Final Response to Referees

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Response to Reviewer 1

We thank the reviewer for the detailed comments. Below we address each point and indicate the corresponding revisions.

General Points

Reviewer Comment: *Are there novel processes that make this application unique or different within estuaries and marginal seas in general? If so, these are things the authors might wish to emphasize in their final version. For example, marginal seas that are strongly forced can be driven into a state of maximal exchange, an idea first floated by Stommel and Farmer (1952). They used a two-layer estuary system as an example, but it has turned out that the main applications are the Mediterranean Sea and the ancient Red Sea. Maximal exchange occurs when the inflow/outflow is choked by some narrow passage (the Desertores section, perhaps?), and the mixing within the Ancud Gulf is strong enough to drive the flow to it maximum exchange limit, determined by hydraulics. More generally, is there hydraulic activity in the Desertores Pass?*

Response: We appreciate this suggestion. Our results support a driver-explicit view of exchange in a segmented fjord–basin system, where the dominant controls on subtidal exchange vary across basins and seasons. In addition to gravitational circulation, the TEF diagnostics reveal four recurrent regimes that are not well captured by a single, uniform estuarine conceptual model:

1. **Wind–River Compensation Regime:** In the interior basin (Reloncaví), landward salt import ($Q_{in}\Delta S$) is not controlled by river discharge alone. Instead, the system shows a winter–spring compensation in which down-estuary winds enhance the exchange inflow (Q_{in}) in winter, whereas the spring runoff peak maximizes the stratification (ΔS). This seasonal compensation helps stabilize the seasonal-mean salt import, even though Q_{in}, ΔS, and $Q_{in}\Delta S$ weaken concurrently during austral summer under low discharge and up-estuary winds.
2. **Spring-tide Straining at Constrictions:** At Desertores Pass, the spring–neap modulation indicates a straining-dominated tidal response. The isolated tidal contributions to both inflow and stratification switch from negative during neaps to positive toward spring tides (Fig. 9d,e), consistent with stronger bottom inflow and vertical shear during springs. We interpret this as tidal shear acting on the along-channel salinity gradient, generating residual stratification via straining, while enhanced turbulence during spring tides does not fully offset that effect. As a result, landward salt import ($Q_{in}\Delta S$) shows a pronounced spring-tide enhancement at this constriction (Fig. 9f), i.e., spring tides strengthen (rather than suppress) net salt transport there.
3. **Non-monotonic Wind Response:** The wind impact on exchange is strongly non-linear. Across basins, landward salt import peaks under moderate down-estuary winds, with a maximum for $\tau_y \approx 0$ to -0.10 N m^{-2} (Fig. 10). For stronger down-estuary winds, the increase in Q_{in} does not translate into a proportional increase in $Q_{in}\Delta S$, consistent with wind-driven mixing and reduced ΔS limiting the net salt import. In contrast, persistent up-estuary winds suppress both Q_{in} and ΔS, leading to

weak exchange and low $Q_{in}\Delta S$. We have revised the text to emphasize this non-monotonic behavior (rather than a purely strengthening/weakening view) and to clarify the physical interpretation in terms of competing effects on inflow and stratification.

4. **Large-Scale Teleconnections:** We find exchange flow variability at periods consistent with the Baroclinic Annular Mode (25–35 d) and the Madden–Julian Oscillation (40–70 d). These bands are also present in low-frequency envelopes of local wind stress and river discharge, suggesting that large-scale climate variability can project onto regional atmospheric and hydrological forcing that modulates exchange on subseasonal timescales. In our model configuration, the open boundary conditions prescribe only a seasonal T–S cycle (i.e., no explicit intraseasonal remote ocean variability), so the 25–70 d variability in this hindcast cannot be attributed to time-varying ocean boundary forcing. However, we do not rule out that in the real system remote ocean variability at similar periods may contribute alongside atmospheric and runoff pathways; isolating that contribution would require experiments or boundary conditions with intraseasonal variability explicitly represented.

