Review of "Along-channel Variability of Total Exchange Flow in a Narrow, Well-mixed Estuary: Influence of the M4 Tide"

Response to Reviewer 2

The authors would like to thank Reviewer 2 for the thorough reading of the manuscript and for the insightful and useful comments and suggestions that have greatly helped improve the quality of this manuscript. The manuscript has undergone a thorough revision according to the editor and reviewers' comments.

Please find below a point-to-point reply to your comments. The original Comments are written in blue. Authors' answers are written in black. Text modifications made in the revised version of the manuscript are indicated in *violet italic*.

Reviewer 2

RC2: 'Comment on egusphere-2025-6526', Anonymous Referee #2, 17 Mar 2026

This article presents an analysis of exchange fluxes in the Guadalquivir River based on a comprehensive set of long-term current and salinity time series data from 7 stations located along the river. The analysis focuses on periods of low river flow, when water transport is dominated by tidal current dynamics. The proposed topic is of considerable interest and can provide valuable complementary information for understanding current processes affecting the Guadalquivir River, such as the progressive salinization of inland waters, which is particularly pronounced during periods of low river flow. The available database is well-suited to yield truly conclusive results from the analysis. So, the research topic proposed in the article is relevant, and the results derived from this article have the potential for great scientific interest. However, I honestly believe that the current version of the article can be improved, and I recommend reviewing several aspects of the work that should be addressed before proceeding with its acceptance for publication.

The following lines outline the main issues and suggestions that I believe the authors should consider:

Q.2.1 — The advantages of estimating exchange flows using the TEF method compared to traditional Eulerian estimates in the Guadalquivir estuary should be explained. I have the impression that the same results could be obtained using averages based on Eulerian estimates. If this is not the case, it should be justified how the TEF method improves exchange flow estimates in this estuary.

R.2.1 This is very interesting point. Thank you for pointing it out. The reason why Total Exchange Flow (TEF) is used here instead of Eulerian exchange flow is that it is closer related to estuarine mixing.

The TEF analysis framework provides one consistent calculation method that allows computing the exchange flow and its characteristic salinities using salinity (isohaline) coordinates (MacCready, 2011; Burchard et al., 2019). With this, TEF provides for each estuarine transect profiles of transports of volume and salt per salinity class, as function of a salinity coordinate substituting the two-dimensional Eulerian coordinate of the transect. In fact, the Eulerian approach substantially simplifies the representation of the exchange flow. Also, the TEF could be mapped back from salinity coordinates to vertical (Eulerian) coordinates. However, as shown by (e.g.) MacCready, (2011); Sutherland et al., (2011); and Burchard et al., (2018a), this Eulerian method strongly underestimates the exchange flow. A parcel of water that is flowing into the estuary across the transect at a certain salinity class and afterwards flowing out at the same salinity class but possibly at a different area of the transect (i.e., without having been mixed), does not contribute to TEF. In contrast to that, such an exchange of water parcels without mixing would contribute to Eulerian exchange flow. This shows that TEF is closely related to salinity mixing in estuaries (see Burchard et al., 2025, for more details). The TEF analysis framework determines the most representative Knudsen-bulk estimates by finding the correct values of incoming salinity s_{in} and outgoing s_{out}, namely the Knudsen-consistent salinity values or estimates. Tidally-averaged net volume and mass transport through an estuarine cross-section are thus obtained sorted by salinity classes (transports as a function of salinity class). Among its outstanding features of TEF are: its estimates include transports due to covariance of current velocity and salinity, thereby generalizing the classical Knudsen relations; and TEF naturally allows quantifying volume-integrated mixing, which in turn controls the inflow and outflow transport of water and salinity.

We are explaining this now with a modified text in the introduction:

