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

Response to Reviewer 1

The authors would like to thank Reviewer 1 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 1

RC1: 'Comment on egusphere-2025-6526', Anonymous Referee #1, 09 Feb 2026

General

This article deals with the calculation of the Total Exchange Flow (TEF) from observations in the Guadalquivir estuary, and focuses on the role of the M4 tide. I think the article could be a nice contribution to the knowledge of the dynamics of the Guadalquivir estuary and similar systems, the computation of the TEF from observations and the role of different tidal constituents in the exchange of an estuary with the adjacent sea. However, I have some suggestions for improvements, see below.

Major

Q.1.1 — What I miss in the introduction is a clear motivation why to do this study. The methodology is discussed in the introduction. But, what is the knowledge gap that this study is trying to address? And what is the context of that knowledge gap?

R.1.1 We agree with the reviewer. Knowledge gaps were not clearly stated. Burchard et al. (2019) proposed a simple, sectionally-homogeneous analytical scenario considering only the M2 constituent to show that Total Exchange Flow (TEF) can also develop even under tidally-energetic conditions. However, the influence of tidal asymmetry on TEF remained unexplored. Our study addresses this gap within the Guadalquivir estuary, a highly energetic tidal system. 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 is essential for understanding its direct implications for water quality, residence times, and primary productivity.

Accordingly, the text in the Introduction has been rewritten as follows,

Burchard et al. (2019) proposed a simple, sectionally-homogeneous analytical scenario considering only the M2 constituent to show that TEF can also develop even under tidally-energetic conditions. [...]

However, the influence of tidal asymmetry on TEF remained unexplored. The M4 overtide is known to create ebb-flood asymmetry in levels and currents (e.g. Speer and Aubrey, 1985; Parker, 1991; Friedrichs and Aubrey, 1994) and affects the transport of particulate matter (e.g. de Swart and Zimmerman, 2009; Burchard et al., 2018b), thus 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 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.

Q.1.2 — Q2. In section 3.2, the mixing completeness is 67%, which is framed as evidence for the poorly-stratified character of the Guadalquivir estuary. However, in order to obtain this result, it was assumed that the cross-sections are well-mixed laterally and vertically. So to me it appears that this is input to the analysis, and can therefore not be framed as a result.

R.1.2 This is an interesting discussion point. For a cross-section with homogeneous salinity, the mixing completeness is the tidally-averaged salinity during ebb divided by the tidally averaged salinity during flood. Depending on the river discharge and the mixing up-estuary of the transect, the mixing completeness can have any value, fully independently of the distribution of salinity across the transect. A very weak river discharge would typically result in a high mixing completeness, while a strong river discharge generally gives a low mixing completeness. We have now adapted the abstract, Section 3.2 and the conclusions accordingly.

Knudsen bulk quantities are consistent with the weakly-stratified character of the Guadalquivir estuary, whose mixing completeness is larger than 67% at all cross-sections.

The small relative differences between representative TEF bulk salinity values for inflows and outflows, i.e. $1 - s_{out}/s_{in}$ *(Figure 5), ensue from the high rates of mixing in the Guadalquivir estuary. [...] The mixing completeness attains* $\sim 72\%$ *at the cross-section nearest to the mouth of the estuary. The net TEF exchange of variance upstream, at the tidal river part, is negligible due to vanishing salinities, such that the mixing is complete (100%). While the mixing completeness can range between zero and 100% in estuaries (Burchard et al., 2026), the Guadalquivir estuary can be rated as of relatively high mixing completeness compared to other estuaries which typically at high discharge or neap-tide conditions are more stratified and therefore of lower mixing completeness (below 50%).*

This is consistent with the the poorly-stratified character of the Guadalquivir estuary, with a mixing completeness larger than 67% at all cross-sections. The Guadalquivir estuary can be thus rated as of relatively high mixing completeness.

Q.1.3 — The article often refers to the Knudsen (1900) paper: Knudsen relations, Knudsen-bulk estimates, Knudsen-consistent... , without explaining this terminology. I suggest to limit the different variations of this to a minimum, and explain these terms when introduced, because their exact meaning is not that trivial to me.

R.1.3 We agree with the Reviewer. These terms, which are the fundamentals of the TEF analysis, should be carefully explained.

Knudsen (1900) was the first to propose the simplest, yet insightful quantification of the exchange flow (Knudsen, 1900; Burchard et al., 2018a). Assuming that the river discharge Q_r enters the estuary at zero salinity, the long-term averaged volume and salt budgets in an estuary bounded by a fixed transect have been formulated by Knudsen (1900) as

$$Q_{in} + Q_{out} + Q_r = 0, \quad Q_{in}s_{in} + Q_{out}s_{out} = 0, \tag{1}$$

where s_{in} and s_{out} are the characteristic inflow and outflow salinities, respectively, at the location of the bounding transect.

