Regional Modification Of Air-Sea CO_2 Fluxes Due To The Inclusion Of Quantified Ocean Biological Processes Within Satellite-based Assessments

Daniel J. Ford[1], Gemma Kulk[2], Shubha Sathyendranath[2], Mayra Rodriguez[2], David Moffat[2], Heather Bouman[3], Galen McKinley[4], Amanda Fay[4], Thea Heimdel[4], Marion Gehlen[5], Frederic Chevallier[5] and Jamie D. Shutler[1]

[1] University of Exeter, UK. [2] Plymouth Marine Laboratory, UK. [3] University of Oxford, UK. [4] Columbia University and Lamont-Doherty Earth Observatory, USA.
[5] Laboratoire des Sciences du Climat et de l'Environnement, France.

1) Introduction

The UN and International Oceanographic Commission (IOC) decadal roadmap for Integrated Ocean Carbon Research (IOC-R) highlighted that the role of ocean biology was a key issue to understanding the global ocean CO_2 sink (Arico et al. 2021).

The global ocean sink can be estimated through observation-based approaches that interpolate in situ fugacity of CO_2 in seawater ($fCO_{2\ (sw)}$) using a synergy of satellite and reanalysis observations with sophisticated interpolation techniques.

These approaches generally use chlorophyll-a as a proxy for the biological influence on $fCO_{2\ (sw)}$. Recent work shows the inclusion of quantified biological processes such as net primary production or net community production, modified the regional air-sea CO_2 fluxes within the South Atlantic Ocean (Ford et al. 2022). The impact has not been investigated on the global scale.

In this work, a sensitivity analysis was conducted using global $fCO_{2\ (sw)}$ interpolation approaches, where the effect of including the increasingly complex biological contributions was evaluated at the global and regional scale.

2) Methods

The **University of Exeter Feed Forward Neural Network with uncertainties** (UExP-FNN-U; Ford et al. 2024) as submitted to the Global Carbon Budget (Friedlingstein et al. 2025) was used to interpolate $fCO_{2\ (sw)}$. The **standard setup of the UExP-FNN-U uses physical parameters** including sea surface temperature (SST), sea surface salinity (SSS), mixed layer depth (MLD), dry mixing ratio of CO_2 in atmosphere ($xCO_{2\ (atm)}$) and anomalies of the 4 variables to estimate $fCO_{2\ (sw)}$. **This setup acts as our 'baseline run'.**

We then **ran sensitivity analyses**, where we include **a spatially and temporally complete chlorophyll-a (Ford et al. in prep) or net primary production product** (Kulk et al. 2020) within the UExP-FNN-U. These complete datasets are based on the climate quality Ocean Colour Climate Change Initiative (OC-CCI) dataset.

The **differences in the $fCO_{2\ (sw)}$ produced by the three variants of the UExP-FNN-U were compared**, and the resulting **accuracy and precision** with respect to an independent subset of the Surface Ocean CO_2 Atlas (SOCAT) in situ $fCO_{2\ (sw)}$ **assessed.**

Global air-sea CO_2 fluxes were calculated with a comprehensive uncertainty budget (Ford et al. 2024) and differences in global ocean CO_2 sink compared, as well as any changes in the uncertainties.

3) Results

Variants with chlorophyll-a or net primary production showed improvements in the precision ~1.4 µatm (5 to 7%) (reduction in root mean square difference; RMSD) when compared to in situ observations.

Including chlorophyll-a showed an improved accuracy (reduced bias; **Table 1**)

Table 1: Accuracy and precision estimates of the UExP-FNN-U variants with respect to an independent subset of the SOCAT observations (N = 17,351; ~5%).

UExP-FNN-U variant	Bias (Accuracy; µatm)	Root mean square difference (RMSD; µatm)
Physics only	0.3	20.0
Chlorophyll-a	-0.1	18.6
Net primary production	-0.6	18.8

Regional differences in the $fCO_{2\ (sw)}$ were observed between the physics only and biological variants. **Negative differences** generally observed **in the Southern Ocean** (south of 40 ºS) but a notable **positive difference** in the **subtropical convergence** (green box; Figure 1). **Eastern boundary upwelling regions showed negative differences** (red box; Figure 1).

