Dear Editor and Reviewers,

We sincerely appreciate the Editor's and the Reviewers' insightful and constructive comments on our manuscript. The manuscript has been thoroughly revised based on this valuable feedback. In accordance with your suggestions, the revised manuscript now features:

- **Standardized Formatting:** Adherence to GMD-standard formatting, notations, consistent symbols, and font styles.
- **Enhanced Visuals:** Improved figure quality and clearer captions.
- **Regional Comparisons:** Explicitly writing out regional names and consolidating their characteristics into a new comparison table.
- **Scientific Deepening:** A clearer justification of the added value of using an online-coupled model, alongside a restructured flow across sections to strengthen the scientific interpretation.
- **Future Outlook:** An updated Conclusion section that provides a more explicit and focused discussion on future research directions.

Below are our point-by-point replies to the specific comments and concerns raised by the Editor and the Reviewers.

Reviewer #1
The reviewer comments are formatted in italics and the authors response to the comments are formatted in regular font.
Notation *RC1.P#* represents Reviewers Comment. Paragraph Number

Specific comments:

RC1.1 Inconsistent formatting of variables throughout the manuscript. For example, variables such as U_{10} and Hs are sometimes italicized and sometimes presented in plain text. Scientific notation should be formatted consistently throughout the manuscript.

Response:

Thank you for pointing out the mistake. The notation has been standardized throughout the manuscript, including U_{10}, H_s, u^*, Sc, $k_{w,660}$, $k_{wB,660}$, $k_{wNB,660}$, K_H, K_{a1}, K_{a2}, pH, pCO_2^w, pCO_2^a, and $dpCO_2$.

RC1.2 Inconsistent terminology for standard deviation. In some places the manuscript uses "SD", whereas in others "stdev" is used. A single notation should be adopted throughout the manuscript, figures, captions, and text.

Response:

We have consistently used SD as the abbreviation for standard deviation throughout the revised manuscript. Please see Figs. 2–4 for the changes.

RC1.3. Inconsistent use of symbols and prose. For example, mathematical symbols are sometimes used in sentences to indicate higher/lower values or increases/decreases. Scientific writing should use clear text descriptions where appropriate rather than mixing mathematical notation with narrative text.

Response:

Thank you for your comment. Please see the revised manuscript for these changes.

RC1.4. Table 1 contains formatting inconsistencies, including inconsistent font styles and formatting of references.

Response:

Thank you for your suggestion. We have formatted Table 1 consistently with respect to font styles and reference formatting.

RC1.5. Figure preparation requires substantial improvement. For example:
- Figure 3 and Figure 4 contain poorly aligned subpanels.

Response:

The alignment of the subpanels in Figs. 3–5 has been improved in the revised manuscript to enhance data presentation.

RC1.6. In Figures 3 and 4, some labels and numerical values overlap with plotted lines and bars, reducing readability.

Response:

We have optimized the Y-axis scales and adjusted the positioning of the average value labels in the revised manuscript to eliminate overlap between the labels and numerical values.

RC1.7. The title of panel (b) in Figure 6 appears to be partially cut off.

Response:

In the revised manuscript, we have resized the titles in Fig. 6 to ensure that all text is fully visible and reads clearly.

RC1.8. Several figures contain labels, annotations, and graphical elements that are crowded or difficult to interpret.

Response:

Thank you for your comment. The notations for all physical and chemical variables have been standardized across all figures, including SD, U_{10}, H_s, u^*, Sc, $k_{w,660}$, $k_{wB,660}$, $k_{wNB,660}$, K_H, K_{a1}, K_{a2}, pH, pCO_2^w, pCO_2^a, and $dpCO_2$. Additionally, the font sizes of the titles within the corresponding figure have been standardized to a uniform scale to prevent visual clutter and ensure clarity. In the revised manuscript, the figure caption has been rewritten for clarity to facilitate a more straightforward interpretation of the presented data.

RC1.9. The overall image quality of several figures appears poorer than in the original submission.

Response:

We have upgraded the graphical resolution and standardized the title font sizes across these figures; these updates are detailed in the revised manuscript. Additionally, the coarser resolution observed in Figs. 2e and 2f is an inherent artifact resulting from subtracting the original NOAA CT2022 fields.