The classical Knudsen relations,

$$Q_{in} = \frac{s_{out}}{s_{in} - s_{out}} Q_r, \quad Q_{out} = -\frac{s_{in}}{s_{out} - s_{in}} Q_r, \tag{2}$$

are directly derived from Eqs. (1) and allow calculating the inflowing and outflowing volume transport which are otherwise difficult to estimate. These relations relate the exchange flow (net water volume transport inflow Q_{in} and outflow Q_{out} through an estuarine cross-section) to the river discharge and inflow and outflow with known salinities (s_{in} and s_{out}, respectively).

Using the Knudsen relations Eqs. (2), the exchange flow is thus conveniently estimated in terms of simple bulk values (i.e. Knudsen-bulk values or estimates) which condense the complex dynamics of the exchange flows in estuaries. The Knudsen relations implicitly include mixing of the fresh water discharge with the inflowing ocean water of salinity s_{in}, and the bulk mixing M (salinity variance destruction in the estuary) could be quantified as $M = s_{in}s_{out}Q_r$ (MacCready et al., 2018).

To determine the most representative Knudsen-bulk estimates by finding the correct values of s_{in} and s_{out}, namely the Knudsen-consistent salinity values, the TEF framework analyzes the exchange flow in salinity coordinates since the salt budget is assumed to be controlled by the exchange flow. Therefore, the

TEF analysis framework provides one consistent calculation method for these Knudsen-bulk values.

This explanation has been included in the main text to clarify the terminology. Terms throughout the manuscript have been modified accordingly.

Knudsen (1900) proposed the simplest, yet insightful quantification of the steady-state exchange flow by considering the volume and salt budget in estuaries (see Knudsen work's translation by Burchard et al. (2018a)). The exchange flow is defined here as the tidally-averaged, along-channel net water volume transport inflow (Q_{in}*) and outflow (*Q_{out}*) through an estuarine cross-section (Geyer and MacCready, 2014). Assuming that the river discharge* Q_r *enters the estuary at zero salinity, the long-term averaged volume and salt budgets in an estuary bounded by a fixed transect have been formulated by Knudsen (1900) as*

$$Q_{in} + Q_{out} + Q_r = 0, \quad Q_{in} s_{in} + Q_{out} s_{out} = 0, \tag{3}$$

where s_{in} *and* s_{out} *are the characteristic inflow and outflow salinities, respectively, at the location of the bounding transect. The classical Knudsen relations,*

$$Q_{in} = \frac{s_{out}}{s_{in} - s_{out}} Q_r, \quad Q_{out} = -\frac{s_{in}}{s_{out} - s_{in}} Q_r, \tag{4}$$

are directly derived from (3) *and allow calculating the inflowing and outflowing volume transport which are otherwise difficult to estimate. Using the Knudsen relations* (4)*, the exchange flow is thus conveniently estimated in terms of simple bulk values (i.e. Knudsen-bulk values or estimates) which condense the complex dynamics of the exchange flows in estuaries. The Knudsen relations implicitly include mixing of the fresh water discharge with the inflowing ocean water of salinity* s_{in}*, and the bulk mixing* M *(understood as the salinity variance destruction in the estuary) could be quantified as* $M = s_{in} s_{out} Q_r$ *(MacCready et al., 2018).*

The Total Exchange Flow (TEF) analysis framework provides one consistent calculation method that allows for 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., 2025b, 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.*

Minors

Q.1.4 — The article states (line 3) that an analytical model' is used. The model consists of an expressions of the salinity and along-channel velocity at x,t. I would not so rather call this a model, but merely a set of two analytical equations. See also line 44.

R.1.4 We agree with the Reviewer. Following Burchard et al. (2019) and Lorenz et al. (2019), it is now called either analytical equations or oscillating exchange flow scenario. The text is modified in former Lines 3 and 44, and elsewhere.

The analysis combines three years of observations from a real-time monitoring network with an analytical exchange flow scenario featuring a sectionally-homogeneous $\mathrm{M2}+\mathrm{M4}$ *oscillating tidal flow and salinity.*

Burchard et al. (2019) proposed a simple, sectionally-homogeneous analytical scenario considering only the M2 constituent to show that TEF can also develop even under tidally-energetic conditions.

These authors used the same simple analytical tidal scenario to test the extended dividing salinity method and its convergence.

Figure 6 shows results of Q *and* q *per salinity class at cross-sections* CS_i *for the extended analytical scenario.*

An oscillatory exchange flow scenario including the contributions of $\mathrm{M2}$ *and* $\mathrm{M4}$ *current and salinity is applied to the Guadalquivir estuary to estimate Total Exchange Flow (TEF) for the first time at seven cross-sections during low river flow conditions.*

Q.1.5 — Line 9: “covariance between salinity and current”. I think, when this is used in the text, it applies to the M2 salinity and current, that is, that of the main tidal constituent. I suggest to add this, to be specific. Is this the same quantity as in line 115? Same for lines 237, 316.