The Total Exchange Flow (TEF) analysis framework provides one consistent calculation method that allows computing the exchange flow and its characteristic salinities using salinity (isohaline) coordinates (MacCready, 2011; Burchard et al., 2019). With this, TEF provides for each estuarine transect profiles of transports of volume and salt per salinity class, as function of a salinity coordinate substituting the two-dimensional Eulerian coordinate of the transect, a method that substantially simplifies the representation of the exchange flow. Moreover, the TEF could be mapped back from salinity coordinates to vertical (Eulerian) coordinates. However, as shown by several authors (MacCready, 2011; Sutherland et al., 2011; Burchard et al., 2018a), this Eulerian method strongly underestimates the exchange flow. A parcel of water that is flowing into the estuary across the transect at a certain salinity class and afterwards flowing out at the same salinity class but possibly at a different area of the transect (i.e., without having been mixed), does not contribute to TEF. In contrast to that, such an exchange of water parcels without mixing would contribute to Eulerian exchange flow. This shows that TEF is closely related to salinity mixing in estuaries (see Burchard et al., 2025, for more details). The TEF analysis framework determines the most representative Knudsen-bulk estimates by finding the correct values of s_{in} *and* s_{out}*, namely the Knudsen-consistent salinity values or estimates. Tidally-averaged net volume and mass transport through an estuarine cross-section are thus obtained sorted by salinity classes (transports as a function of salinity class). Among its outstanding features are: TEF estimates include transports due to covariance of current velocity and salinity, thereby generalizing the classical Knudsen relations; and TEF naturally allows quantifying volume-integrated mixing, which in turn controls the inflow and outflow transport of water and salinity.*

Q.2.2 — Why isn't the TEF method applied directly to the observations before applying it to the synthetic series constructed from the tidal harmonic components M2 and M4? What motivates not applying the method to the original observed signals? I think it's interesting to decompose the contribution of the different tidal constituents in the exchanges, following the procedure presented in the article, but after presenting the actual estimates considering the total signal. In that sense, I think it's also interesting to evaluate the contribution of the next tidal constituent S2 and the reduced water component MS4 originating from the interaction between constituents M2 and S2.

R.2.2 Both reviewers pointed this out. We thank them for raising this important point.

One of the main objectives of this study is to assess the influence of the M4 constituent on Total Exchange Flow. As the Reviewer mentioned, the M4 is the first overtide of the M2, and it is known to generate tidal asymmetry in both water levels and currents (e.g., Speer and Aubrey, 1985; Parker, 1991; Friedrichs and Aubrey, 1994). The M4, which is nonlinearly generated from the primary tidal constituent M2, affects the residual transport of water, solutes, and particulate matter (e.g. de Swart and Zimmerman, 2009; Burchard et al., 2018), and is therefore expected to also influence TEF. However, the specific impact of tidal asymmetry on TEF has remained largely unexplored. This study aims to address this knowledge gap by analyzing data from the Guadalquivir estuary and carrying out a sensitivity analysis of TEF to the inclusion of the M4 in both the tidal currents and salinity. Understanding the role of the M4 constituent in estuaries is essential for identifying the key mechanisms that control exchange flow and for evaluating their implications for water quality and residence times.

Other semidiurnal constituents, such as S2 and N2, are responsible for the spring-neap modulation of current and salinity time-series. This modulation is also present in the TEF (see, e.g., Wang et al., 2017). In the case of this study, the largest contribution in magnitude to the TEF comes from M2. Figure 1 in this response document shows the outgoing and incoming water and salinity volume transports (left and right panels, respectively), and the Knudsen-consistent salinities for inflows and outflows (middle panel). The results for M2 only (blue curves and circles; the results already shown in the manuscript), for the semidiurnal band D2 at neap tide (black), and at spring tide (red) are shown. Amplitude and phase values for salinity and velocity in the semidiurnal D2 band were obtained through harmonic analysis at spring tide and neap tide, thus relaxing the stationarity assumption. With these values, an estimate of the spring–neap modulation in TEF is obtained. The result is that the modulation produced by the spring–neap cycles seems to represent a small fraction relative to the M2-only values at all cross-sections. This occurs because the analysis in the manuscript spanned several months to ensure a zero residual net salt flux, and the TEF obtained from the M2 appears to adequately represent the steady-state TEF, as an average over the spring–neap cycle.

Accordingly, after several comments from both Reviewers, a new Section **3.4 Scope and Limitations**, has been added to the revised version of the manuscript. This section includes a discussion of no-stationarity, choice of constituents, lateral and vertical variability, and the TEF vs. Eulerian approaches..