RC1.10. Several figures raise questions regarding consistency and interpretation that should be clarified:
- In Figure 2, "stdev" is used in the figure whereas "SD" is used in the caption.

Response:

We have consistently used SD as the abbreviation for standard deviation throughout the revised manuscript. Please see Figs. 2–4 for the changes.

RC1.11. Figure 2 contains underlined labels (e.g., NWP and EEP) without explanation.

Response:

In the revised manuscript, we have added a detailed explanation in Section 2.3 clarifying that the underlined labels denote the regions exhibiting the most pronounced maximum positive CO_2 flux (<u>EEP</u>) and maximum negative CO_2 flux (<u>NEP</u>).

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RC1.12. The dashed lines in Figure 2 are described as denoting "other significant areas", but the meaning of "significant" is unclear.

Response:

The black dashed lines mark regions with an air–sea CO_2 flux below -2 mol m^{-2} yr^{-1}. Please see the revised manuscript for the changes.

RC1.13. A low-value region near southern Africa appears not to be enclosed by a highlighted region, unlike other areas. The rationale should be explained.

Response:

Thank you for your comment. The region near southern Africa is included within the South Atlantic Ocean (SAO) domain in Fig. 2d. For this region, the SAO exhibits close agreement between the model-simulated CO_2 fluxes and the NOAA CT2022 dataset (Fig. 3). Additionally, the Southern Hemisphere exhibits large monthly SDs alongside relatively strong negative air–sea CO_2 fluxes during the boreal summer, particularly in regions such as SPO1, SIO1, and SAO (section 3.1).

RC1.14. Figure 7 uses thick contour lines whose meaning is unclear. The distinction between contour types in panels (b) and (d) should be clearly explained.

Response:

Thank you for your constructive comment and for pointing out the areas where the manuscript needed improvement. The revised figure caption is provided below:

Figure 7. Effects of atmospheric factors and wave components on average gas transfer velocity: (a) Shaded areas represent 10-m wind speed (U_{10}, m s^{-1}) and contours show sea level pressure (PSL, mb); (b) color denotes the ratio of bubble-mediated ($k_{\mathrm{wB},660}$) to POP2–waves $k_{\mathrm{w},660}$ components, with contours representing significant wave height H_s (m) and thick lines marking H_s = 1.5m; (c) shading represents $k_{\mathrm{w},660}$ (B–CTL) and contours represent the difference $k_{\mathrm{w},660}$ (POP2–waves − B–CTL) in cm hr^{-1}; (d) shading shows the non-bubble-mediated component ($k_{\mathrm{wNB},660}$) and contours show the difference ($k_{wNB,660}$ − $k_{\mathrm{wB},660}$) in cm hr^{-1}, with the thick contour lines at 0.

RC1.15. In Figure 4, it is unclear why underscores appear for some B-CTL values.

Response:

Regional-average values are distinguished by a black underline for B–CTL, red font for POP2–waves, and blue italics for NOAA CT2022. Please see the revised Fig. 3 capture for the change.

> *RC1.16. In Figure 6, it is not clear how the plotted data points were obtained, how many data points are included, and whether any filtering or aggregation was applied.*

Response:

We selected monthly mean air–sea CO_2 flux data from the Western Pacific (WP) (160–180°E, 35–40°N) based on 30-year B–CTL and POP2-waves simulations. The data were filtered to include only grid points where the monthly mean $U_{10} > 10$ m s^{-1}, and were subsequently regional-averaged. Because not all months contained grid points meeting this U_{10} threshold, a final subset of 154 data points was utilized for the linear regression analysis. Please see section 3.3 for the change.

> *RC1.17. Some textual errors remain despite previous revision. For example:*
> *- Line 652: "for release CESM1.2.2" should be "for releasing CESM1.2.2".*
> *- Multiple typographical and formatting inconsistencies remain throughout the manuscript.*

Response:

Please see revised manuscript for the change.