Changes to the manuscript:

To explicitly frame these findings as novel contributions to estuarine physics, we have revised the manuscript as follows:

- **Abstract & Intro:** We have rewritten the Abstract to list these four distinct regimes (Compensation, Tidal Straining, Non-monotonic Wind, and Teleconnections) as the primary physical insights of the study.
- **Tidal Regimes (Section 4.1):** We expanded the discussion on mechanistic controls to specifically contrast the "Spring-tide Straining" observed at Desertores Pass against classic mixing-dominated systems (e.g., the Salish Sea). This emphasizes the unique behavior where spring tides maximize rather than reduce the salt flux.
- **Clarifying Wind Dynamics (Section 4.1):** We added a specific description of the "Non-monotonic" wind response to highlight how moderate winds act as a stratifying agent in this system, countering the typical assumption that wind primarily induces mixing.
- **Teleconnections Context (Discussion):** We integrated the BAM/MJO-period bands into the discussion of exchange variability and clarified that, in this model configuration, the signal is expressed through local wind and discharge envelopes. We present this as a consistency result that suggests a potential (testable) source of subseasonal predictability, rather than a direct attribution to time-varying ocean boundary forcing.

Regarding hydraulic activity and maximal exchange in Desertores Pass:

We agree with the reviewer that hydraulic control is a highly relevant dynamical process for interpreting exchange in this region. A first-order scale analysis using characteristic values for Desertores Pass (tidal currents $U \sim 0.8$–1.0 m s^{-1}, stratification $\Delta S \sim 1$–2 g kg^{-1}, and layer depth $h \sim 50$ m) suggests that the internal Froude number can approach unity ($G^2 \approx 1$) during peak spring tides, which is the classical threshold for internal hydraulic control in two-layer exchange: when the composite internal Froude number approaches unity ($G^2 \to 1$), information cannot propagate upstream in both layers and the exchange can become hydraulically constrained ("choked"). Values $G^2 < 1$ indicate subcritical exchange in which the flow can adjust to upstream conditions, whereas $G^2 > 1$ indicates that the exchange may become hydraulically constrained, so that local dynamics at the constriction can partially set the exchange magnitude, consistent with the maximal-exchange theory. However, applying classic "maximal exchange" theory is not straightforward here because Desertores is an archipelago with multiple passages, so any control is likely distributed rather than localized at a single choke point. A rigorous test would require local, instantaneous diagnostics at specific constrictions, whereas our paper focuses on section-integrated subtidal exchange using TEF. Accordingly, we acknowledge intermittent hydraulic effects as plausible during strong tides, but we do not treat the exchange as being set by a single maximal-control limit in this study.

Changes to the manuscript:

- We have added a paragraph in Section 4.1 acknowledging the relevance of hydraulic control.
- We included the scale analysis ($G^2 \approx 1$) to show that control is physically possible during spring tides.
- We explicitly state that a rigorous analysis of hydraulic control points in this complex archipelago requires a local, instantaneous approach that differs from the section-integrated (TEF) focus of this paper.

Reviewer Comment: *One other general topic that I want to ask the authors about: Mixing seems crucial to metrics such as Q_{in} and ΔS. For example, a run performed with only river runoff and with no mixing allowed would end up with $Q_{in} \approx 0$. Wind and tides contribute to mixing, and when these are shut off, the mixing generally decrease. So the results shown in Figure 4, which suggest that the magnitude of Q_{in} and ΔS are largely captured in experiments where wind and tides are shut off, suggests: 1) that mixing is coming from a source other than winds and tides, or 2): that even though winds and tides are absence, the turbulence parameterization in the model are somehow retaining tides and wind as energy sources, even though tides and wind have been turned off. I know that scenario #2 has been a focus of concern in other types of modeling studies, usually where the wind has been turned on and off, and that some modelers will decrease their eddy coefficients when the wind is turned off. What is the situation here?*

Response: We clarify that our results align with what the reviewer presented as 'Scenario 1' in their comment (mixing from sources other than wind/tides). We deliberately maintained the same turbulence closure scheme (k-ϵ) across all experiments. We did not tune these parameters between runs to strictly isolate the forcing effects. Q_{in} observed in the Baroclinic-only run (B) is driven by the pressure gradient from river discharge (gravitational circulation). This flow generates internal interfacial shear, which sustains the necessary turbulence for exchange. Importantly, as noted in the results, this run exhibits the highest ΔS compared to wind- or tide-inclusive runs. This confirms that while internal shear generates enough mixing to support Q_{in}, it remains physically weaker than the mixing driven by external mechanical forcing (which would further erode stratification). We have updated Section 2.4 (Numerical Experiments) to explicitly state that the turbulence parametrization was kept constant across all simulations to strictly isolate the effects of the forcing terms.