However, the influence of tidal asymmetry on TEF remains unexplored. The non-linear generation of the overtide M4 from the primary tidal constituent M2 is known to create ebb-flood asymmetry in water levels and currents (e.g. Speer and Aubrey, 1985; Parker, 1991; Friedrichs and Aubrey, 1994) and affects the transport of solutes and particulate matter (e.g. de Swart and Zimmerman, 2009; Burchard et al., 2018). Consequently, it is expected to have an impact on TEF. In this study, the M2 oscillating exchange flow scenario devised by Burchard et al. (2019) is extended to include the contribution of the M4 tidal constituent, thereby requiring the prescription of both M2 and M4 amplitudes and phases both in current and salinity. The extended approach is applied to the Guadalquivir estuary, which is a tidally-energetic estuary, to estimate TEF at various cross-sections. While previous TEF research has focused predominantly on highly- or partially-stratified semi-enclosed basins, the tidally-energetic part of the estuarine parameter space has been overlooked. Furthermore, no TEF estimates currently exist for the Guadalquivir estuary. Quantifying TEF from observations and unraveling the role of the M4 constituent in the Guadalquivir estuary is essential for understanding its direct implications for water quality, residence times, and primary productivity (e.g. Díez-Minguito and de Swart, 2020; Castillo et al., 2025). A sensitivity analysis of TEF to the inclusion of the M4 to the tidal current and salinity equations is carried out in this study as well.

The choice to consider only the most energetic constituent $\mathrm{M2}$ *and its main overtide* $\mathrm{M4}$ *allows for a first reliable and approximate assessment of TEF in estuaries at low computational cost, particularly in cases where no complex high-resolution model is available, or as a benchmark prior to its implementation, highlighting the importance of the covariance between salinity and current. Additionally, this simplified scenario has allowed the effect on TEF of including* $\mathrm{M4}$*, which accounts for tidal asymmetry, to be evaluated. However, it must be acknowledge that this simplification is a limitation that does not allow for an accurate estimation of TEF capable of* *capturing its spatio-temporal variability, which is controlled by fluvial–tidal interaction and complex bathymetry. In this regard, a precise estimation of TEF and its variability in the Guadalquivir estuary should be the subject of future research. To this end, it should be considered other semidiurnal tides to capture the spring–neap modulation; diurnal constituents which generate diurnal inequality and also contribute to a semidiurnal–diurnal tidal asymmetry (Hoitink et al., 2003); as well as their corresponding compound tides and overtides.*

Wang, T., Geyer, W. R., and MacCready, P. (2017). Total exchange flow, entrainment, and diffusive salt flux in estuaries. Journal of Physical Oceanography, 47(5), 1205-1220. https://doi.org/10.1175/JPO-D-16-0258.1

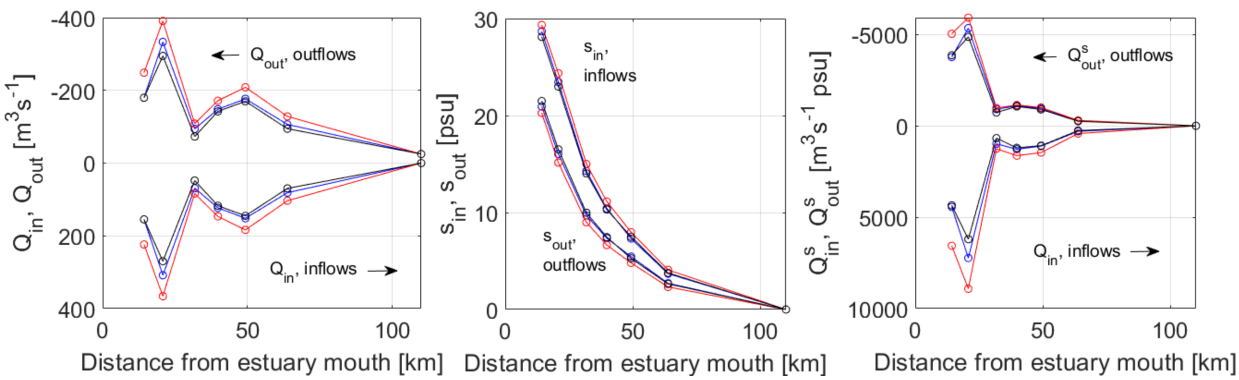

Figure 1: Left panel: Outgoing Q_{out} and incoming Q_{in} volume transports. Middle panel: Knudsen-consistent salinities for inflows, s_{in}, and outflows, s_{out}. Right panel: Incoming Q^s_{in} and outgoing Q^s_{out} salinity volume transports. Estimates at each cross-section CS$_i$ at given during the whole analysis period (blue curves and circles), a spring tide (red curves and circles), and a neap tide (black curves and cicles).