Anonymous Reviewer #2
The reviewer comments are formatted in italics and the authors response to the comments are formatted in regular font.
Notation *RC2.P#* represents Reviewers Comment. Paragraph Number

General recommendations:

RC2.1 in L239, it could be clearer that you are comparing two CESM1.2.2 model simulations: one with the wind formulation ('control' instead of B-CTL, which makes for easier reading and recall) and the other with the waves ('POP2-waves'), and evaluate them against an 'obs-based estimate' (namely the NOAA CT2022).

Response:

In the NCAR Community Earth System Model (CESM), a component set (compset) specifies the configuration of active model components, such as the atmosphere, ocean, sea ice, land, river runoff, and glaciers. In this study, following the naming convention of Tseng et al. (2015), we designate the control run as 'B–CTL'. Here, 'B' denotes a fully coupled atmosphere–ocean–sea ice–land system, while 'CTL' refers to the control simulation. Using the B–CTL convention provides immediate clarity to readers familiar with CESM architecture regarding the baseline coupled configuration used.

Reference:

Tseng, W.-L., Tsuang, B.-J., Keenlyside, N. S., Tu, C.-Y., and Hsu, H.-H.: Resolving the upper-ocean warm layer improves the simulation of the Madden–Julian oscillation, Clim. Dyn., 44, 1487–1503, https://doi.org/10.1007/s00382-014-2315-1, 2015.

RC2.2 Another example would be replacing positive/negative fluxes with outgassing/uptake regions (e.g, L260/262/284/408 or L340, where it's more or less uptake).

Response:

Thank you for the suggestion. We agree that focusing on the direction of the physical processes is clearer for the reader. We have revised the sentence to directly refer to "outgassing/uptake" rather than positive/negative fluxes.

RC2.3 In section 3.3, the same can be done with high-wind conditions, which is defined in L325 but missing the term, and then used in L329.

Response:

Thank you for the suggestion. Please see revised section 3.3 for the change.

RC2.4 *In many parts of the draft, information is included in the figure caption and then repeated in the text—for example, L255-257, L286-291, L382-286. Instead of repeating information, it would be better to skip to the interpretation and reference the figure.*

Response:

In accordance with the reviewer's suggestion, all descriptive figure caption details (previously referencing Figs. 1 through 11) have been systematically removed from the main text to eliminate redundancy. The manuscript body now focuses strictly on the scientific interpretation and physical mechanisms. Please see the revised manuscript for these structural updates.

RC2.5 *I'd also recommend writing out the names of the regions, as it's hard to understand the patterns without referencing Figure 3, or consolidating the regions if it's easier.*

Response:

We sincerely thank the reviewer for this constructive suggestion regarding readability. We agree that relying solely on abstract region abbreviations created an unnecessary cognitive burden for the reader.

To resolve this and improve the clarity of our spatial analysis without making the text overly redundant, we have taken the following multi-step approach in the revised manuscript:

1. Contextual Geography: We now explicitly write out the localized geographical names upon their first appearance in key sections (e.g., changing standalone "SPO1" to "the subtropical South Pacific (SPO1)").
2. Regional Consolidation: In Section 4.1, we have consolidated the discussion of regions that share identical physical mechanisms (e.g., grouping NWP, NEP, NAO1, and NAO2 as "high-latitude regions of the Pacific and Atlantic") to help the reader track large-scale climate patterns more intuitively.
3. Establish a Quick-Reference Mechanism: The geographic definitions and abbreviations of all 12 regions are detailed in Table 1 and illustrated in Fig. 3, and added brief abbreviation keys to the captions.

Table 1. Characteristics of the 12 key regions exhibiting prominent air–sea CO_2 flux variability across the three major ocean basins.

Basins	Key regions
the Pacific Ocean	the Northwestern Pacific (NWP), Eastern Equatorial Pacific (EEP), Northeastern Pacific (NEP), South Pacific Ocean 1 (SPO1), and South Pacific Ocean 2 (SPO2)
the Indian Ocean	the North Indian Ocean (NIO), South Indian Ocean 1 (SIO1), and South Indian Ocean 2 (SIO2)
the Atlantic Ocean	the North Atlantic Ocean 1 (NAO1), North Atlantic Ocean 2 (NAO2), Equatorial Atlantic Ocean (EAO), and South Atlantic Ocean (SAO)

Detailed comments:

RC2.6 Please correct the tenses in the title of the paper: "Wave effect mechanisms enhance air-sea CO2 exchange and modulate* seawater carbonate-pH in the POP2-waves coupled model". The word 'adaptation' can be misleading here.*

Response:

We sincerely appreciate the reviewer's valuable feedback on the title's grammar and terminology.