R.1.5 'M2 covariance' added in abstract and Lines 237 and 316. Line 115 is rephrased.

The covariance between M2 *salinity and current seems to play a more important role in exchange flow in the Guadalquivir estuary than the effects due to tidal asymmetry.*

The transport due to the M2 *and* M4 *covariance of current velocity and suspended sediment explains the setting of Estuarine Turbidity Maxima.*

This seems to ensue that the covariance between M2 *salinity and current is a mechanism more significant controlling the exchange flow in the Guadalquivir estuary than the tidal asymmetry.*

Q.1.6 — Line 25: It may be good to specify here what is meant with “exchange flow”, as different definitions are possible. See also line 116.

R.1.6 In this article, the exchange flow is defined as the tidally-averaged, along-channel net water volume transport inflow (Q_{in}) and outflow (Q_{out}) through an estuarine cross-section (Geyer and MacCready, 2014).

The Guadalquivir estuary is well-mixed in terms of salinity, except probably in its lower part near the mouth, where the water column is partially-mixed. Only in that part could be a subtidal along-channel flow, commonly structured in two layers, with persistent inflow of deeper water and persistent outflow above. As indicated in the Section 3.1 (within Results and Discussion Section), in well-mixed systems 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. 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.

The exchange flow is defined here as the tidally-averaged, along-channel net water volume transport inflow (Q_{in}) and outflow (Q_{out}) through an estuarine cross-section Geyer and MacCready, 2014.

Q.1.7 — Line 35: it is a bit unclear to me why the M4 tide is considered as extension of the tidal module, and not for instance the S2 tide, which has a stronger amplitude. I assume this is because the M4 tide is the overtide of the M2, which makes the analysis simpler? But I think the article would benefit from some elaboration on this important choice.

R.1.7 We agree with the Reviewer. This important point was not enough detailed or clearly stated in the previous version of the manuscript.

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, the motivation and aims of the study has been rewritten and more details are provided to highlight the importance of M4 in the study.

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* 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

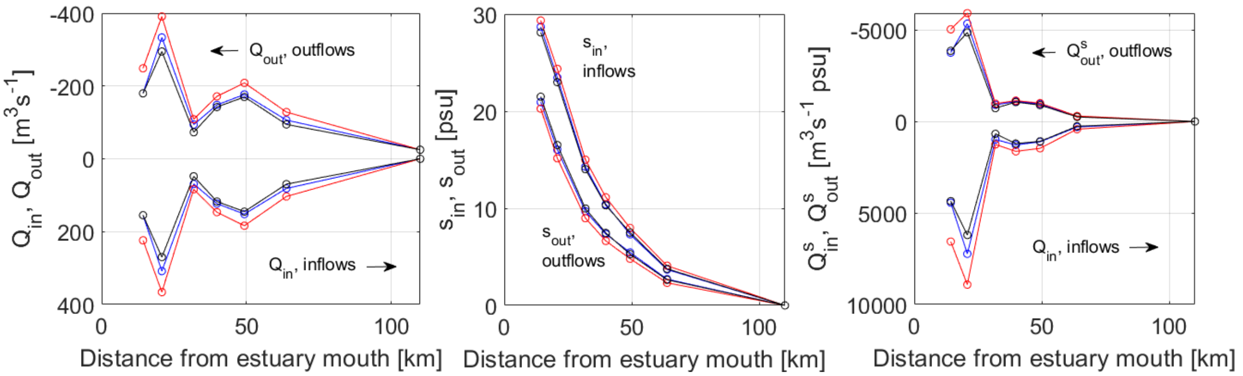

Figure 1: Left panel: Outgoing Q_{out} and incoming Q_{in} volume transports. Middle panel: Knudsen-consistent salinities for inflows, s_{in}, and outflows, s_{out}. Right panel: Incoming Q^s_{in} and outgoing Q^s_{out} salinity volume transports. Estimates at each cross-section CS$_i$ at given during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

Q.1.8 — Line 41 and later: "notable" cross-sections: what is meant with 'notable'.

R.1.8 Right. In this context, the term is vague and subjective. The term 'notable' has been removed from the revised version altogether. The cross-sections where the exchange flow is estimated in this manuscript vary in morphology, ranging from curved meanders to mostly straight stretches. The reaches in the lower estuary are characterized by the highest levels, yet reduced in magnitude, of primary production in the estuary.

Q.1.9 — Line 75: “volume-integrated” - over which volume is integrated?