Specific Comments

Reviewer Comment: *Sec. 2.3.2 The partitioning into Q_{in} and Q_{out} seems to presuppose a 2-layer system. Sometimes people will define an "interfacial" layer, one that is created by mixing between upper and lower layers. Does the actual stratification in the model generally look like at 2-layer system?*

Response: This is an important clarification. We employ the *extended dividing-salinity method* (Lorenz et al., 2019), which computes the exchange transport by integrating fluxes across the entire cross-section in salinity space, rather than physical space.

This approach is specifically chosen because it does not presuppose a specific spatial geometry for the "layers." Since TEF aggregates transport based purely on salinity classes, it effectively captures the net exchange regardless of whether the flow structure is vertically stratified (gravitational circulation) or laterally segregated (e.g., by Coriolis effects in wide channels).

Therefore, when we report Q_{in} and Q_{out}, these represent the bulk landward and seaward transport of saltier and fresher water masses, respectively, summing over any complex vertical or lateral interleaving that may exist locally. We have updated Section 2.3 to explicitly state that this method integrates over both vertical and lateral shears, allowing us to collapse complex multi-dimensional flow structures into a consistent bulk exchange budget.

Reviewer Comment: *Eqs. (1)-(4). The reader's question on seeing these is why is there not* $Y^B - Y^{B(E)}$*?*

Response: We actually utilize this specific decomposition to quantify the "Internal" (River) contribution shown in **Figure 5** (labeled as "I (rivers)"), but we inadvertently omitted its formal definition in the methodology section. We have now added Equation (5) to Section 2.4.1 defining $Y^I = Y^B - Y^{B(E)}$ to ensure the definitions aligns fully with the components presented in Figure 5.

Reviewer Comment: *Line 93: states that tidal current of up to 4m/s occur in Reloncav Sound (should it be Reloncavi?) but Fig. 3c suggests otherwise.*

Response: We appreciate the correction. The text intended to contrast the high tidal *ranges* (elevations) in Reloncaví Sound (due to resonance) against the high tidal *currents* in constrictions like Chacao Channel. As shown in Figure 3c, Reloncaví Sound indeed has weak currents despite its large tidal range. We have corrected the spelling to "Reloncaví" and split the sentence in Section 2.1 to clearly distinguish that while Reloncaví Sound experiences the largest tidal *ranges* (6–7 m), the extreme currents (> 4 m s^{-1}) are confined to the Chacao Channel constriction.

Reviewer Comment: *Line 190: Has stratification "index" been defined?*

Response: We thank the reviewer for finding this oversight. We acknowledge that the formal definition of the "stratification index" was inadvertently omitted from the main text and appeared only in the caption of Figure 2. For this study, we calculated this index as the difference between the depth-averaged salinity of the bottom layer (> 25 m) and the surface layer (0–25 m). We agree that this definition must be present in the main body of the manuscript and have inserted it into the main text in Section 3.1 (Results), ensuring it is clearly defined before its first usage in the analysis.

Reviewer Comment: *Fig. 6. It appears to me that the lagged correlation between the salinity gradient and inflow would be much higher if the first 3 months or so of the record were excluded. In Jan-March, the two time series seem to be anticorrelated. What is happening during this period?*

Response: We appreciate this insightful observation. The difference in correlation indeed suggests a seasonal asymmetry in the driving mechanisms. While a complete explanation would require a detailed analysis of the far-field hydrography (beyond the scope of this study), we propose the following hypothesis based on the regional dynamics:

1. **Winter:** The strong correlation in winter is likely driven by the regional coherence of freshwater discharge. The freshening of the external boundary (Boca del Guafo / Corcovado Gulf) is heavily influenced by the discharge from large southern rivers (e.g., Palena River) located near the domain's entrance. Therefore, both the fjord head (Reloncaví) and the fjord mouth are responding to the same regional freshwater pulse. This creates a synchronized, quasi-local adjustment of the pressure gradient and the flow.

2. **Summer:** In contrast, the salinity recovery in Jan–March (which rebuilds the salinity gradient) relies on the physical transport of high-salinity water from the open ocean. This is an advective process that must overcome the inertia of the basin. The "anticorrelation" or lag likely reflects the slow timescale of this oceanic intrusion propagating into the fjord, compared to the rapid, buoyancy-driven adjustment seen in winter.