1. Tense Correction: We have corrected the verbs to ensure proper agreement and standard journal phrasing.
2. Removal of 'Adaptation': We agree that the term "adaptation" carries specific ecological or climate-policy connotations that could mislead readers regarding physical/chemical modeling mechanisms. We have verified that this term is completely removed from the title and carefully screened its usage in the abstract and main text to ensure scientific precision.

Following your suggestions, we have revised the title of the manuscript to: [Enhancing air–sea CO_2 exchange and modulating seawater carbonate–pH dynamics: the role of wave effect mechanisms in the POP2–waves coupled model].

RC2.7 L64-68: Sea spray is the inverse of the wave-breaking phenomenon and doesn't contribute to air-sea exchange, but rather to cloud condensation nucleation. Clarify/modify this section.

Response:

We thank the reviewer for this insightful clarification regarding the distinct roles of sea spray and wave breaking. We agree that sea spray droplets ejected into the atmosphere primarily contribute to cloud condensation nucleation upon evaporation, rather than acting as a direct vehicle for gaseous CO_2 exchange. We have revised the text to clarify that the enhanced CO_2 exchange at high wind speeds is driven by wave-breaking dynamics and bubble mediation, while properly contextualizing the role of sea spray.

> *RC2.8 L80-88: It's not clear how the discussion about eddy covariance methods that are used to get to the gas transfer velocity relates to the limitations of the pCO2-based products. The information should be reordered to set up the problem statement more clearly.*

Response:

We agree that the connection between pCO_2-based products, the gas transfer velocity ($k_{w,660}$), and the eddy covariance (EC) instrumentation was not presented with sufficient clarity.

To set up the problem statement clearly, we have thoroughly reorganized this section. We explicitly introduce the bulk flux formula (Eq. 1) first to highlight that pCO_2-based products depend heavily on empirical parameterizations of $k_{w,660}$, which are prone to large uncertainties. We then explain the role of the EC method as an independent and direct technique to measure F_{CO_2}, which allows us to inversely calculate $k_{w,660}$ ($k_{w,660} = F_{CO_2}/ (k_0 \times dpCO_2)$) and thereby validate these empirical products (Dong et al., 2021). Finally, we transition into the technical challenges of the EC method itself (the open- vs. closed-path analyzer comparison). We believe this restructuring creates a robust, step-by-step logical bridge for the reader. Please see revised manuscript for the change.

Reference:

Dong, Y., Yang, M., Bakker, D. C. E., Kitidis, V., and Bell, T. G.: Uncertainties in eddy covariance air–sea CO_2 flux measurements and implications for gas transfer velocity parameterisations, Atmos. Chem. Phys., 21, 8089–8110, https://doi.org/10.5194/acp-21-8089-2021, 2021.

> *RC2.9 L104: Consider rewording 'non-model simulations' to observation-based products or some equivalent term.*

Response:

We use 'observation-based products' instead of non-model simulations in the sentence.

RC2.10 L105-111: Rustogi et al. (2025) used ocean models that are forced by reanalysis and wave model output. How would that contrast with your model setup? You introduce their setup, but it's not clear what the limitation or value-add is of using a coupled model like yours.

Response:

We thank the reviewer for pointing out the need for a clearer contrast between our model setup and that of Rustogi et al. (2025). This comparison is indeed essential for highlighting the distinct value-add of our study. As the reviewer noted, Rustogi et al. (2025) utilized an ocean-biogeochemistry system forced by offline atmospheric reanalysis and wave model outputs. While comprehensive, such an offline-forced setup is limited in its ability to capture high-frequency, episodic, and synchronous interactions between physical wave states and surface water chemistry during rapid weather transitions.

