SOCOMv2: The impact of near-surface vertical temperature gradients on the ocean carbon sink within the fCO_2 product ensemble

Daniel J. Ford[1], Amanda Fay[2], Thea Hatlen Heimdal[2], Galen A. Mckinley[2], Victor Cabanay[3], Marion Gehlen[3], Frederic Chevallier[3], Alizée Roobaert[4], Christian Rödenbeck[5], Jacqueline Behncke[6], Annika Jersild[7], Nicolas Gruber[8], Luke Gregor[8], Judith Hauck[9, 10], Sreeush Mohanan[9], Laique M. Djeutchouang[11], Jiye Zeng[12], Yosuke Iida[13], Andrew Watson[1], Peter Landschützer[4] and Jamie D. Shutler[1]

[1] University of Exeter, UK, [2] Columbia University and Lamont-Doherty Earth Observatory, New York, 10964 USA, [3] Laboratoire des Sciences du Climat et de l'Environnement, LSCE-IPSL, CEA-CNRS-UVSQ, Université Paris-Saclay, Gif-sur-Yvette, France, [4] Flanders Marine Institute (VLIZ), Oostende, Belgium, [5] Max Planck Institute for Biogeochemistry, Germany, [6] Max Planck Institute for Meteorology, Germany, [7] ESSIC, University of Maryland College Park, Maryland, USA, [8] Environmental Physics, Institute of Biogeochemistry and Pollutant Dynamics, ETH Zürich, Zürich, Switzerland, [9] Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research, Bremerhaven, Germany, [10] University of Bremen, Bremen, Germany, [11] School for Climate Studies, Stellenbosch University, Stellenbosch, South Africa, [12] National Institute for Environmental Studies, Tsukuba, Japan, [13] Atmosphere and Ocean Department, Japan Meteorological Agency, Tokyo, Japan

1) Introduction

Surface ocean observations of the fugacity of CO_2 ($sfCO_2$) and the global fCO_2 products that are interpolated from them are one of the most pivotal constraints for the oceanic sink of CO_2 and a key component of the annually published Global Carbon Budget (GCB; Friedlingstein et al. 2025).

Evidence has however been growing that the ocean CO_2 sink is likely underestimated due to omission of near-surface vertical temperature gradients. These gradients comprise three components:

(1) The cool skin, where the surface ~2 mm of the ocean is cooler than waters below.
(2) The warm layers, where low winds and high insolation causes the surface ~6 m to warm
(3) A warm bias present in the in situ fCO_2 data (Ford et al. 2025).

Until now, the effects of these temperature gradients have been investigated based on only one $sfCO_2$ mapping method (SOM-FFN; Watson et al. 2020; Dong et al. 2022). The Surface Ocean CO_2 Mapping intercomparison (SOCOM) community project entered a second phase and has incorporated an experiment that investigates the effects of these vertical temperature gradient adjustments on a more diverse set of $sfCO_2$ mapping methods.

2) Methods

The experiment involved 8 $sfCO_2$ mapping methods (7 which submit to the GCB), who were each provided with two sets of monthly 1 degree gridded in situ Surface Ocean CO_2 Atlas (SOCATv2024; Bakker et al. 2016) fCO_2 observations.

Each set of observations was interpolated using a consistent sea surface temperature (SST) and salinity (SSS) dataset. Any other inputs required by each group to interpolate the $sfCO_2$ were retrieved from their respective sources.

The first set of observations comprised the original SOCAT observations, which represents a typical GCB submission (with no corrections for temperature gradients).

The second set of observations comprised SOCAT observations that have been recalculated to the CCI-SSTv3 satellite SST observations to correct for the impact of warm layers (2) and a warm bias (3).

All $sfCO_2$ mapping methods provided complete fCO_2 fields generated from each set of in situ observations (i.e two globally complete fields).