This interpretation is supported by Dijkstra (2024), who demonstrated that the estuarine salinity adjustment lag is not constant but depends critically on the **forcing timescale**. In our case, the shift from rapid, synoptic river forcing in winter to slower, seasonal oceanic recovery in summer likely creates the distinct lag regimes observed. We have added a discussion in Section 3.3 suggesting that the seasonal discrepancy is due to the differences in the nature of the forcing seasonally (rapid regional freshwater pulses vs. slower oceanic advection), explicitly citing Dijkstra (2024) to support the concept of timescale-dependent adjustment lags.

Reviewer Comment: *Line 273. Are you referring to Fig. 8 here?*

Response: Yes, you are absolutely correct. The text was intended to reference (Fig. 8). We have corrected the reference in the text to point to Figure 8.

Reviewer Comment: *Figure 9. As mentioned in the text, the left-hand panels suggest that Q_{in} is enhanced at the Desertores and Corcovado sections during periods of spring tides, which is consistent with greater mixing. This makes sense. During neap tides, Q_{in} is decreased at all three sections, and the idea put forth here is that the tides are too weak to cause any mixing and that they are inhibiting the inflow through some other mechanism. The accompanying text (lines 280-290) don't make it clear what that mechanism is. Can something be said?*

Response: We appreciate this constructive comment. You are correct that the spring-tide enhancement is consistent with mixing-driven processes, and we acknowledge that the Results section was vague regarding the specific physical mechanism leading to the decrease during neaps.

Based on the Total Exchange Flow (TEF) framework and recent findings by MacCready and Geyer (2024), we interpret these results as a modulation of the tidally driven transport components. Specifically, we suggest that the exchange flow Q_{in} in this region is supported by tidal pumping ($\langle u'S' \rangle$) during spring tides. Under this interpretation, the "inhibition" observed during neap tides (negative anomalies) represents the weakening of these tidal contributions. As the tidal covariance term and vertical entrainment diminish, the system reverts to a state dominated by weaker gravitational circulation. We have added a brief clarification in Section 3.4 (Results) stating that the neap tide exchange flow "inhibition" reflects the absence of the tidal pumping mechanisms that drive the enhanced exchange inflow during spring tides. We have also added references to Section 4 (Discussion), where we now provide a more comprehensive analysis of this mechanism in the context of recent literature (e.g., MacCready and Geyer, 2024).

Reviewer Comment: *Figure 10. The wind arrow in the upper left panel is labeled upwind/downwind. ... Or should the label on the wind vector be "down estuary/up estuary"? Same comment for Fig. 11.*

Response: We agree that the labels "upwind/downwind" were ambiguous. We have replaced this nomenclature with the geographically fixed terms "Up-fjord" and "Down-fjord" to avoid confusion. To clarify the sign convention used in the figures:

- **Positive stress (+):** Corresponds to **Up-fjord winds** (directed Northward, pushing water towards the head of the basin).
- **Negative stress (–):** Corresponds to **Down-fjord winds** (directed Southward, pushing water towards the ocean/mouth).

This convention is fixed relative to the basin geometry. We have updated the labels in Figure 10 and Figure 11 to read "Up-fjord wind" and "Down-fjord wind". We have also explicitly defined this directional convention in the figure captions.

Reviewer Comment: *Line 307. Eq. XX ?*

Response: We apologize for this oversight. The placeholder "XX" was a compilation error. We have corrected the reference to point to the appropriate equation number in the revised manuscript.

Reviewer Comment: *Line 313. There has been some mention of wind straining, and here the "wind straining window". ... does "straining" refer to the horizontal divergence of the flow ...? As I see it, straining in the horizontal can certainly cause changes in the horizontal salinity gradient and this, in* *turn, could affect salinity gradients in the vertical. ... (When we get to lines 353-354 we seem to have a definition of tidal straining... Perhaps this should be explained further, at least for those of us who are not estuary experts.)*

Response: We agree that the terminology was introduced confusingly. To clarify: "Straining" does not refer to horizontal divergence, but to the interaction between vertical shear and the horizontal density gradient (SIPS mechanism, Simpson et al. (1990)). We have rewritten the explanation to clearly define both mechanisms based on the relative direction of the shear:

- **Tidal Straining:** Occurs due to the asymmetry of tidal shear and salinity. During ebb, faster surface currents advect fresh water seaward over slower salty water, tilting isopycnals and enhancing stratification. During flood, the shear is reversed (or reduced), which tends to weaken stratification via mixing or convective overturning.
- **Wind Straining:** Operates analogously but driven by wind stress. Down-fjord winds enhance seaward surface flow, increasing the shear and strengthening stratification. Up-fjord winds oppose the estuarine circulation, reducing shear and promoting destratification.