In contrast, our study implements an online coupling framework. The key value-add of our setup is its capacity to simulate step-by-step, interactive feedbacks where wave properties dynamically alter the gas transfer velocity ($k_{w,660}$) and physical mixing in real-time. This allows our model to capture non-linear, high-resolution impacts on the air–sea CO_2 flux during highly dynamic conditions, which are often smoothed out in offline-forced simulations. We have thoroughly revised this introduction section to explicitly contrast these two methodologies and clarify our model's specific advantages.

RC2.11 L153-155: Move this section below to where you introduce the Reichl and Deike formulation that uses u.*

Response:

Sentences L153–155 were removed, as Section 2.2 had already introduced friction velocity following the discussion of the Reichl and Deike formulations.

RC2.12 Section 2.2: Clarify if the wave radiation equation includes information about locally wind-generated and remotely generated swell waves in the significant wave height output.

Response:

Thank you for the comment. We would like to clarify that the significant wave height (H_s) output, which drives the wave radiation equation, inherently includes information from both locally wind-generated wind seas and remotely generated swell waves.Following the coupled wave-current modeling framework described by Mellor et al. (2008), the wave radiation stress terms are calculated using the total wave energy spectrum (or integral bulk parameters derived from it, such as H_s and wave periods). Because the underlying wave model accounts for both local winds forcing (producing wind seas) and non-local wave propagation (resulting in swells), their combined energy is reflected in the H_s output. Consequently, the wave radiation equation implicitly incorporates the effects of both wind seas and swells on the ocean circulation. We have added a brief clarification in Section 2.2 of the revised manuscript to state this explicitly.

RC2.13 L246: Could you quantify 'more closely resemble'? It seems like the outgassing in the equatorial Pacific diverges more with waves than the control compared to the obs-based estimate? Could you state what the global integral of the flux is and whether it's closer?

Response:

Following the reviewer's suggestion, we have replaced the vague phrase "more closely resemble" with precise quantitative descriptions in Section 3.1 and Table RC2.13.1, and explicitly noted the higher monthly standard deviation (SD) in the POP2–waves experiment.

Table RC2.13.1. Relative magnitudes of model–data biases (%), defined as the monthly mean absolute deviation normalized by the model's corresponding monthly variability range (95th minus 5th percentile)

Model	NWP	EEP	NEP	SPO1	NIO	SIO1	NAO1	EAO	SAO
POP2–waves	21.9	46.5	24.7	21.1	14.5	17.8	14.3	15.0	31.6
B–CTL (baseline)	26.8	71.5	25.3	22.1	16.2	21.9	15.4	11.9	36.0

Note:
Abbreviations: NWP: Northwestern Pacific; EEP: Eastern Equatorial Pacific; NEP: Northeastern Pacific; SPO1: South Pacific Ocean 1; NIO: North Indian Ocean; SIO1: South Indian Ocean 1; NAO1: North Atlantic Ocean 1; EAO: *Equatorial Atlantic Ocean;* SAO: South Atlantic Ocean.
The relative magnitude of model–data bias (%) across the 360-month period is defined and calculated as follows:

$$\text{Model} - \text{data biases } (\%) = \frac{1}{12}\sum_{i=1}^{12}\frac{|Mi - Oi|}{P_{95}(M) - P_{5}(M)}$$

where *M*i and *O*i represent the monthly mean values simulated by (POP2–waves or B–CTL) and observed (NOAA CT2022) air–sea CO_2 fluxes for the month mean of month i (i = 1, 2, …, 12), respectively. P_{95} (*M*) and P_5 (*M*) denote the 95th and 5th percentiles, respectively, of each calendar month's values over the 30-year period, representing the corresponding range of monthly variability in the model.

RC2.14 L252: How do you shortlist regions? Is it using correlations of the time series of the 'control' with the obs-based estimate? If so, please clarify the criteria in the text. In that case, it's the phasing that determines the close agreements, since all regions have discrepancies.

Response:

We appreciate the reviewer's professional insight. The reviewer is completely correct that seasonal phasing is a primary determinant in identifying regions of "close agreement," given that numerical discrepancies exist across all regions to some extent.

