Response to Ken Johnson:

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We thank the reviewer for their feedback and comments on our manuscript. Here are a few points we would like to respond to regarding the review.

1. We have not argued that float data is useless and negative; on the contrary, we are well aware of and respect the outstanding contribution of float data to understanding the dynamics of carbon in the Southern Ocean. The coverage of floats fills many observational gaps and increases the possibility of understanding biogeochemical processes at high spatial and temporal precision. Our aim in this manuscript is based on the belief that the float data are very precious and valuable. For this reason, our comprehensive examination of float data accuracy is very useful for a proper understanding of carbon fluxes in the Southern Ocean.

2. In our opinion, the point that "this bias is already well known" is debatable. A great deal of very recent work makes use of float pCO_2 data but simply does not consider or discuss possible biases in it (Chen et al., 2022, Claustre et al., 2020, Djeutchouang et al., 2022, Hauck et al., 2023, Keppler and Landschützer, 2019, Landschützer et al., 2023, Menviel et al., 2023, Mo et al., 2023, Nevison et al., 2020, Prend et al., 2022a, Prend et al., 2022b, Swart et al., 2023, Yang et al., 2024, Huang et al., 2023)

   Even in studies that have considered the possible existence of float bias, there is no agreement on the magnitude of float bias and the distribution of floats with bias. Gray et al. (2018) considered the bias to be 3.6 µatm according to the crossover comparison between float data and SOCAT data. However, we verified that due to spatial and temporal limitations of the cross-comparisons, the float data used for the comparisons were only from the first three days of deployment, and that large amounts of data from later periods were not included in the cross-comparisons. Wu and Qi (2022) took the Drake passage as a case study and found the float-based pCO_2 values are overall higher than ship-based values in winter, by 6 to 20 µatm (averaged 14 µatm), which can't be fully explained by the upwelling. This study is limited to the Drake Passage region, rather than a basin-scale comparison across the Southern Ocean.

Bushinsky and Cerovečki (2023) compared the mean ΔpCO_2 of SAMW at the time of formation between float, SOCAT and GLODAP data. They found the float based ΔpCO_2 to be 17–20 μatm higher, of which 6 μatm can be explained by the “possible bias” and the remainder attributed to sampling bias. The data compared in this study include only the time and area of SAMW formation (ACC northern) and do not directly compare data for pCO_2 across the Southern Ocean, particularly in the high-latitude ASZ region. It is unconvincing to claim that it is a more comprehensive comparison in terms of float pCO_2 data examination.

In summary, there is a large body of research that ignores the bias in float pCO_2. The magnitude of float pCO_2 bias is still unclear. Whether the pCO_2 bias is prevalent in floats throughout the Southern Ocean or only in parts of it has not been determined. The cause and solution of the float pCO_2 bias have not yet been determined. We further identify pCO_2 discrepancies in the subsurface water measurements, which has not been a consensus from previous works. Therefore, this manuscript of basin-scale comparisons certainly can provide new insight into these questions.

3. The key issue for air-sea CO_2 fluxes is whether averaged float estimates of pCO_2 are accurate rather than whether individual observations are precise (Bushinsky and Cerovečki, 2023). Uncertainty in the individual float data has little effect on the mean value of the bulk data. Williams et al. (2017) estimated the uncertainty of an individual float pCO_2 value to be around ±11 μatm when float pCO_2 is 400 μatm; Gregor et al. (2019) estimated the uncertainty of GLODAP pCO_2 to be 12 μatm at 400 μatm. In the figure below we show the probability density function of average float pCO_2 and ship pCO_2 from 1000 Monte Carlo iterations as well as the difference. This figure was generated by the following procedure: (1) assuming float average pCO_2 to be 400 μatm and ship average pCO_2 to be 390 μatm, (2) generating 30,000 independent float pCO_2 values, each equal to $400 + G(0,11)$ and 3,000 independent ship pCO_2 values (according to the amount of ship and float data used in the study), each equal to $390 + G(0,12)$, where $G(\mu, \sigma)$ is a random number from a normal (Gaussian) distribution with mean of μ and standard deviation of σ, (3) calculate the average float pCO_2, ship pCO_2 and then the difference between ship and float average values, (4) repeat 1000 times to obtain 1000 differences, (5) plot the frequency distribution of the

differences. The effect of uncertainty in each single point of float or ship pCO_2 data on the difference in the final float mean is minor (Figure.1).

