

We thank the editor, Prof. Ilker Fer, and anonymous referee #1 for carefully reviewing the revised version of the manuscript and for providing helpful feedback to enhance the paper's quality. We addressed all issues raised in the comments below and incorporated the revised changes into the manuscript. The comments are included below in black, and our responses to the comments are in blue. The line numbers in the responses refer to the marked-up manuscript; modified text is presented in red in the marked-up version and presented below in the responses as *italic text*.

Response to the editor, Prof. Ilker Fer

Dear authors,

I apologize for the lengthy delay in the review process. The second reviewer was substantially delayed and, ultimately, was unable to provide a report because of other commitments. Therefore, I stepped in and reviewed the revised manuscript myself.

The manuscript has improved substantially, and I find that you have addressed the reviewers' comments satisfactorily overall. However, a few important issues remain, some of which are also noted in the reviewer's report. In addition, I have several concerns regarding the presentation and interpretation of the Thorpe scale and the derived diffusivity estimates. Please address these points carefully in your revision.

I also strongly recommend including at least one detailed example profile to illustrate the processing steps and support the interpretation of the results. I will review the revised manuscript and will not send it out to reviewers.

Thank you, Prof. Fer, for handling the manuscript and for your time and effort in reviewing it; we really appreciate it. We have addressed your comments and resolved your concerns, as shown in the responses below. As recommended, we added a detailed example profile to illustrate the processing steps and support the interpretation of the results in the supplementary material (Figures S1-S3 and Table S1).

My comments:

The CTD (SeaCAT) appears to have been profiled at a relatively slow rate of approximately 0.24 m/s. Was the instrument mounted on a sufficiently heavy frame to ensure stable profiling in the presence of strong currents?

Thank you for this comment. The CTD was attached to a rosette water sampler to ensure stability in the water. We added this to the Methods for clarity; please check lines 95-97, quoted below:

“at 4 Hz and attached to a rosette water sampler to ensure stability during deployment. However, we did not collect water samples to adjust the CTD measurements.”

Did you observe substantial variations in dP/dt , including periods of reduced profiling speed? If so, could this have affected the derived salinity and density measurements, and consequently the estimates of N^2 ? A discussion of these issues would help establish confidence in the data quality.

Thank you for this comment. We examined the full dP/dt for all CTDs, yielding median values of 0.35 m s^{-1} and 0.0875 m for the profiling speed and vertical sampling interval, respectively. During profiling (as shown in Figure S1), we stopped at 50 m intervals to collect continuous oxygen measurements for a few minutes for another purpose unrelated to the current work. However, as is clear from the dP/dt compared to the density profile in Figure S1, these stops have no significant effect on salinity or density. We added this explanation to the manuscript; please check lines 98-101, quoted below:

“During profiling, we stopped at 50 m intervals to collect continuous oxygen measurements for a few minutes for another purpose unrelated to the current work. However, as the data quality control (Figure S1) illustrates, these stops had no significant effect on salinity or density.”

In Figure 3, the Thorpe scale appears to be saturated at a minimum value of 2 m. The absence of detectable overturns should not automatically be assigned $LT=2 \text{ m}$, as this would imply a non-negligible dissipation rate and, consequently, substantial diffusivity. In its current form, this aspect of the analysis does not appear physically credible.

Thank you for this comment. We regenerated the figure using only the accepted patches at the station locations, without interpolation between adjacent stations to avoid unreal values. Please check the revised Figure 3. We actually repeated the process, starting from N^2 and Tu calculations, then moving to Thorpe scale analysis, to ensure consistency and robustness. Please also check the updated Figure 2d and f. We used the CTD's original resolution for the analysis; we clarified this in the Methods (lines 149-150): *“The Thorpe analysis was performed using the original-resolution profiles.”*

I suggest avoiding gridded contour plots of interpolated LT and Krho (Fig. 3). Instead, consider displaying station-based estimates using horizontal bars or color-coded markers plotted at the station locations. This would more faithfully represent the actual sampling. Related to this point, the background values of diffusivity appear quite large and do not seem consistent with the description of "low diffusivity" in line 250.