To clarify our shortlisting criteria, the 12 regions were categorized based on two quantitative features:

1. Seasonal phasing consistency: Whether the simulated seasonal cycles (temporal trends) align with the NOAA CT2022 atmospheric inversion framework.
2. Relative magnitudes of model–data biases: The monthly averaged deviation as a percentage of the overall range (95% minus 5%) relative to the NOAACT2022 baseline.

The nine regions in Fig. 3 exhibit both highly coherent seasonal phasing and relatively small monthly model–data biases. In contrast, the three regions in Fig. 4 display prominent structural mismatches, such as inverted seasonal trends. Importantly, these temporal phase misalignments directly amplify the calculated monthly model–data biases, as the model and data fluctuate in opposing directions throughout the annual cycle. This phase mismatch ultimately leads to substantially larger relative monthly mean biases; specifically, the model–data biases averaged across the three regions in Fig. 4 (32.9 %) are significantly larger than those in the nine regions of Fig. 3 (27.5% in B–CTL and 23.0% in POP2–waves, respectively).

We have revised L252 to state these classification criteria explicitly, ensuring transparency and reproducibility.

RC2.15 You discuss the standard deviation but don't comment on the mean values, which, in around half of the regions, have a larger discrepancy in the wave simulation compared to the control. Can you comment on this?

Response:

We thank the reviewer for this insightful comment; we have thoroughly revised this paragraph to present a balanced discussion of both the variability and the mean states (see section 3.1). Specifically, we have explicitly acknowledged this mean-value discrepancy while highlighting that the wave-coupled model still provides crucial advantages in capturing key seasonal mechanisms, such as the sink-to-source transition in the NWP.

Traditional wind-only parameterizations of gas transfer velocity tend to underestimate fluxes under high-wind conditions ($U_{10} > 10$ m s^{-1}) or high significant wave heights ($H_s > 1.5$ m) (e.g., Gutiérrez-Loza et al., 2022; Zhou et al., 2023). The inclusion of wave dynamics in POP2-waves successfully rectifies this underestimation, bringing the simulated maximum sink values in the Northwest Pacific (NWP) and maximum source values in the Equatorial Eastern Pacific (EEP) into closer agreement with NOAA CT2022.

While this adjustment significantly improves the simulation of temporal variability and extreme events, the widespread increase in transfer velocity introduces a systematic offset in the regional mean values. Consequently, this leads to a larger mean discrepancy in around half of the regions compared to the B–CTL control, which lacks these high-wind wave dynamics.

RC2.16 L301-304, L348-350: Should be moved to the discussion.

Response:

These two paragraphs have been relocated to Section 4.2. Please refer to the revised manuscript for the detailed changes.

RC2.17 Figure 7/L371: The difference in contours and the shading on the same map is really hard to interpret. Could you separate the maps? I would have expected the largest difference to appear in the Southern Ocean, and it's up to 10 cm/hr higher there. In contrast, in L381, you state that the largest difference is in the tropics, where the wave heights are generally weak. Could you clarify?

Response:

Thank you for this constructive comment. We closely considered the suggestion to separate the contours and shading. However, since Fig. 7 contains four panels (a–d), separating them would result in a total of eight panels, which we feel would make the figure overly lengthy and difficult for readers to compare across panels.

Specifically, we adjusted the transparency of the shading, sharpened the contour lines, and optimized their spacing. These modifications significantly enhance the clarity, making it much easier to distinguish between the contours and shading on the same map.

Regarding the text contradiction you pointed out, we sincerely apologize for the confusion. In the previous version, we updated Fig. 7c from the relative difference ($\frac{\text{POP2−waves − B−CTL}}{\text{B−CTL}}$) to the absolute difference (POP2–waves – B–CTL), but unfortunately missed updating the corresponding text. This oversight caused the contradiction between lines 371 and 381.

We have now corrected the text to align with the absolute difference shown in Fig. 7c. The largest absolute differences do indeed occur in the high-H_s regions of the Southern Ocean, rather than the tropics. Lines 371–381 have been revised as follows: The structural differences in $k_{w,660}$ (POP2–waves − B–CTL) reveal that the most pronounced discrepancies are primarily distributed in regions characterized by elevated H_s, particularly in the Southern and South Indian Oceans. (Fig. 7c).