R.1.9 Molecular mixing is quantified as the scalar dissipation rate of salinity variance per unit volume. Burchard and Rennau (2008) proposed to use the *volume integral* of the molecular mixing for applications at basin (hydrodynamic) scale. At this scale, volume-integrated (macroscopic) mixing M is the dissipation or destruction of salinity variance in the basin. The advantage of using salinity variance to estimate volume-integrated mixing is that can easily be calculated from numerical model results and observations. In addition to quantifying the total volume of (inflowing and outgoing) water within specific salinity ranges, the TEF approach allows for the quantification of volume-integrated mixing. In the context of the present work, volume-integrated mixing is defined as the mixing occurring within the control volume surrounding the cross-sections where exchange flows are calculated. Burchard et al. (2019) and MacCready et al., (2018) refer to a number of TEF applications and volume-integrated mixing estimates in semi-enclosed basins.

> *The Knudsen relations implicitly include mixing of the freshwater discharge with the inflowing ocean water of salinity* s_{in}*, and the volume-integrated mixing* M*, which is understood as the salinity variance destruction in the estuary, could be quantified as* $M = s_{in} s_{out} Q_r$ *(MacCready et al., 2018).*

Burchard and H. Rennau (2008) Comparative quantification of physically and numerically induced mixing in ocean models. Ocean Modelling, 20, 293–311, https://doi.org/10.1016/j.ocemod.2007.10.003.

Q.1.10 — Line 85: “mean salinity”. I suppose tidally-averaged is meant here?

R.1.10 Yes. This has been indicated in the revised manuscript.

> *[...]* s_r *the residual or tidally-averaged salinity, [...]*

Q.1.11 — Line 105: I assume the subscript means one standard deviation, but this is nowhere specified. Equation 11: this is a simplification of the real profiles. Can you comment on how large the error is that you are making with this assumption?

R.1.11 The subscript indicates the 95% confidence interval in the last significant figure. The 95% confidence interval is also indicated for the fitted coefficients in Equation 11, i.e. $A_0 = 5800_{900}\,\mathrm{m}^2$ and $a_0 = 60_5\,\mathrm{km}$.

The estuary is convergent with tidally-averaged cross-sections approximately decreasing exponentially from the mouth to the landward end according to

$$A(x) = A_0 \exp\left(-x/a_0\right) , \tag{5}$$

with $A_0 = 5800_{900}\,\mathrm{m}^2$ *and* $a_0 = 60_5\,\mathrm{km}$*, where the subscript indicates the 95% confidence interval in the last significant figure.*

Errors (subscripts) corresponds to the 95% confidence interval.

Q.1.12 — Line 125: If I understand correctly, there is one value for along-channel current and salinity for the entire cross-section (this becomes clear later in the text, I suggest to stress it here). In reality, there will be variations over depth and the lateral direction. Can you comment on the magnitude of the error that you are making here? In general, I think the article would benefit from some more explicit (if possible quantitative) reflection on the uncertainty of the results in terms of volume transports, dividing salinity classes and mixing completeness.

R.1.12 Indeed, as the reviewer points out, there are lateral and vertical variations not considered in this work that should be acknowledged. Vertical salinity variations are negligible in an estuary that is mostly well-mixed, except perhaps in the lower reach near the mouth, where partial stratification may occur (Díez-Minguito et al., 2013; Cobos et al., 2020). Vertical variations in tidal currents are more significant and, apparently, the approach adopted in this work may be overestimating total exchange flows. According to the figures shown by Losada et al. (2017), within a monitored water column of $6\,\mathrm{m}$, differences close to 50% can occur between the M2 semimajor axis amplitude of the tidal ellipse at the surface and at the bottom. Vertical differences in the M2 tidal ellipse phase do not appear to be significant.

Regarding lateral variations, with the available data it is difficult to quantify them. However, there is indirect evidence in the Guadalquivir estuary of their importance (Díez-Minguito et al., 2013) and, therefore, they should be included in future detailed studies to achieve a more accurate estimation of exchange flows. Lateral separation of the subtidal flow in estuaries occurs due to, e.g., tidal residual currents or lateral variations in the estuarine circulation (Burchard et al., 2011, Geyer and MacCready, 2014). It is also well-known that local topographic features, such as bends, may have considerable influence on the lateral mixing driven by secondary flows and hence on the salt transport and exchange flows (e.g., Smith, 1976; Lewis and Lewis, 1983; Pein et al., 2018). Recently, Kummel et al. (2025) studied the salt transport mechanisms in the North German Weser River Estuary using a detailed transport decomposition method applied to a high-resolution numerical model. These authors found that opposing flows often occur between the channel and adjacent shoals in this estuary. Outflow subtidal depth-averaged transport occurs on the shoals, whereas a net inflow occurs on the inner part of the channel. Also, in the bends of the Weser estuary, an outflow is found in the outer part of the bend, whereas in the center of the channel as well as the inner shoals, a residual inflow occurs. In the Guadalquivir estuary, Díez-Minguito et al., (2013) provided indirect evidences of lateral separation of salt fluxes from analysis of observations near the *thalweg*. These authors noticed that during several months the 2-psu isohaline location (salt intrusion point X_2) did not show appreciable variations besides its spring-neap variability. However, there was a persistent net salt influx on the inner part of the channel, thereby suggesting the presence of lateral variations over the cross-section and a compensating net salt outflux on the shoals.