Air-sea CO_2 fluxes were then calculated in a traceable and consistent framework (FluxEngine; Shutler et al. 2016; Holding et al. 2019). The global ocean CO_2 sink was estimated for the two sets of interpolations. For the second set of interpolations, a second air-sea CO_2 flux calculation was completed that included the effect of the cool salty skin (1). Uncertainties on the ocean CO_2 sink were calculated following Ford et al. (2024).

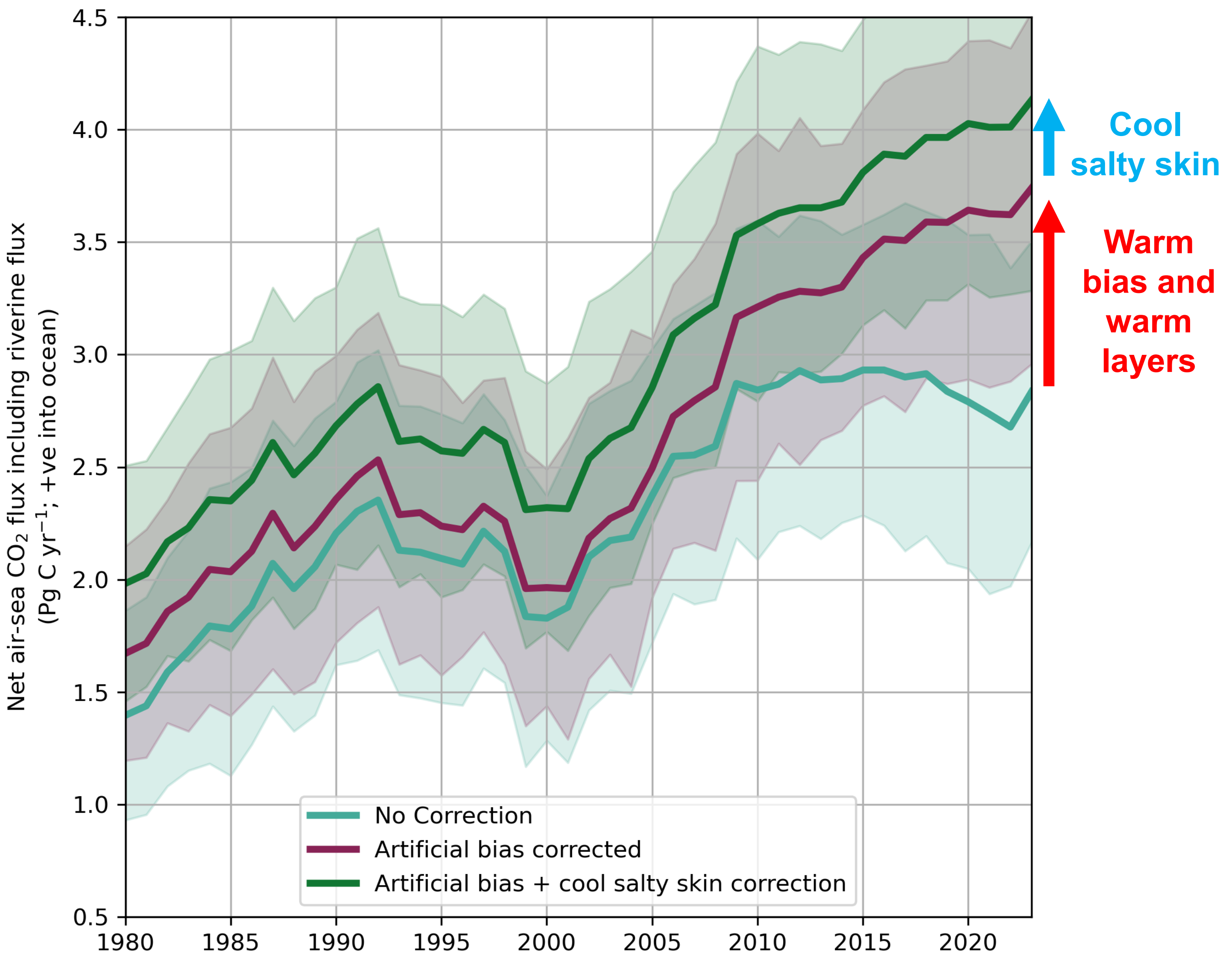

Figure 1: An example output for one $sfCO_2$ mapping method. The teal line uses the original SOCAT observations. The purple line shows the impact of using the recalculated SOCAT observations correcting for the warm bias and warm layers. The green line uses the recalculated SOCAT observations and applies the cool salty skin within the air-sea CO_2 flux calculation. Gas transfer was calculated using ERA5 winds with Wanninkhof et al. (2014) scaled to the ^{14}C constraint (Naeglar 2009).