We have moved the physical definitions of tidal and wind straining to the introduction of the results section so the concept is clear to the reader before it is applied in the analysis.

Reviewer Comment: *Lines 310-311. I'm not sure where the 2.7 comes from. The maxim amplification at Reloncavi is about 2.0, whereas the maximum at Corcovado is 9.5. A comparison of the two would give an amplification of 9.5/2, so the authors must be referring to something else.*

Response: We apologize for this discrepancy. You are correct; the figure yields a ratio closer to 4.8 ($9.5/2.0$) rather than 2.7. We have corrected the value in the text to match the ratio observed in the figure ($\sim$4.8).

Reviewer Comment: *Line 316. It is stated that up-estuary winds frequently damp Q_{in} through mixing, but an increase in mixing alone should tend to increase the volume exchange rate... I would have thought that the reason is that it is essentially dragging the upper layer up into the estuary. So this really seems like momentum/pressure gradient effect.*

Response: We completely agree with the reviewer's physical interpretation. While wind-induced mixing does reduce the vertical exchange flow by breaking down stratification, the **dominant mechanism** for the sharp reduction of inflow (Q_{in}) during strong up-estuary wind events is the direct wind stress (momentum transfer). The wind pushes the surface layer landward (opposing the residual outflow) and sets up a barotropic pressure gradient that opposes the gravitational circulation. We acknowledge that attributing this solely to "mixing" in the original text was imprecise. We have refined the explanation in Section 3.3 to emphasize that the damping of Q_{in} is primarily due to the wind stress altering the momentum balance and the barotropic pressure gradient, with vertical mixing playing a secondary role in this specific dynamic.

Reviewer Comment: *Line 399-401. Elevated power at 14-16 days is found at Corcovado for a model run that does not include tides. This is attributed to nonlinear interactions between tidal currents and baroclinicity over the spring-neap cycle. I don't understand how a model run without tides can capture nonlinear interactions with tides.*

Response: You are correct: a baroclinicity-only simulation cannot represent nonlinear interactions involving tides. In that run, the 14–16 day variability reflects temporal variability in the prescribed river discharge, not tidal dynamics. We have corrected Section 3.5 by removing the tidal-interaction interpretation and explicitly attributing the 14–16 day band in the baroclinicity-only case to discharge fluctuations.

Response to Reviewer 2

Reviewer Comment: *A major concern regarding this exercise is the verification of model results. Salinity data from only one location are used for model verification. It is thus not shown that salinity and vertical stratification in all parts of the model area are correctly computed by the model. Another worry concerns vertical mixing in the model that is parameterized but not verified using observations from the model area. ... The present manuscript should not be published because the conclusions are based on results from a model that has not been verified for the actual area regarding vertical mixing, salinity, and transport.*

Response: We agree that the validation presented in the original manuscript, limited to a single point, was insufficient to demonstrate the model's reliability across the entire domain, particularly regarding vertical mixing and salinity.

To address this fundamental concern, we have performed a comprehensive validation overhaul using extensive observational datasets that were not included in the first draft. These analyses, including new figures, have been compiled into a new **Supplementary Material** document.

For the reviewer's convenience, we invite you to review the new Supplementary Material attached as a separate PDF. Below, we provide a brief overview of the content, methodology, and key validation metrics contained therein, which are also included in the Supplementary Material document. However all accompanying figures are only shown in the Supplementary Material document itself.

Overview

We evaluate the hydrodynamic model and forcings using three complementary diagnostics: (i) time–series overlays to assess biases in amplitude and timing; (ii) model–observation scatter to quantify linear skill (Pearson r) and typical errors (RMSE); and (iii) the global Morlet wavelet spectrum (Torrence and Compo, 1998), i.e., the time–averaged wavelet power as a function of period, which summarizes how variance is distributed across bands (semidiurnal/diurnal tides, fortnightly spring–neap, synoptic 3–12 d, and intraseasonal 25–70 d). We pair the wavelet analysis with time series and scatter to verify both order of magnitude agreement and banded co-variability. This is essential because our process attribution and TEF analyses rely on signals organized by those frequency bands.

Data Sources: The observational dataset used for validation, specifically hydrographic profiles (CTD), was obtained from the monitoring efforts conducted by the Fisheries Development Institute (IFOP) under the project "High-Resolution Modeling Applied to Hydrodynamic Transport within the Chiloé Inner Sea, X Los Lagos Region" (Soto et al., 2018).