Differences were **generally smaller in magnitude** for the **net primary production** compared to chlorophyll-a variant (compare Figure 1b to 1a).

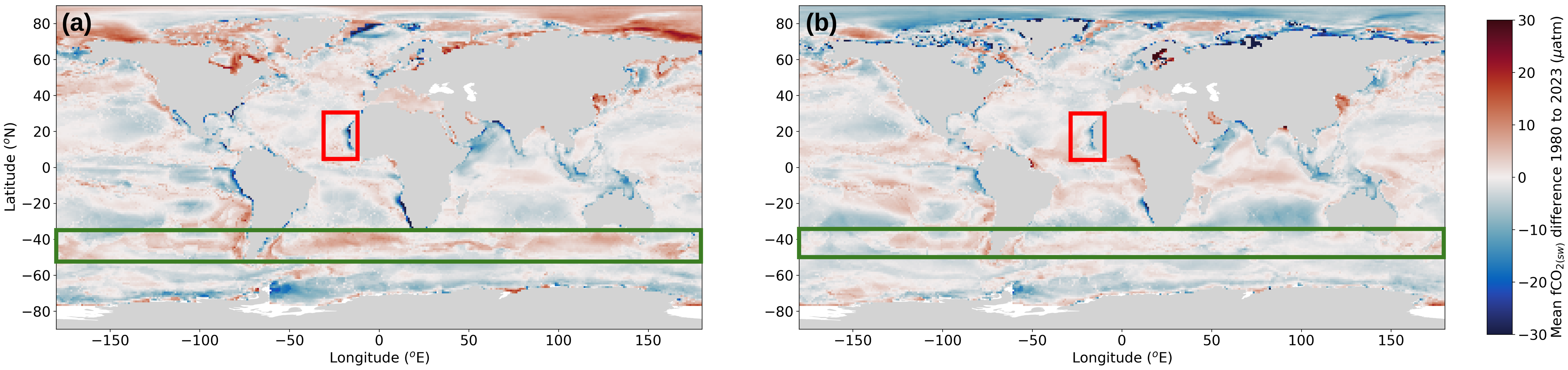

Figure 1: (a) The $fCO_{2\ (sw)}$ difference between the physics only and the chlorophyll-a variant of the UExP-FNN-U as a climatological mean from 1980 to 2023. (b) same as (a) for the net primary production variant. Difference calculated as physics only minus biological variant.

The **ocean CO_2 sink estimated from the three variants showed differences** after ~2005 (Figure 2)

The **physics only variant showed a larger CO_2 sink compared to the biological variants**. Investigation into the region/s that this occurs from is in progress.

The **uncertainty on the ocean CO_2 sink was ~7 % lower** for the **biological variants** compared to the physics only.