Thank you for this comment. As mentioned above, we regenerated Figure 3 using only the accepted patches at the station locations, without interpolation between adjacent stations. Please check the revised Figure 3.

I recommend including detailed profiles from Station 29 (e.g. in the supplementary material) as an illustrative example. In addition to density, LT, and Krho, it would be helpful to provide profiling speed (dP/dt) and any other quantities relevant to quality control and overturn detection. Such examples would allow readers to better evaluate the robustness of the methodology.

Thank you for this comment. As recommended, we added a detailed example profile (Station 29) to illustrate the processing steps and support the interpretation of the results (please see Figures S1-S3 and Table S1). We also added detailed QC parameters for the Thorpe analysis to the Methods. Please check lines 147-178, quoted below:

“The Thorpe analysis was performed on the CTD profiles and each used density profile was quality-controlled following Park et al. (2014) and Gargett and Garner (2008), retaining only vertically coherent, well-resolved overturns (Figures S1-S3 and Table S1). The Thorpe analysis was performed using the original-resolution profiles. Pressure reversals and observations with smoothed positive-down profiling speeds below 0.25 dbar s^{-1} ($\sim 0.25 \text{ m s}^{-1}$) were removed before the hydrographic and overturn analyses. Following Park et al. (2014), the first 20 m below the sea surface were excluded from the analysis because near-surface measurements are often highly contaminated, likely by turbulence generated by the hull. The density variable used for overturn detection was the potential density anomaly referenced to the surface or 0 dbar (σ_0 , IOC et al., 2010). Apparent density inversions were initially treated as candidate overturns. They were retained only if they were vertically coherent, exceeded the adopted density-noise threshold, and passed the overturn-ratio criterion. A fixed dataset-level effective residual density noise floor was estimated from detrended σ_0 residuals within screened, locally well-mixed intervals. The median residual root-mean-square density variability was $4.9 \times 10^{-4} \text{ kg m}^{-3}$. Thresholds corresponding to

three-, four-, and fivefold this value were tested. The principal overturn distribution varied only slightly among these tests. The five-times-RMS value, $2.46 \times 10^{-3} \text{ kg m}^{-3}$, was adopted for the primary analysis because it produced the clearest and most stable overturn boundaries while retaining the principal vertically coherent patches. The estimated RMS is interpreted as a dataset-specific effective residual noise floor that may include unresolved natural fine structure in addition to instrumental noise. Top-down and bottom-up intermediate-density profiles were constructed using the adopted density-noise threshold following Gargett and Garner (2008) and Park et al. (2014). The average of the top-down and bottom-up intermediate profiles was then used for the primary overturn analysis. Sensitivity tests using the measured, top-down, bottom-up, and averaged intermediate profiles showed that the averaged profile retained the principal overturns identified in both processing directions while minimizing isolated and direction-dependent features. Candidate overturn patches were identified using the MixSea Thorpe-reordering procedure (Voet et al., 2023). The overturn ratio (R_o), which represents a data-filtering criterion used to distinguish genuine turbulent density overturns from artificial, instrument-induced false inversions (Gargett and Garner, 2008), was also used. Only candidate patches satisfying $R_o \geq 0.25$ were retained. Sensitivity tests using R_o values from 0.10 to 0.30 produced the same principal overturn pattern, whereas $R_o = 0.35$ removed several otherwise coherent patches. A minimum of 0.5 m for L_T and 1.5 m for patch thickness were used as additional Thorpe QC criteria.”

Li 304-309: I fully agree that overflow regions can be highly energetic and turbulent environments where overturns are expected. However, given the importance of the derived turbulence estimates, I encourage you to provide a more cautious discussion of the methodology, particularly regarding the occurrence of $N^2 < 0$. Additional discussion of measurement uncertainty, noise levels, and the interpretation of negative stratification would strengthen this section and increase confidence in the conclusions.

Thank you for your comment. We update the methodology for the N^2 as quoted below (lines 132-135):

“Positive values of N^2 represent statically stable stratification, and negative values represent density inversion. Density inversions were interpreted as physically meaningful overturning only where the associated density structure exceeded the adopted density-noise threshold and passed the Thorpe-overturn quality-control criteria (Section 2.2.2).”

