to contradict each other as currents are indeed stronger and more persistent during EL19 and thus not comparable during both cruises. Or am I not grasping something here?

You're right! We changed the beginning of the paragraph on LL 441 of the tracked changes version to: "Mooring ADCP data show that during EL19, a flow reversal occurred only once, *from the dominant northward direction to southward flowing currents on the second day of the cruise. In contrast, during EL20,…"*

15. Figure 6: It looks there is an argument here that the wind sets up a ssh difference responsible for a barotropic signal. Wouldn't be possible to filter out the pressure-based signal to show the residual (estuarine-type?) circulation? Will a EOF-based approach work?

An EOF based approach would be a good idea to separate different modes of variability. However, we find that it is difficult to conclude much on barotropic vs. baroclinic motions from our ADCP mooring data set as it does not cover the upper 50 m of the water column.

16. Figure 7: just to point out that the velocities are indeed weaker but also less barotropic

Good point to mention. We added the information on LL 456 of the tracked changes version which now reads: "Overall currents north of the sill changed direction more frequently, were weaker, and less barotropic during EL20 compared to EL19 (compare Fig. 7 with Fig. 8a)."

17. Figure 8: impressed by the large numbers here. Why do kz values increase below 200 m for the unperturbed profiles?

Thank you for pointing this out. We added on LL 492 of the tracked changes version: "The increase in vertical diffusivities below 200 m depth in the EL19 reference measurements (Fig. 9e, black lines) is likely related to the decrease in buoyancy frequency (Fig. 9c, black lines), as the measured dissipation rates are close to the noise level of the profiler."

Why are the yellow lines useful or, in other words, what is the point of reporting values for the north-western part? For comparison?

Because we talk about water being modified along its way through the Aland Sea in many different areas. The sill that we discus is one big part but we think it is important to note that the sill is just part of the puzzle and there are many other mixing hotspots in the region. We added the yellow lines to compare this other region to the sill region. Furthermore we find it interesting to see how much T,S profiles, including halocline and mixed layer depth change over just a couple kilometers.

18. L515: please report here (and also in the abstract) also the diffusivity values

On LL 26 in the abstract we now included all values: "Dissipation rates of turbulent kinetic energy, vertical turbulent diffusivities and vertical salt flux rates were increased by 3-4 orders of *magnitude in the entire water column in the vicinity of the sill compared to reference stations not directly influenced by overflow with average dissipation rates near the sill between 10^{-7} and 10^{-6} W kg^{-1}, average vertical diffusivities of 0.001 m^2 s^{-1} in the halocline and up to 0.1 m^2 s^{-1} below the halocline, and average vertical salt flux rates around 0.01 g m^{-2} s^{-1} in the halocline and between 0.1 and 1 g m^{-2} s^{-1} below the halocline."*

On L 560 we also included the values of vertical diffusivities: "Average energy dissipation rates (10^{-7}-10^{-6} W kg^{-1}), vertical diffusivities (0.001-0.1 m^2 s^{-1}) and salt flux rates (0.01-1 g $m^{-2}s^{-1}$) were increased by 3-4 orders of magnitude in a reversing stratified overflow…"

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*Additionally, we included a new reference to Eilola and Stigebrandt for Baltic Sea circulation and replaced with it the previously given reference to Hakanson and Bryhm 2008 as this one is less original. LL 211 of the tracked changes version now reads: "southward flowing water, which becomes part of the surface water in the Northern Baltic Proper (Hela, 1958; **Eilola and Stigebrandt, 1998**; Markus Meier et al., 2006)."*