Q.2.3 — The TEF method is presented as if it were applied to a two-layer estuary, when the Guadalquivir is a well-mixed estuary, and this is especially true during the low-discharge periods that are the focus of the analysis. It should be made clear that in this case the method is applied to a vertically mixed estuary, and the presentation and discussion of the results should be adapted to this actual configuration.

R.2.3 We agree with the Reviewer, and thank you for this comment. In fact, both Reviewers point out to this issue (see also Comment Q.1.13). Several statements throughout the manuscript were indeed misleading.

The two layers are in the salinity space, i.e. in salinity coordinates S, not in the vertical z. As it is indicated in the main text of the manuscript, the exchange flow in a well-mixed estuary does not mean that there is a distinct upstream flow of salty water near the bottom and a downstream flow of brackish water near the surface, even though the exchange profiles in salinity coordinates are structured in two layers. The exchange flow following the Kundsen's theory is formulated in salinity coordinates and means that the outflow Q_{out} occurs at lower salinities than the inflow Q_{in}. During flood a water parcel with a specific salinity passes through a transect, leaving an upstream flux contribution at a certain salinity class. Upstream of the transect, this water parcel exchanges salinity with other water parcels, such that during ebb it passes the transect at a different salinity, leaving a downstream contribution at this different salinity. Statistically, the flood flux happens at a higher salinity than the ebb flux, due to the lower salinities upstream, caused by the freshwater discharge. This is why the fully cross-sectionally mixed idealized estuarine situation still results in an estuarine exchange flow, when formulated in salinity coordinates. Given that the Guadalquivir estuary is well-mixed during low river discharge, except for its partially-mixed lower part near the mouth, a vertically-structured exchange flow with persistent deep-water inflow and surface outflow might only develop in that lower region.

Confusing statements regarding the two-layer behavior of the exchange profile in the salinity space have been rephrased or rewritten throughout the manuscript.

The inclusion of the M4 constituent changes the exchange flow profile by salinity class, modifying the range of salinities of both the seaward and landward flows.

The M4 contribution, which is known to account for the tidal asymmetry, increases the range of salinities of the seaward flow at all cross-sections, except at CS_2 and CS_5 where the lower inflowing salinity range increases due to the relatively low relative M2-M4 phase difference ($\psi_a - 2\,\psi_b$) at these locations (Table 3).

The goodness of the convergence behavior allows extending the method to exchange flows with more than two layers in the salinity space (see, e.g., Burchard et al. (2025)).

In general, Eq. 5 assumes the incoming and outgoing flows arrange in two layers in salinity *coordinates S the salinity space (not necessarily in the vertical coordinates as occurs with the classical estuarine circulation). Lorenz et al. (2019) also generalized the formulation for exchange flows with more than two layers in the salinity space.*

The exchange profile $q(S)$ per salinity class is structured in two layers at all locations, thereby showing a incoming transport of water per salinity class (q_{in}) at higher salinity and an outgoing transport at lower salinity (q_{out}).

It should be noted that exchange flow in a well-mixed estuary does not mean that there is a distinct upstream flow of salty water near the bottom and a downstream flow of brackish water near the surface, even though the exchange profiles in salinity coordinates $q(S)$ are structured in two layers (as in Fig. 2).

The M4 inclusion does not change the two-layered feature of the exchange profile in salinity coordinates. However, it changes the thickness of the layers, being understood the thickness in terms of the salinity coordinate not in terms of the vertical coordinate.

Overall, the inclusion of the M4 constituent changes the magnitude of the exchange flow by salinity class, and also the range of salinities of inflows and outflows.

This case indicates that the inclusion of M4, relative to the M2-only scenario, increases the range of salinities of outflows in the $q(S)$ profile for all discharge values.

In Case D, it is likewise observed that the inclusion of M4 increases the range of salinities associated to outflows (upper layer of the $q(S)$ profile) compared to the M2-only for the three discharge values simulated, although, again, without significant variations.

An increase in the thickness of the upper salinity range of the $q(S)$ profile relative to the M2-only case is evident for all three freshwater discharge values. The sensitivity analysis shows

that the M4 constituent changes magnitude of the exchange flow by salinity class and range of salinities associated to outflows and inflows.

Finally, the authors wish to close this Response document by again thanking Reviewer 2 for the thorough reading of the manuscript and for the criticism, which has greatly helped to improve it.