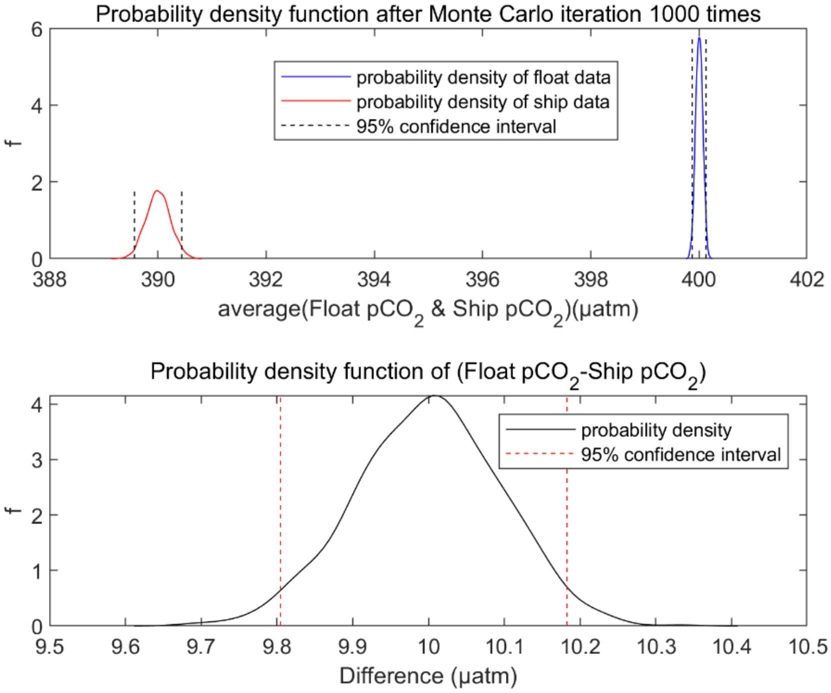

Figure (1): Assessment of the impact of uncertainty in individual float pCO_2 and ship pCO_2data on respective averages and the uncertainty in the overall value of (float pCO_2 – ship pCO_2), based on Monte Carlo calculations.

This result is based on the assumption that errors are random and independent. It does not hold for systematic biases, but that of course is what we are investigating in our study.

Reference:

BUSHINSKY, S. M. & CEROVEČKI, I. 2023. Subantarctic Mode Water biogeochemical formation properties and interannual variability. *Agu Advances,* 4, e2022AV000722.

CHEN, H., HAUMANN, F. A., TALLEY, L. D., JOHNSON, K. S. & SARMIENTO, J. L. 2022. The deep ocean's carbon exhaust. *Global Biogeochemical Cycles,* 36, e2021GB007156.

CLAUSTRE, H., JOHNSON, K. S. & TAKESHITA, Y. 2020. Observing the global ocean with biogeochemical-Argo. *Annual review of marine science,* 12, 23-48.

DJEUTCHOUANG, L. M., CHANG, N., GREGOR, L., VICHI, M. & MONTEIRO, P. 2022. The sensitivity of pCO 2 reconstructions to sampling scales across a Southern Ocean sub-domain: a semi-idealized ocean sampling simulation approach. *Biogeosciences,* 19, 4171-4195.

GRAY, A. R., JOHNSON, K. S., BUSHINSKY, S. M., RISER, S. C., RUSSELL, J. L., TALLEY, L. D., WANNINKHOF, R., WILLIAMS, N. L. & SARMIENTO, J. L. 2018. Autonomous biogeochemical floats detect significant carbon dioxide outgassing in the high-latitude Southern Ocean. *Geophysical Research Letters,* 45, 9049-9057.

GREGOR, L., LEBEHOT, A. D., KOK, S. & SCHEEL MONTEIRO, P. M. 2019. A comparative assessment of the uncertainties of global surface ocean CO< sub> 2</sub> estimates using a machine-learning ensemble (CSIR-ML6 version 2019a)–have we hit the wall? *Geoscientific Model Development,* 12, 5113-5136.