3) Results

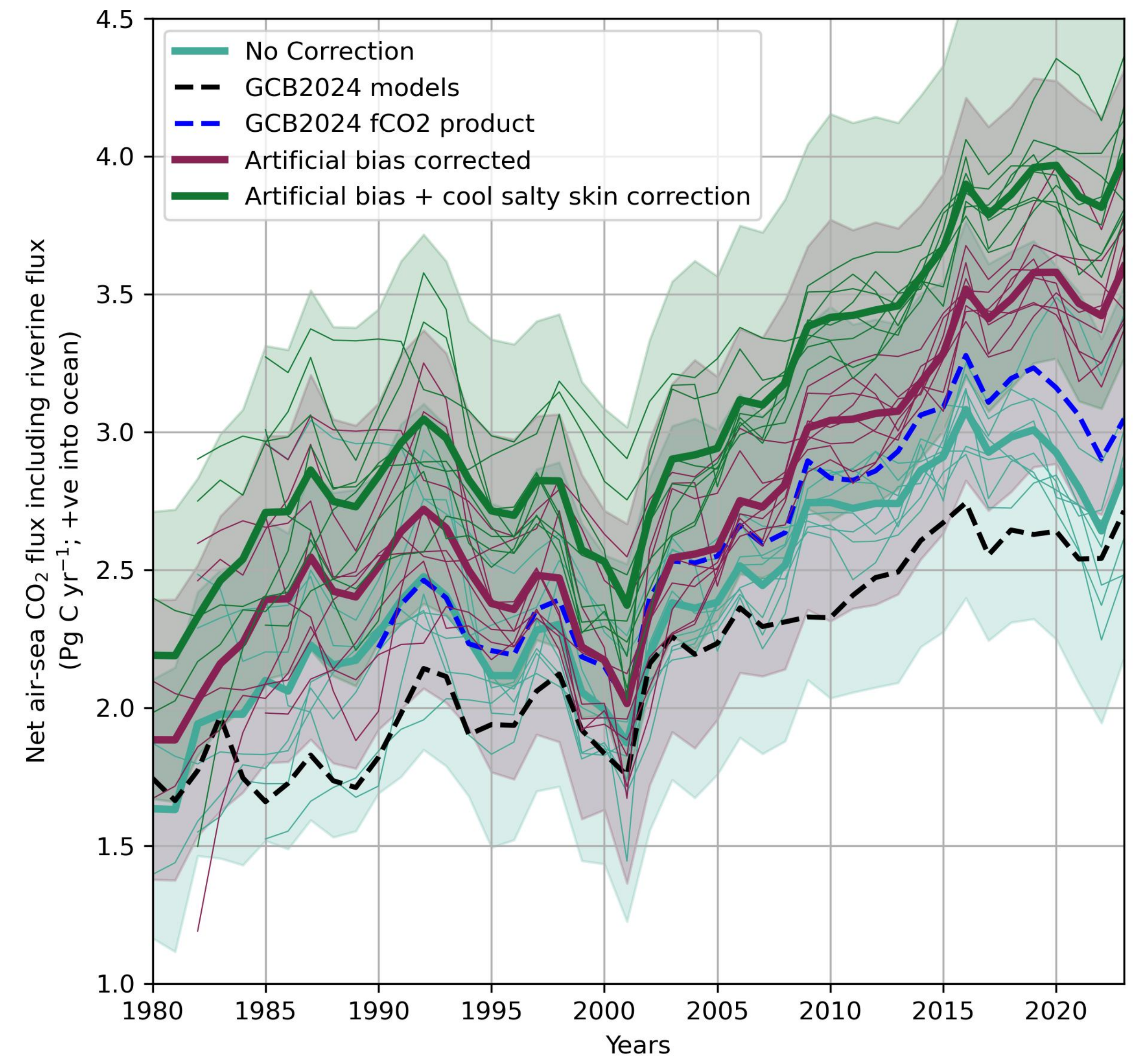

Figure 2: Ensemble mean ocean CO_2 uptake for the three ensembles, compared to the GCB2024 reported CO_2 uptake. Thicker solid lines are the ensemble mean, and thin lines are individual fCO_2-products.

The uncorrected ensemble mean was slightly lower than the GCB2024 ensemble mean due to 2 data products not being present in this experiment (compare teal to dark blue dashed; Figure 2).

The impact of **using the recalculated SOCAT observations** showed an **increase of 0.42 Pg C yr^{-1} in the ocean CO_2 sink** between 2010-2020 (compare teal and purple; Figure 2).

$sfCO_2$ mapping methods tended to show different sensitivities to the recalculated SOCAT data. Some show a strong increase in the correction after ~2005 (Figure 1), whereas others show a more static response through time (Figure 3)

The **impact of the cool salty skin** indicated a further **increase in the ocean CO_2 sink of 0.38 Pg C yr^{-1}** between 2010-2020 (compare purple with green; Figure 2).

The **total impact** of the vertical temperature gradients indicates a **~0.8 Pg C yr^{-1} increase** in the ocean CO_2 sink (or **a ~30 % increase**) reported by the $sfCO_2$ mapping methods.