Additionally, as mentioned earlier, we repeated the process, starting with N^2 and Tu calculations, then moving to Thorpe scale analysis, to ensure consistency and robustness. We updated the N^2 and Tu figures accordingly (please check Figure 2d and f).

Other minor remarks from my reading: (line numbers from the author's tracked version)

Li 14: use regular first letter for Marginal

Thank you for your comment. We updated the text as requested. Please check line 14.

Li 17-18: UAE, CTD, ROV are not defined. Avoid acronyms in the abstract if not using more than once. Introduce acronyms and use them in the main text.

We updated the text as requested. Please check lines 17-19.

Li 19: consider hydraulic transition (instead of hydraulic-jump-like transition)

We updated the text as requested. Please check line 20.

Li 20, can quantify the thickening instead of “dramatically”

We added quantities for the layer thickness and thickening; please check lines 19-20, quoted below:

“The P/AG outflow forms a thin (10-30 m) bottom-attached layer that, on crossing an abrupt bathymetric step, undergoes a hydraulic transition and thickens to 200 m”

Li 27: may alter the outflow dynamics, its detachment depth, ...

We updated the text as requested. Please check lines 27-28.

Li 43: define UAE

We defined the abbreviation as requested. Please check line 43.

Li 51: have been suggested

We updated the text as requested. Please check line 51.

Li 96-97: turn this sentence around: average speed is... corresponding to an average vertical sampling interval ...

This sentence has been modified. Please check line 97.

Li 98: affected also by the wake of the frame, I think. Improve wording on “No bottle sampling....”

We modified this part; please check lines 96-97.

Li 100: N2 is not defined; better to use words (instead of N2) here to avoid introducing an equation

We updated the text as requested. Please check line 102.

Li 107: define SA and CT, and remember capitalized first letters (the standard symbols for these are S_A and Θ)

We defined the parameters as requested. Please check lines 109-110.

Li 116: reword plume top

We reworded it to “*the upper depth of the outflow and its thickness*”. Please check line 118.

Li 120: replace “Whereas core” with “The plume core”

We updated the text as requested. Please check line 122.

Li 122: Define (by equations), T_u and N_2

Thank you for your comment. We defined the parameters by equations as requested. Please check lines 124-125.

Li 127: Replace the sentence with “Positive values of N_2 represent statically stable stratification, and negative values represent density inversions.”

We updated the text as requested. Please check lines 132-133.

Li 130: cross-reference the section where density-noise and QC are addressed

Done as requested. Please check line 135.

Li 131-132: All these references are misplaced, and should be put where relevant (not for interpolation and gridding for plotting).

We moved the references to their correct position. Please check lines 131.

Li 133: this subsection title can be improved

We changed the subsection title to “*Hydrographic Proxies for Hydraulic Adjustment and Mixing*”, please check line 136.

Li 134: ADCP/LADCP not defined

We defined the abbreviation as requested; please check line 137.

Li 140: replace “CTD density profile” with “density overturn” (because LT is calculated over overturns)

We updated the text as requested. Please check line 143.

Li 149: say what σ_0 is

We defined σ_0 as requested; please check lines 154-155.

Li 153: what is the density-noise threshold? Ideally this should be defined for the data set (not per profile) as you are using the same instrument.

We added details on the density-noise threshold; please check lines 158-166, quoted below:

“A fixed dataset-level effective residual density noise floor was estimated from detrended σ_0 residuals within screened, locally well-mixed intervals. The median residual root-mean-square density variability was $4.9 \times 10^{-4} \text{ kg m}^{-3}$. Thresholds corresponding to three-, four-, and fivefold this value were tested. The principal overturn distribution varied only slightly among these tests. The five-times-RMS value, $2.46 \times 10^{-3} \text{ kg m}^{-3}$, was adopted for the primary analysis because it produced the clearest and most stable overturn boundaries while retaining the principal vertically coherent patches. The estimated RMS is interpreted as a dataset-specific effective residual noise floor that may include unresolved natural fine structure in addition to instrumental noise.”