HAUCK, J., NISSEN, C., LANDSCHüTZER, P., RöDENBECK, C., BUSHINSKY, S. & OLSEN, A. 2023. Sparse observations induce large biases in estimates of the global ocean CO_2 sink: an ocean model subsampling experiment. *Philosophical Transactions of the Royal Society A,* 381, 20220063.

HUANG, Y., FASSBENDER, A. J. & BUSHINSKY, S. M. 2023. Biogenic carbon pool production maintains the Southern Ocean carbon sink. *Proceedings of the National Academy of Sciences,* 120, e2217909120.

KEPPLER, L. & LANDSCHüTZER, P. 2019. Regional wind variability modulates the Southern Ocean carbon sink. *Scientific reports,* 9, 7384.

LANDSCHüTZER, P., TANHUA, T., BEHNCKE, J. & KEPPLER, L. 2023. Sailing through the southern seas of air–sea CO_2 flux uncertainty. *Philosophical Transactions of the Royal Society A,* 381, 20220064.

MENVIEL, L. C., SPENCE, P., KISS, A. E., CHAMBERLAIN, M. A., HAYASHIDA, H., ENGLAND, M. H. & WAUGH, D. 2023. Enhanced Southern Ocean CO 2 outgassing as a result of stronger and poleward shifted southern hemispheric westerlies. *Biogeosciences,* 20, 4413-4431.

MO, A., PARK, K., PARK, J., HAHM, D., KIM, K., KO, Y. H., IRIARTE, J. L., CHOI, J.-O. & KIM, T.-W. 2023. Assessment of austral autumn air–sea CO_2 exchange in the Pacific sector of the Southern Ocean and dominant controlling factors. *Frontiers in Marine Science,* 10, 1192959.

NEVISON, C. D., MUNRO, D. R., LOVENDUSKI, N. S., KEELING, R. F., MANIZZA, M., MORGAN, E. J. & RöDENBECK, C. 2020. Southern Annular Mode influence on wintertime ventilation of the Southern Ocean detected in atmospheric O_2 and CO_2 measurements. *Geophysical Research Letters,* 47, e2019GL085667.

PREND, C. J., GRAY, A. R., TALLEY, L. D., GILLE, S. T., HAUMANN, F. A., JOHNSON, K. S., RISER, S. C., ROSSO, I., SAUVé, J. & SARMIENTO, J. L. 2022a. Indo-Pacific sector dominates Southern Ocean carbon outgassing. *Global Biogeochemical Cycles,* 36, e2021GB007226.

PREND, C. J., HUNT, J. M., MAZLOFF, M. R., GILLE, S. T. & TALLEY, L. D. 2022b. Controls on the boundary between thermally and non-thermally driven pCO_2 regimes in the South Pacific. *Geophysical Research Letters,* 49, e2021GL095797.

SWART, S., DU PLESSIS, M. D., NICHOLSON, S.-A., MONTEIRO, P. M., DOVE, L. A., THOMALLA, S., THOMPSON, A. F., BIDDLE, L. C., EDHOLM, J. M. & GIDDY, I. 2023. The Southern Ocean mixed layer and its boundary fluxes: fine-scale observational progress and future research priorities. *Philosophical Transactions of the Royal Society A,* 381, 20220058.

WILLIAMS, N., JURANEK, L., FEELY, R., JOHNSON, K., SARMIENTO, J. L., TALLEY, L., DICKSON, A., GRAY, A., WANNINKHOF, R. & RUSSELL, J. 2017. Calculating surface ocean pCO2 from biogeochemical Argo floats equipped with pH: An uncertainty analysis. *Global Biogeochemical Cycles,* 31**,** 591-604.

WU, Y. & QI, D. 2022. Inconsistency between ship-and Argo float-based p CO 2 at the intense upwelling region of the Drake Passage, Southern Ocean. *Frontiers in Marine Science,* 9.

YANG, X., WYNN‐EDWARDS, C. A., STRUTTON, P. G. & SHADWICK, E. H. 2024. Drivers of Air‐Sea CO2 Flux in the Subantarctic Zone Revealed by Time Series Observations. *Global Biogeochemical Cycles,* 38**,** e2023GB007766.