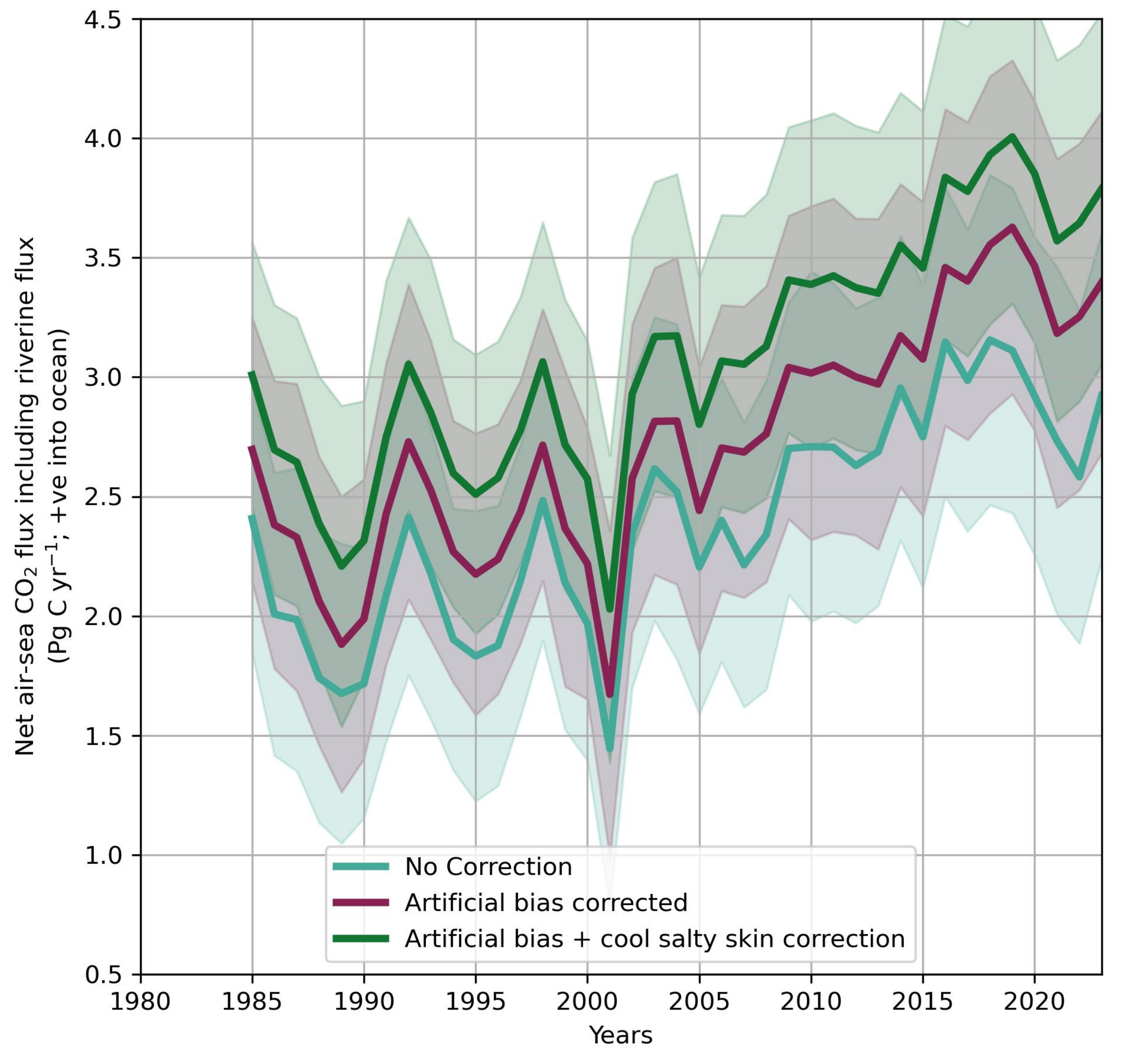

Figure 3: Example of an $sfCO_2$ mapping method with a different sensitivity to the recalculated SOCAT observations, indicating a more static adjustment between teal and purple, compared to Figure 1.