Li 159: define overturn ratio

We defined the overturn ratio as requested. Please check lines 173-177, quoted below:

“The overturn ratio (R_o), which represents a data-filtering criterion used to distinguish genuine turbulent density overturns from artificial, instrument-induced false inversions (Gargett and

Garner, 2008), was also used. Only candidate patches satisfying $R_o \geq 0.25$ were retained. Sensitivity tests using R_o values from 0.10 to 0.30 produced the same principal overturn pattern, whereas $R_o = 0.35$ removed several otherwise coherent patches.”

Li 163: define effective vertical detection scale

We added a sentence about the minimum L_T and patch thickness thresholds used. Please check lines 177-178, quoted below:

“A minimum of 0.5 m for L_T and 1.5 m for patch thickness were used as additional Thorpe QC criteria.”

Li 1164: Thorpe-derived diapycnal diffusivity proxy -> diapycnal diffusivity estimate based on Thorpe scales

We updated the text as requested. Please check lines 184-185.

Li 166: the link between K_{rho} using L_T , and L_O and K_{rho} using dissipation rate is not clear. It will be clear if you define the Ozmidov length, L_O .

Thank you for this comment. We updated the explanation of L_T , and L_O and K_p for clarity. Please check lines 179-189, quoted below:

“The Ozmidov length, L_o , represents the largest turbulent length scale that is not strongly constrained by stable stratification and was defined as $L_o = \sqrt[3]{(\epsilon/N^3)}$, where ϵ is the turbulent kinetic energy dissipation rate, and N is the buoyancy frequency. The empirical Dillon-type relationship was expressed as $L_o = \alpha L_t$, where α is the Ozmidov-to-Thorpe scale ratio. A value of $\alpha = 0.80$ was adopted. Combining the Ozmidov-scale definition with this relationship gives the Thorpe-derived dissipation proxy $\epsilon_t = \alpha^2 L_t^2 N^3$ and therefore $\epsilon_t = 0.64 L_t^2 N^3$. The corresponding diapycnal diffusivity estimate based on Thorpe scales ($K_p^{(T)}$) was calculated using the Osborn relationship $K_p^{(T)} = \Gamma \epsilon_t / N^2$, which gives $K_p^{(T)} = \alpha^2 \Gamma L_t^2 N$. A mixing efficiency of $\Gamma = 0.20$ was assumed. Using $\alpha = 0.80$ and $\Gamma = 0.20$ gives $K_p^{(T)} = 0.128 L_t^2 N$ (Dillon, 1982; Ozmidov, 1965; Osborn, 1980). The resulting L_T , ϵ_T , and $K_p^{(T)}$ estimates are interpreted as relative hydrographic indicators of overturning and mixing susceptibility rather than direct turbulence measurements.”

Li 167: The values of Thorpe scale proxies are interpreted as relative-> The diffusivity estimates from Thorpe scale analysis bear large, unquantified uncertainties and can be interpreted as a mixing proxy, as relative.....

We updated the text as requested. Please check lines 190-191.

Li 170: The horizontal resolution

We updated the text as requested. Please check line 201.

Li 187: “: where an...” ->“. A flow with speed exceeding c_i is supercritical... and a slower flow is ...”

We updated the text as requested. Please check lines 220-221.

Fig 2d, N2: this figure shows the entire deep layer ($x > 45\text{km}$, $z > 350\text{m}$) as unstable. This section needs care. Also note, Tu defines this part as SF (not US); so there is a mismatch. In general I am too skeptical to your $N2 < 0$ using 2-m processed SeaCAT data.

Thank you for this comment. As mentioned earlier, we repeated the process (using the original CTD resolution), starting with N^2 and Tu calculations, then moving to Thorpe scale analysis, to ensure consistency and robustness. We updated the N^2 and Tu figures accordingly (please check Figure 2d and f).

Li 370: what is “interfingering”?

Thank you for this comment. We replaced “interfingering” with “interleaving”, please check line 404.