> RC2.19 *Section 4.1: I think this belongs in the results section since it's in the paper's title.*

Response:

We have revised the manuscript structure accordingly. The discussion on the mean state and model differences in pCO_2^w and surface pH has been relocated to Section 3.5, while the evaluation of POP2-waves and its comparison with other models remains in Section 4.1.

> RC2.20 *L422-454: This should be in the methods section, except for L449, which is part of the results.*

Response:

Thank you for the suggestion. We have moved the description of the marine carbonate system to the Methods section (now Section 2.1). As suggested, the text regarding the pH results remains in Section 3.5.

RC2.21 The 'traditional approach' here is the obs-based products. The ocean and earth system models include feedbacks. Please clarify, and perhaps move to the discussion.

Response:

In the revised discussion (Section 4.1), we clarify that the POP2–waves framework explicitly captures interactive, $dpCO_2$-driven negative feedbacks within the Earth system. This coupled behavior stands in contrast to observation-based statistical products (e.g., Reichl and Deike, 2020), which typically treat wave-induced $k_{w,660}$ and $dpCO_2$ as decoupled or independent variables. Furthermore, it represents an advance over standard ocean models driven by offline-forced atmospheric reanalysis and wave outputs (e.g., Rustogi et al., 2025) that lack fully integrated feedback loops.

RC2.22 L473: I'd caution against using the word 'mitigation' here, as it is usually understood as being an action to prevent/reduce greenhouse gas emissions and enhance natural carbon sinks, and what you're describing is part of the natural/forced ocean carbon cycle.

Response:

We sincerely thank the reviewer for this insightful caution. We agree that the term "mitigation" should be reserved for anthropogenic climate actions. To avoid any confusion and ensure scientific accuracy, we have revised the sentence by replacing "mitigates" with "alleviates" in the revised manuscript (Section 3.5) to purely describe the natural response of the ocean carbon cycle.

RC2.23 L585: I disagree that the patterns are better represented with waves compared to NOAA CT2022. This concern also relates to my comments on L258 and L585, where the manuscript states that the wave simulation improves agreement with observations, but the evidence presented appears mixed depending on the metric considered.

Response:

We agree that the term "better represented" was overly broad, as the impact of incorporating wave effects varies across different ocean basins and metrics.

In the revised manuscript, we have toned down our statements and provided a more nuanced discussion. Specifically, we clarify that while the POP2–waves simulation shows a closer alignment with the NOAA CT2022 inversion product in terms of spatial distribution across the majority of the 12 key high-variability regions, the improvement is indeed region-dependent. Notable discrepancies and mixed performances persist in specific sectors, such as the South Pacific Ocean 2, South Indian Ocean 2, and North Atlantic Ocean 2.

To reflect this balanced view, we have revised the text around L585 as follows: "Our regional evaluation reveals a mixed and basin-dependent performance when introducing wave effects. Across the majority of the 12 key regions of high variability defined by NOAA CT2022, the POP2–waves simulation shows a closer structural agreement with the inversion data compared to the uncoupled B–CTL baseline. However, this improvement is not universal; notable discrepancies persist within specific sectors, including the South Pacific Ocean 2, South Indian Ocean 2, and North Atlantic Ocean 2, where the wave-coupled model does not clearly outperform the baseline."

We have revised the text around L258 as follows:

"The POP2–waves simulation generally exhibits higher SD than B–CTL, reflecting an amplified seasonal variability (Figs. 3–4). Although these SD values typically remaining below 3 mol m^{-2} yr^{-1}, they peak during boreal winter, a phenomenon driven by intense oceanic CO_2 uptake in high-latitude regions of the Northern Hemisphere, such as the Northwestern and Northeastern Pacific, and North Atlantic Ocean 1."

RC2.24 Conclusions: The conclusions would benefit from a brief outlook section. For example, the rebuttal mentions ongoing efforts to further improve gas transfer formulations, but these future directions are currently absent from the manuscript.