To document the performance of the forcing and the hydrodynamic response, we validated (i) surface salinity against the probe on oceanographic buoy of Reloncaví Marine Observatory (OMARE) (Pérez-Santos et al., 2021) time series in Reloncaví Sound, (ii) depth-averaged axial currents at Desertores Pass against an ADCP record from oceanographic monitoring by IFOP (Soto et al., 2018), (iii) along-estuary wind from the WRF–IFOP hindcast against the weather station on the OMARE oceanographic buoy, (iv) Puelo River discharge estimates against the flow gauge, and (v) sea level against the SHOA (Navy Oceanographic Service) tide gauge at Puerto Montt (site map and description in Figs. S1–S6). In order: surface salinity reproduces seasonal and subtidal variability ($r \approx 0.70$; Fig. S2); currents capture spring–neap modulation with skill ($r \approx 0.93$, RMSE $\sim$0.11 m s^{-1}; Fig. S3); the along-estuary wind compares favorably to the buoy ($r \approx 0.84$, RMSE $\sim$2.3 m s^{-1}; Fig. S4); Puelo discharge is well represented from synoptic to intraseasonal scales ($r \approx 0.86$, RMSE $\sim$188 m^3 s^{-1}; Fig. S5); and sea level matches the dominant tidal bands with high linear agreement ($r \approx 0.97$, RMSE $\sim$0.40 m; Fig. S6). Taken together, the model output matches the order of magnitude of the observational data and exhibits coherent variance peaks across the bands that underpin our mechanism tests, indicating it is sufficient to quantify the TEF diagnostics presented, within the stated limitations.

Vertical Structure and Stratification Assessment

To assess the model's ability to reproduce the stratification patterns, we utilized the Potential Energy Anomaly (PEA, ϕ) (Simpson, 1981). This metric represents the mechanical work required to instantaneously homogenize the water column. PEA provides a depth-integrated measure of stratification strength that accounts for the shape of the vertical density profile, making it an ideal diagnostic to evaluate whether the model correctly reproduces the spatial transition from mixed to stratified regimes.

Methodology: To facilitate inter-seasonal comparison despite slight variations in cast coordinates, stations located within a 2 km radius were grouped under a single Station ID (ordered north to south; see Table S1). Given that each oceanographic campaign spanned approximately 6–12 days, the model fields were time-averaged over the specific duration of each cruise. Consequently, the validation compares the observed profiles against the temporal mean of the model for that specific synoptic window, rather than instantaneous snapshots. This approach ensures that the comparison focuses on the dominant subtidal stratification structure. The PEA was calculated as:

$$\phi = \frac{1}{H} \int_{-H}^{0} (\bar{\rho} - \rho(z)) g z \, dz \tag{1}$$

where $\rho(z)$ represents the density profiles derived directly from the CTD observations and the model output, respectively.

Validation Results: The model demonstrates adequate skill in reproducing the spatial and seasonal evolution of the density structure. The PEA comparison shows linear agreement between observations and model output, with correlation coefficients (r) ranging from 0.75 in spring to 0.95 in winter **(Figs. S8–S10)**. Spatially, the model effectively captures the spatial gradient of the system: ranging from vertically mixed conditions at the oceanic boundary (southern and western side, low ϕ) to stratified conditions in the fjord regions (eastern and northern regions, high ϕ) **(see profiles in Figs. S8–S10 and maps in Fig. S11)**.

Furthermore, the spatial synthesis of the time-averaged PEA confirms that the model captures the persistent density structure and its seasonal intensification, correctly simulating ϕ magnitudes exceeding 800 J m^{-3} during summer **(Fig. S10 and S11)**. This accurate representation of vertical density gradients is fundamental, as it governs the baroclinic pressure forces driving the exchange flow mechanisms analyzed in the main manuscript.

It is worth noting that the scatter analysis reveals a systematic positive bias **(Figs. S8–S10)**, indicating a tendency for the model to overestimate absolute stratification. While this suggests that the magnitude of the density-driven component of the exchange flow may be slightly overestimated, the high linear correlations ($r > 0.75$) confirm that the model correctly simulates the variability and relative response to physical forcings. Consequently, the resulting baroclinic pressure gradients and their interaction with wind and tides remain dynamically consistent with the observed system.

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