Response to Referee #1

Revised title: Hydrographic Transformation of the Persian/Arabian Gulf Outflow over Rough Shelf Bathymetry in the Gulf of Oman

Author(s): Ahmed Abdelmaksoud, Aisha H. Al-Suwaidi, Gerd Bruss, Kaveh Samimi-Namin, and Mohammed Y. Ali

MS No.: egusphere-2026-1925

MS type: Research article

Iteration: First revision

The authors have placed a greater emphasis on the core of the study, the water mass modifications of the P/AG outflow. They have produced more details about the data processing (CTDs) and added some useful calculations of derived quantities (L_T , K_v , c_i) that help strengthening the discussion about turbulence, mixing and flow evolution along the shelf. Overall, I find the manuscript significantly improved, more focused, and most importantly, more convincing. Consequently, I recommend the manuscript for publication after bringing some answers (and modifications if needed) to the following comments:

We thank the respected reviewer for the time and effort in reviewing it and providing constructive feedback. We have addressed your comments and resolved your concerns, as shown in the responses below.

Fig. 3a: The authors states that, L_T , must pass several criteria found in the literature to be validated: vertical coherence, density-noise threshold (please, provide its value along lines 152-154), overturn ratio criterion. Consequently, I would expect that, on such a wide section, many areas would failed passing those criteria (= L_T undefined), or L_T would be zero because the fluid is stably stratified. However, Fig. 3a exhibits $L_T \geq 2$ m everywhere, how can that be?

Thank you for this comment. We agree that the QC and validation criteria for the Thorpe scale analysis were not described in detail. We updated the Methodology on that part. We also added a detailed example profile (Station 29) to illustrate the processing steps and support the interpretation of the results (please check Figures S1-S3 and Table S1). Additionally, we regenerated Figure 3

using only the accepted patches at the station locations, without interpolation between adjacent stations to avoid unreal values. Please check the revised Figure 3.

Please check lines 147-178, quoted below:

“The Thorpe analysis was performed on the CTD profiles and each used density profile was quality-controlled following Park et al. (2014) and Gargett and Garner (2008), retaining only vertically coherent, well-resolved overturns (Figures S1-S3 and Table S1). The Thorpe analysis was performed using the original-resolution profiles. Pressure reversals and observations with smoothed positive-down profiling speeds below 0.25 dbar s^{-1} ($\sim 0.25 \text{ m s}^{-1}$) were removed before the hydrographic and overturn analyses. Following Park et al. (2014), the first 20 m below the sea surface were excluded from the analysis because near-surface measurements are often highly contaminated, likely by turbulence generated by the hull. The density variable used for overturn detection was the potential density anomaly referenced to the surface or 0 dbar (σ_0 , IOC et al., 2010). Apparent density inversions were initially treated as candidate overturns. They were retained only if they were vertically coherent, exceeded the adopted density-noise threshold, and passed the overturn-ratio criterion. A fixed dataset-level effective residual density noise floor was estimated from detrended σ_0 residuals within screened, locally well-mixed intervals. The median residual root-mean-square density variability was $4.9 \times 10^{-4} \text{ kg m}^{-3}$. Thresholds corresponding to three-, four-, and fivefold this value were tested. The principal overturn distribution varied only slightly among these tests. The five-times-RMS value, $2.46 \times 10^{-3} \text{ kg m}^{-3}$, was adopted for the primary analysis because it produced the clearest and most stable overturn boundaries while retaining the principal vertically coherent patches. The estimated RMS is interpreted as a dataset-specific effective residual noise floor that may include unresolved natural fine structure in addition to instrumental noise. Top-down and bottom-up intermediate-density profiles were constructed using the adopted density-noise threshold following Gargett and Garner (2008) and Park et al. (2014). The average of the top-down and bottom-up intermediate profiles was then used for the primary overturn analysis. Sensitivity tests using the measured, top-down, bottom-up, and averaged intermediate profiles showed that the averaged profile retained the principal overturns identified in both processing directions while minimizing isolated and direction-dependent features. Candidate overturn patches were identified using the MixSea Thorpe-reordering procedure (Voet et al., 2023). The overturn ratio (R_o), which represents a data-filtering criterion

used to distinguish genuine turbulent density overturns from artificial, instrument-induced false inversions (Gargett and Garner, 2008), was also used. Only candidate patches satisfying $R_o \geq 0.25$ were retained. Sensitivity tests using R_o values from 0.10 to 0.30 produced the same principal overturn pattern, whereas $R_o = 0.35$ removed several otherwise coherent patches. A minimum of 0.5 m for L_T and 1.5 m for patch thickness were used as additional Thorpe QC criteria.”