Response:

We sincerely thank the reviewer for this excellent and constructive suggestion. We agree that incorporating these precise future directions strongly enhances the forward-looking nature of our conclusions. Following reviewer's advice, we have added a dedicated "Future Outlook" paragraph at the end of the Conclusions section (Section 5) in the revised manuscript. In this section, we explicitly outline our ongoing and future model development plans, specifically noting the integration of the new generalized formulation by Deike et al. (2025) to evaluate asymmetric bubble flux contributions and their potential impacts on both CO_2 and O_2 fluxes. The newly added text reads as follows:

"While the current POP2–waves framework demonstrates the critical importance of online coupling and dpCO_2-driven feedbacks, several avenues remain for future model refinement. A key priority is the continuous improvement of gas transfer velocity formulations. Future efforts will focus on transitioning to the new generalized formulation proposed by Deike et al. (2025), which incorporates updated coefficients and accounts for an asymmetric bubble flux contribution. While this advancement is expected to have a minor impact on oceanic CO_2 flux estimations, it holds potential significance for constraining global marine O_2 fluxes. Furthermore, moving toward a fully coupled Earth System Model (ESM)—which integrates dynamic atmospheric feedback alongside ocean and wave components—will be essential to fully unravelling the long-term impacts of wave-induced processes on global marine biogeochemical cycles."

Reference:

Deike, L., Zhou, X., Rustogi, P., Stanley, R. H. R., Reichl, B. G., Bushinsky, S. M., and Resplandy, L.: A universal wind–wave–bubble formulation for air–sea gas exchange and its impact on oxygen fluxes, Proc. Natl. Acad. Sci. U.S.A., 122, e2419319122, https://doi.org/10.1073/pnas.2419319122, 2025.

Minor comments:

RC2.25 L38/332: Units for the terms are missing.

Response:

We thank the reviewer for pointing out the missing units, which are crucial for clarifying the dimensional consistency of the flux equation. We have added the corresponding units for all terms in the revised text around L38/332. Furthermore, we have explicitly specified the necessary dimensional conversion factor (8.76×10^{-5}) that reconciles the hourly/centimeter scales of gas transfer velocity and micro-atmospheres of partial pressure with the annual/meter scales of the final CO_2 flux.

The text has been updated as follows (L38):

"where the air–sea CO_2 flux (F_{CO_2}; mol m^{-2} yr^{-1}) is determined by the gas transfer velocity expressed relative to a Schmidt number of 660 ($k_{w,660}$; cm hr^{-1}), the difference in partial pressure of CO_2 ($dpCO_2$; μatm) between the seawater and atmosphere (indicated by superscripts " *w* " and " *a* ", respectively), and the solubility constant (k_0; mol m^{-3} atm^{-1}), which varies with salinity and temperature (Weiss, 1974). Note that an appropriate scaling factor (8.76×10^{-5}) is implicitly required to convert the dimensions of $k_{w,660}$ and $dpCO_2$ into the final flux unit (mol m^{-2} yr^{-1})."

The text has been updated as follows (L332):

"The slopes of the regression equations (–0.77 mol m^{-2} yr^{-1} per m s^{-1} for B–CTL and –1.40 mol m^{-2} yr^{-1} per m s^{-1} for POP2–waves)…"

RC2.26 L119-128, L169-173: Please check the grammar and tenses in these sections.

Response:

Thank you for your careful reading and helpful suggestion. We have thoroughly reviewed and revised the grammar, tenses, and sentence structures in both sections to ensure clarity and academic rigor.

RC2.27 L178: Remove 'In addition'.

Response:

Thank you for the suggestion. We have removed "In addition" from the revised manuscript to improve the flow of the text.

RC2.28 L395: Spell out OGCMs.

Response:

Thank you for the reminder. We have spelled out the acronym "OGCMs" as "ocean general circulation models" upon its first appearance in Section 4.1.

We hope these revisions successfully address all the concerns raised. Thank you again for your time and efforts in reviewing our manuscript.

Sincerely,
Yung-Yao Lan, Huang-Hsiung Hsu, Wei-Liang Lee and Simon Chou