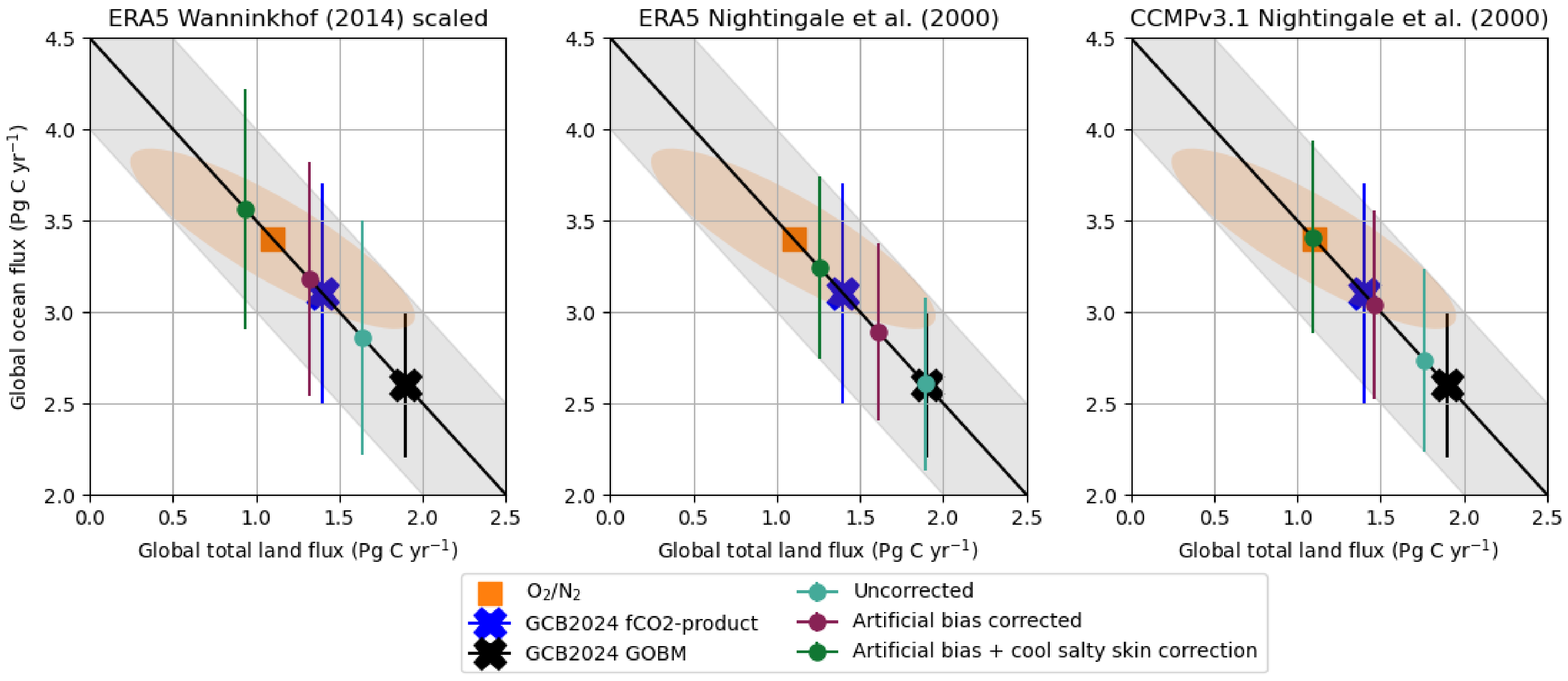

Figure 4: Decadal mean ocean CO_2 sink estimates (2014-2023) compared to the GCB2024 reported O_2/N_2 constraint for three different gas transfer implementations. Black line indicates the fossil fuel emissions minus the atmospheric CO_2 growth rate.

Decadal means of the ocean CO_2 sink can be compared to the **independent O_2/N_2 constraint** (Figure 4).

If no corrections are applied, within this experiment than the resulting **ocean CO_2 sink does not satisfy the O_2/N_2 constraint** (teal dots).

Applying **all temperature gradients corrections, aligns the decadal mean to the O_2/N_2 constraint** (green dots).

4) Conclusions

The impact of vertical temperature gradients on the individual fCO_2 mapping methods shows **increased ocean CO_2 uptake**

This equates to a **~0.8 Pg C yr^{-1} increase** in the uptake between 2010-2020. **0.42 Pg C yr^{-1}** due to **warm layers and a warm bias. 0.38 Pg C yr^{-1}** due to **the cool salty skin.**

Comparing to **the independent O_2/N_2 ocean sink constraint** the fCO_2-product ensemble that **considers all vertical temperature gradients are consistent**

Acknowledgements

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References: Friedlingstein et al. (2025; https://doi.org/10.5194/essd-17-965-2025); Ford et al. (2025; https://doi.org/10.21203/rs.3.rs-8260066/v1); Watson et al. (2020; https://doi.org/10.1038/s41467-020-18203-3); Dong et al. (2022; https://doi.org/10.1029/2022GB007360); Bakker et al. (2016; https://doi.org/10.5194/essd-8-383-2016); Shutler et al. (2016; https://doi.org/10.1175/JTECH-D-14-00204.1); Holding et al. (2019; https://doi.org/10.5194/os-15-1707-2019); Ford et al. (2024; https://doi.org/10.1029/2024GB008188); Wanninkhof (2014; https://doi.org/10.4319/lom.2014.12.351); Naeglar (2009; https://doi.org/10.1111/j.1600-0889.2008.00408.x); Nightingale et al. (2000; https://doi.org/10.1029/1999GB900091)