This discussion is now included in the revised version of the manuscript. Following this comment (and others from both reviewers), it has been decided to include, within the Results and Discussion section (Section 3), a specific subsection in which the possible limitations of our approach are discussed (Subsection 3.4).

3.4 Scope and Limitations of the Approach

The idealized approach used in this study is simplified and does not take all physical processes affecting exchange flow in estuaries into account. The assumptions made to simplify the equations allow for the construction of a fast and understandable model, but they also limit its scope.

There are lateral and vertical variations unaccounted for in this work that should be mentioned. Vertical salinity variations are negligible in an estuary that is mostly well-mixed, except perhaps in the lower reach near the mouth, where partial stratification may occur. Vertical variability in tidal currents is more significant and, in this regard, the approach adopted in this study may be overestimating total exchange flows. According to Losada et al. (2017), within a monitored water column of $\sim 6\,\mathrm{m}$*, differences close to 50% can occur between the M2 semimajor axis amplitude of the tidal ellipse at the surface and at the bottom. Vertical differences in the M2 tidal ellipse phase do not appear to be significant. Regarding lateral variations, with the available data it is difficult to quantify them. However, there is indirect evidence in the Guadalquivir estuary of their importance Díez-Minguito et al. (2013) and, therefore, they should be included in future detailed studies with high-resolution numerical models to achieve a more accurate estimation of exchange flows. Lateral separation of the subtidal flow in estuaries occurs due to, e.g., tidal residual currents or lateral variations in the estuarine circulation Burchard et al. (2011); Geyer and MacCready (2014). It is also well-known that local topographic features, such as bends, may have considerable influence on the lateral mixing driven by secondary flows and hence on the salt transport and exchange flows (e.g. Smith, 1976; Lewis and Lewis, 1983; Pein et al., 2018).*

Recently, Rummel et al. (2025) studied the salt transport mechanisms in the North German Weser River Estuary using a detailed transport decomposition method applied to a high-resolution numerical model. These authors found that opposing flows often occur between the channel and adjacent shoals in this estuary. Outflow subtidal depth-averaged transport occurs on the shoals, whereas a net inflow occurs on the inner part of the channel. Also, in the bends of the Weser estuary, an outflow is found in the outer part of the bend, whereas in the center of the channel as well as the inner shoals, a residual inflow occurs. In the Guadalquivir estuary, Díez-Minguito et al. (2013) provided indirect evidences of lateral separation of salt fluxes from analysis of observations near the thalweg. These authors noticed that during several months during low river-flows the 2-psu isohaline location (X_2) *did not show appreciable variations besides its a weak spring-neap variability. However, there was a persistent net salt influx on the inner part of the channel, thereby suggesting the presence of lateral variations over the cross-section and a compensating net salt outflux on the shoals.*

Burchard, H., Hetland, R. D., Schulz, E., & Schuttelaars, H. M. (2011). *Drivers of residual estuarine circulation in tidally energetic estuaries: Straight and irrotational channels with parabolic cross section*. Journal of Physical Oceanography, 41(3), 548–570. https://doi.org/10.1175/2010JPO4453.1

Geyer, W. R., and P. MacCready (2014) *The estuarine circulation*. Annual Review of Fluid Mechanics, 46, 175–197. https://doi.org/10.1146/annurev-fluid-010313-141302

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Lewis, R. E., and J. O. Lewis (1983), The principal factors contributing to the flux of salt in a narrow, partially stratified estuary, Estuarine Coastal and Shelf Science, 16(6), 599–626. https://doi.org/10.1016/0272-7714(83)90074-4

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Q.1.13 — Line 154: To me, this phrasing suggest two layers in the vertical are observed. However, that seems not to be the case. I suggest to phrase this differently, to avoid confusion with an exchange flow consisting of two vertical layers.

R.1.13 Thank you for this comment. We agree with the reviewer that several statements throughout the manuscript are confusing. In fact, both Reviewers point out to this (see Comment Q.2.3).

The two layers are in the salinity space, i.e. in salinity coordinates, not in the vertical. 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 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.