Fig. 2d: in the same vein, $N^2 < 0$, everywhere below 400 m. This seems suspicious. Here too, even though this N^2 is calculated with a coarser vertical resolution as done for LT, some threshold should be taken to validate that N^2 is indeed negative.

Thank you for your comment. As mentioned earlier, we repeated the process, starting with N^2 and Tu calculations, then moving to Thorpe scale analysis, to ensure consistency and robustness. We updated the N^2 and Tu figures accordingly (please check Figure 2d and f).

Minor comments:

l. 127: ‘Positive N^2 identifies candidate static instability or density inversion’ ... a bit misleading, positive N^2 = stable while $N^2 < 0$ = unstable

We updated this part for clarity. Please check lines 132-135, quoted below:

“Positive values of N^2 represent statically stable stratification, and negative values represent density inversion. Density inversions were interpreted as physically meaningful overturning only where the associated density structure exceeded the adopted density-noise threshold and passed the Thorpe-overturn quality-control criteria (Section 2.2.2).”

l. 189 – 190: ‘... are unavailable, c_i is not an observed Froude number but a hydrographically derived speed scale that can be compared...’ Confusing! A few lines above, c_i is correctly defined as a phase speed. Suggested change: ‘... are unavailable, the Froude number cannot be estimated but c_i , calculated from hydrographic properties, provides a velocity scale that can be...’

Thank you for this comment. We modified this part; please check lines 220-226, quoted below:

“A flow with speed exceeding c_i is supercritical ($Fr > 1$), and a slower flow is subcritical ($Fr < 1$). Because current measurements are unavailable, the Froude number cannot be estimated but c_i , calculated from hydrographic properties, provides a velocity scale that can be compared with

independent current estimates from the literature. Because c_i depends on the product $g'H$, downstream plume thickening may partly or fully compensate for a decrease in plume-to-ambient density contrast. It is interpreted as consistent with, rather than proof of, a change in hydraulic state.”

l. 191: The decrease in g' due to dilution could possibly balanced the increase in H . in Fig. 3c, it seems that the expected decrease in g' due to water entrainment, has no impact on c_i (e.g. between station 50 and 60). Thus, I was wondering how g' was really calculated?

Thank you for this comment. We agree that the calculation of c_i required a clearer explanation. We modified this part for clarity; please check lines 214-226, quoted below:

“To place the plume-thickness variations in a hydraulic context, we computed a critical velocity, $c_i = \sqrt{g'H}$, the along-section speed at which the Froude number of the bottom-attached layer, $Fr = U/\sqrt{g'H}$, equals unity. Here $g' = g \Delta\rho/\rho_0$ is the reduced gravity from the density contrast between the P/AG plume and the overlying ambient water, and H is the local plume thickness. The plume-to-ambient density contrast was calculated as $\Delta\rho = \rho_p - \rho_a$, where ρ_p is the plume density (P/AGw-weighted mean potential density referenced to 0 dbar) and ρ_a is the ambient density (median potential density within the 50 m layer immediately above the plume top). A flow with speed exceeding c_i is supercritical ($Fr > 1$), and a slower flow is subcritical ($Fr < 1$). Because current measurements are unavailable, the Froude number cannot be estimated but c_i , calculated from hydrographic properties, provides a velocity scale that can be compared with independent current estimates from the literature. Because c_i depends on the product $g'H$, downstream plume thickening may partly or fully compensate for a decrease in plume-to-ambient density contrast. It is interpreted as consistent with, rather than proof of, a change in hydraulic state.”