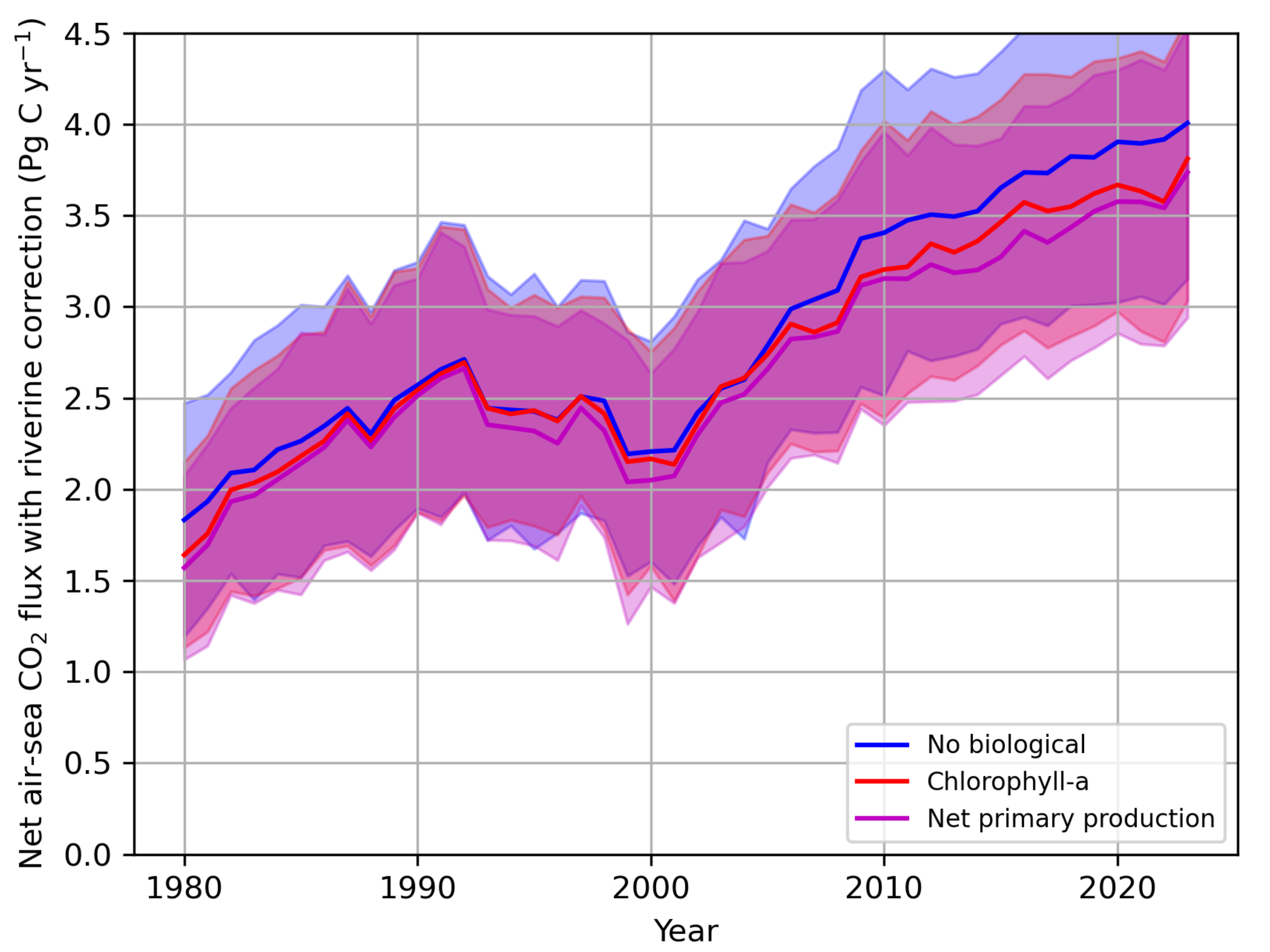

Figure 2: The global ocean CO_2 sink for the variants of the UExP-FNN-U. Coloured banding indicates the 1 sigma uncertainty. +ve indicates atmosphere to ocean exchange (a CO_2 sink)

4) Conclusions and future analysis

The **sensitivity of a global $fCO_{2\ (sw)}$ interpolation approach** (UExP-FNN-U) to the inclusion of **more quantified biological contributions** was evaluated.

An **improvements in the precision and accuracy** of the UExP-FNN-U with respect to independent in situ $fCO_{2\ (sw)}$ observations of **between 5 to 7 %. Regional differences in the resulting $fCO_{2\ (sw)}$ fields observed.**

Reduction in the global ocean CO_2 sink, and a **reduction in uncertainties of ~7 %** indicated by including these quantified biological contributions.

Further analysis of regional air-sea CO_2 fluxes and **the expansion to two more global $fCO_{2\ (sw)}$ interpolation approaches** is in progress (LDEO-pCO2residual and CMEMS-FFNN).

Acknowledgements

This work was supported by funding from the European Space Agency under the projects 'Satellite-based observations of Carbon in the Ocean: Pools, Fluxes and Exchanges' (SCOPE) and 'Ocean Carbon for Climate' (OC4C).

References: Arico et al. (2021; http://dx.doi.org/10.25607/h0gj-pq41); Ford et al. (2022; https://doi.org/10.5194/bg-19-93-2022); Ford et al. (2024; https://doi.org/10.1029/2024GB008188); Friedlingstein et al. (2025; https://doi.org/10.5194/essd-17-965-2025); Kulk et al. (2020; http://dx.doi.org/10.3390/rs12050826); Ford et al. (in prep) - Decadal global and polar wintertime chlorophyll-a data record from satellite and Argo observations;