Q.1.14 — Line 160-161: But this is a different quantity than in Reyes-Merlo et al. (2013), because there only gravitational circulation is considered, while the current results also include tidal flow if I understand correctly. I suggest to make this more clear to avoid confusion (also for example in line 179). Also, since transport of salt by tidal currents is thought to be large in this estuary (Diez-Minguito et al., 2013, Biemond et al, 2024), wouldn't you expect a larger value than 10%?

R.1.14 The reviewer is right. It is a different quantity than in Reyes-Merlo et al. (2013), who estimated the density-driven flow using an eulerian approach at CS0 and CS1, in the lower part of the estuary. This is clarified in the revised version of the manuscript.

That is a very good question. Thank you.

On the one hand, since the present study only considers the contribution of the M2 tidal constituent, the actual difference is likely to be larger, as other constituents also contribute to salinity variability, potentially enhancing tidal salt transport. Díez-Minguito et al. (2013) observed that tidal salt transport is dominant, showing that Stokes transport and tidal pumping estimated from observations are at least one order of magnitude larger than those induced by vertically sheared currents.

On the other hand, the water column structure in the lower part of the estuary is partially stratified rather than well-mixed, showing the residual horizontal currents a clear vertically-sheared profile (Reyes-Merlo et al., 2013). Modelling results by Biemond et al. (2024) highlighted the importance of accounting for density-driven flow when estimating salt transport, particularly in this lower section of the estuary. They showed that this transport mechanism cannot be neglected in that region. According to Biemond et al. (2024), salt transport due to density-driven flow interacts with that associated with current–salinity correlations, and both contributions are equally important in the Guadalquivir Estuary.

The apparent differences between modelling and observations were, in fact, discussed by Biemond et al. (2024). They indicate that their model is likely to overestimate the influence of density-driven flow on the exchange flow since other processes, such as tidal straining (Burchard & Hetland, 2010; Burchard et al., 2011), which also contribute to the exchange flow, were not taken into account. In addition, these authors indicated that tidal transport estimates may be underestimated in their model because they only consider the M2 tidal constituent (as we do in the present study), whereas Díez-Minguito et al. (2013) showed that other constituents also contribute to salinity variability, potentially enhancing tidal salt transport.

This discussion is included in the revised version of the manuscript.

Incoming and outgoing water volume transports estimated here in the lower part of the estuary are about 10% larger than volume transports inferred from the tidally-averaged horizontal current profiles shown by Reyes-Merlo et al. (2013), who considered the density-driven flow only using an Eulerian approach at CS_0 *and* CS_1.

TEF estimates of incoming and outgoing water volume transports in the lower part of the estuary are about 10% larger than volume transports inferred from a tidally-averaged Eulerian approach by Reyes-Merlo et al. (2013), who only considered the contribution of the density-driven flow to the exchange. The actual differences from these two different approaches are likely to be larger since the present study only considers the contribution of the M2 tidal constituent to TEF. Other constituents also contribute to salinity variability, potentially enhancing tidal salt transport. Díez-Minguito et al. (2013) observed in fact that tidal salt transport is dominant, showing that Stokes transport and tidal pumping are at least one order of magnitude larger than those induced by vertically-sheared currents. Nevertheless, the water column structure in the lower part of the estuary is partially stratified rather than well-mixed, showing the residual horizontal currents an evident vertically-sheared profile (Reyes-Merlo et al. 2013). Semi-analytical model results by Biemond et al. (2024) highlighted the importance of accounting for density-driven flow when estimating salt transport, particularly in this lower part of the estuary. They showed that this transport mechanism cannot be neglected. Salt transport due to density-driven flow interacts with that associated with current–salinity correlations, and both contributions are equally important in the lower part of the Guadalquivir Estuary.

Burchard, H., & Hetland, R. D. (2010). *Quantifying the contributions of tidal straining and gravitational circulation to residual circulation in periodically stratified tidal estuaries*. Journal of Physical Oceanography, 40(6), 1243–1262. https://doi.org/10.1175/2010JPO4270.1

Burchard, H., Hetland, R. D., Schulz, E., & Schuttelaars, H. M. (2011). *Drivers of residual estuarine circulation in tidally energetic estuaries: Straight and irrotational channels with parabolic cross section*. Journal of Physical Oceanography, 41(3), 548–570. https://doi.org/10.1175/2010JPO4453.1

Q.1.15 — Line 178: larger than what?

R.1.15 It is meant that, in practice, this would imply longer residence times for conservative pollutants than in the absence of recirculation. The text has been changed accordingly.

In practice, this would imply longer residence times for conservative pollutants than in the absence of recirculation.

Q.1.16 — Line 196: small with respect to what?

R.1.16 This is clarified in the revised manuscript. It was meant that the small relative differences between representative TEF bulk salinity values for inflows and outflows, i.e. $1 - s_{out}/s_{in}$ (Figure 4), ensue from the high rates of mixing in the Guadalquivir estuary.

The main text is changed accordingly.

The small relative differences between representative TEF bulk salinity values for inflows and outflows, i.e. $1 - s_{out}/s_{in}$ *(Figure 4), ensue from the high rates of mixing in the Guadalquivir estuary.*

Q.1.17 — Figure 5: why use an inset here? I suggest to plot the two lines in the same graph, with the y-axis for MC[%] on the right of the figure.

R.1.17 Done. The figure (and text) has been modified as in Fig. 2 in this file.

Q.1.18 — Line 226: ‘increases the thickness of the upper outflowing layer’ I found this confusing, because it suggests that it refers to a surface layer. I suggest to use something like “increases the range of salinities of the seaward flow”

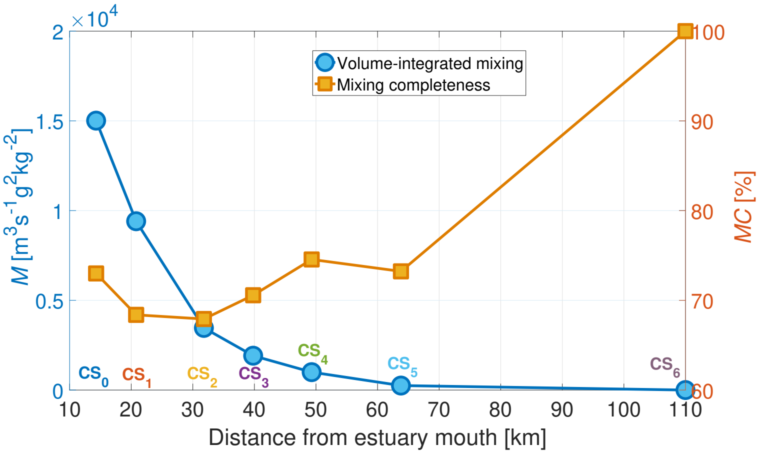

Figure 2: Volume-integrated mixing (left y-axis; dark blue curve, circles) and mixing completeness (right y-axis; dark yellow curve, squares).

R.1.18 We agree with the Reviewer. This comment is related to issue Q.1.13 (see response above). This sentence has been rewritten.

> *[...] increases the range of salinities of the seaward flow at all cross-sections [...]*

Q.1.19 — Line 227: "except at CS2 and CS5 where the lower inflowing layer thickness increases". Can you explain this?

R.1.19 The reason is the relatively low relative phase difference $\psi_a - 2\,\psi_b$ (relative phase difference $\mathrm{M2} - 2\,\mathrm{M4}$) of salinity at these locations (see Table 3). This modifies the zero residual salinity flux conditions at these locations.

The reason for this is included in the statement in the revised manuscript.

> *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 layer thickness increases due to the relatively low relative M2-M4 phase difference ($\psi_a - 2\,\psi_b$) at these locations (Table 3).*

Q.1.20 — In line 275: Differences between the different values of R are impossible to see in Figure 7. I suggest another way to visualize this, or alternatively, just state in the text that the results are practically independent of the value of R in the range 10-40, as evidenced by the numbers given in lines 277-279.

R.1.20 We agree with the reviewer. Overall, s_{in} and s_{out} values are rather insensitive to changes in R within the low river flow range analyzed ($R = 10{-}40\,\mathrm{m^3s^{-1}}$). This has explicitly been stated in the text now.

Overall, s_{in} and s_{out} values are rather insensitive to changes in R within the low river flow range analyzed ($R = 10 - 40\,\mathrm{m^3s^{-1}}$).

Q.1.21 — Section 3.3.2: In general, I think the added value of this analysis needs somewhat better motivation. It would be good to have reference values to compare the results with. For instance, how big are the changes in the numbers when vertical stratification would be considered? Or irregular bathymetry? In that manner, the interpretation of the quantitative results in this section would have a better context.

R.1.21 We agree with the Reviewer that the interpretation of the results and sensitivity analysis regarding the inclusion of the M4 need a better context. In the revised version of the manuscript the range of values of ratio of the M4 and M2 amplitudes is better justified. However, the idealized nature of the approach used in this study is simplified and does not allow to compare the effect of the M4 inclusion with that of changes in the water column stratification. This limitation is discussed in the new subsection *3.4 Scope and Limitations of the Approach*. The effects of the bathymetry in TEF are compared with that of the inclusion of the M4.

Regarding the range of values of ratio of the M4 and M2 amplitudes, in the Guadalquvir estuary, the ratio of the M4 and M2 tidal water level amplitudes do not exceed 0.12 (Díez-Minguito et al. 2012). This value rarely exceeds 0.15 (Friedrichs and Aubrey, 1988), although higher ratios are usually observed in tidal creeks and tidal flats. Ratios of M4 and M2 tidal current amplitudes in the Guadalquivir estuary range from 0.04 to 0.15 (Table 2). Similar ranges were found by Blanton et al. (2002) in their study on the tidal current asymmetry in the Satilla River estuary.

Regarding the changes in bathymetry, a sensitivity analysis is carried out to evaluate its effects in TEF. The results of this analysis will be compared with those of the influence on the TEF of including M4, thereby helping to better interpret the latter. With this view, the incoming and outgoing volume transports are determined when the cross-sections along the channel (Eq. 13 in the revised version of the manuscript) are varied. Cross-section at the mouth A_0 and the convergence length a_0 in $A(x) = A_0 \exp\left(-x/a_0\right)$ are varied. The convergence length parameter a_0 is varied within the range $40 - 90\,\mathrm{km}$ and the cross-section at the mouth A_0 within $5000 - 7000, \mathrm{m}^2$, being in this study the reference values $a_0 = 60\,\mathrm{km}$ and $A_0 = 5800\,\mathrm{m}^2$ (Eq. 13).

The outgoing and incoming volume transports with the M4 contribution at each cross-section $\mathrm{CS_i}$ (Table 4) are compared with those obtained for the M2 tide only with bathymetric changes, either due to variations in the convergence length or in the cross-section at the mouth. Overall, the increase in the cross-sectional areas, whether due to an increase in the convergence length or in the cross-section at the mouth, enhances the exchange flow. It is found that a change in the convergence length when increased from $a_0 = 60\,\mathrm{km}$ to $90\,\mathrm{km}$ (50% increase) produces outgoing and incoming volume transports similar to those obtained by including M4 in the section closest to the estuary mouth $(\mathrm{CS_0})$. At the other locations $\mathrm{CS_i}$, the results are reproduced for convergence lengths between $65\,\mathrm{km}$ and $70\,\mathrm{km}$. Similarly, a sensitivity analysis carried out with the cross-sectional area at the mouth A_0 indicates that a increase from $A_0 = 5800\,\mathrm{m}^2$ to $A_0 = 6250\,\mathrm{m}^2$ produces outgoing and incoming volume transports close to those obtained by including M4 at all cross-sections.

This considerations triggered by the interesting questions arrised by the Reviewer are now included in the revised version of the manuscript.

The ratio between M4 and M2 current amplitudes, u_b/u_a, is varied from 0% to 15%, according to observations in a number of estuaries. The ratio of the M4 and M2 tidal water level amplitudes rarely exceeds 0.15 (Friedrichs and Aubrey, 1988), although higher ratios are usually observed in tidal creeks and tidal flats. Ratios of M4 and M2 tidal current amplitudes in the Guadalquivir estuary range from 0.04 to 0.15 (Table 2). Similar ranges were found by Blanton et al. (2002) in their study on the tidal current asymmetry in the Satilla River estuary.

With a view to gaining insight into the effects of including M4 and to better interpret the results, these effects are compared with those produced in the TEF by changes in the bathymetry. The outgoing and incoming volume transports with the M4 contribution at each cross-section

$\mathrm{CS_i}$ *are compared with those obtained for the M2 tide only considering bathymetric changes. New incoming and outgoing volume transports are thus estimated when cross-sections according to Eq. 13 are varied, either due to variations in the convergence length* a_0 *or in the cross-section at the mouth* A_0*. Reference values* $a_0 = 60\,\mathrm{km}$ *and* $A_0 = 5800\,\mathrm{m^2}$ *are those in Eq. 13. Overall, the increase in the cross-sectional areas, whether due to an increase in the convergence length or in the cross-section at the mouth, enhances the exchange flow. It is found that a change in the convergence length when increased from* $a_0 = 60\,\mathrm{km}$ *to* $90\,\mathrm{km}$ *(50% increase) produces outgoing and incoming volume transports similar to those obtained by including M4 in the section closest to the estuary mouth (*$\mathrm{CS_0}$*). At the other locations* $\mathrm{CS_i}$*, the results are reproduced for convergence lengths between* $65\,\mathrm{km}$ *and* $70\,\mathrm{km}$*. Similarly, a sensitivity analysis carried out with the cross-sectional area at the mouth* A_0 *indicates that a increase from* $A_0 = 5800\,\mathrm{m^2}$ *to* $A_0 = 6250\,\mathrm{m^2}$ *produces outgoing and incoming volume transports close to those obtained by including M4 at all cross-sections. Therefore, the increase in TEF due to the inclusion of M4 corresponds to appreciable increases in the cross-sectional areas of the estuary.*

Finally, the authors wish to close this Response document by again thanking both Reviewer 1 for the thorough reading of the manuscript and for the criticism, which has greatly helped to improve it.