



Observation System Simulation Experiments for surface ocean $p\text{CO}_2$ reconstructions in the Atlantic Ocean

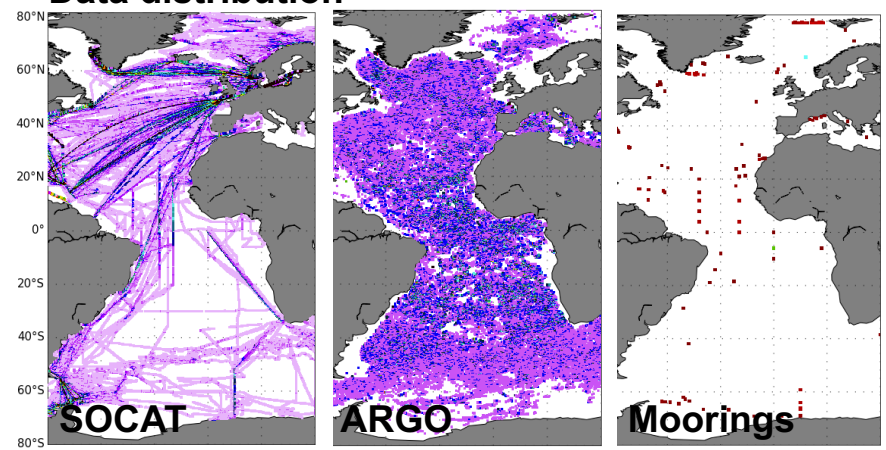
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Aims:

- Identification of an optimal observational network for surface ocean $p\text{CO}_2$ in the Atlantic Ocean and the Atlantic sector of the Southern Ocean.
- Improvement of the accuracy of ocean surface $p\text{CO}_2$ reconstructions and consequently sea-air CO_2 flux.

Data distribution



SOCAT - synthesis files SOCATv5 with the daily measurements for 2001-2010.

Argo - synthetic homogeneous distribution of 1 profiler per $3^\circ \times 3^\circ$ grid box for 2008-2010 provided by Mercator Ocean.

Mooredings - OceanSITES for whole period.

Observation System Simulation Experiments (OSSE):

Pseudo-observations were obtained by sub-sampling model output at sites of real-world observations.

We used the numerical output from an online-coupled physical-biogeochemical global ocean model, the **NEMO/PISCES** model, at 5-day resolution, nominal $1/4^\circ$ resolution.

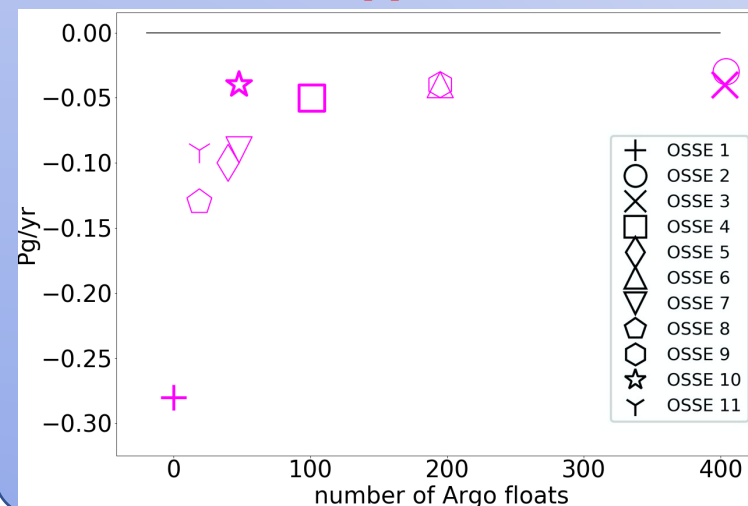
Results of reconstruction for 2008-2010 based on NEMO/PISCES outputs [1]:

OSSE1 – only SOCAT for period 2001–2010 – what we want to improve

OSSE 3 – SOCAT 2001-2010 and Argo complete synthetic homogeneous distribution 2008–2010 – unrealistic case, we use it as benchmark

OSSE 10 – SOCAT 2001–2010, Moorings, 25% of Argo initial synthetic homogeneous distribution only in the South Hemisphere – OSSE that shows results close to the OSSE 3 and is closer to the possible realistic data distribution

Number of Argo profiles vs. averaged differences between OSSE and NEMO sea-air CO_2 flux [1]



OSSE1: 0 Argo profiles, error = -0.28 Pg/yr

OSSE 3: 403 Argo profiles, error = -0.04 Pg/yr

OSSE 10: 48 Argo profiles, error = -0.04 Pg/yr

Main Results:

- Importance of additional data from mooring stations.
- Needs of an improved coverage of the southern Hemisphere with biogeochemical ARGO floats corresponding to at least 25% of the density of active floats.
- Reduce the bias of derived estimates of sea-air CO_2 fluxes by 74%.

[1] Denvil-Sommer, A., Gehlen, M., and Vrac, M.: Observation System Simulation Experiments in the Atlantic Ocean for enhanced surface ocean $p\text{CO}_2$ reconstructions, Ocean Sci. Discuss. [preprint], <https://doi.org/10.5194/os-2021-17>, in review, 2021.

Motivation

- The Surface Ocean CO₂ Atlas (SOCAT) (Bakker et al., 2016) represents global observations of the sea surface fugacity of CO₂ ($f\text{CO}_2$) starting in 1970. However, the data density is not homogenous, Southern latitudes being less well sampled in space and time. Sparse data coverage and the lack of observations covering the full seasonal cycle challenge mapping methods and result in noisy reconstructions of surface ocean $p\text{CO}_2$ and disagreements between different models [1].
- Starting from measurements extracted from the SOCAT database, the goal was to identify how and where the new data from biogeochemical ARGO floats can improve surface ocean $p\text{CO}_2$ reconstructions and how to optimally integrate them with other existing platforms [1].

Observation System Simulation Experiments

Data	OSSE number	Period for training	averaged number of Argo floats per 5 days
SOCAT	OSSE 1	2001-2010	0
Argo (3°x3°)	OSSE 2	2008-2010	404
SOCAT + Argo (3°x3°)	OSSE 3	2001-2010 (SOCAT) + 2008-2010 (Argo)	403
SOCAT + Argo 25% (3°x3°)	OSSE 4	2001-2010 (SOCAT) + 2008-2010 (Argo)	101
SOCAT + Argo 10% (3°x3°)	OSSE 5	2001-2010 (SOCAT) + 2008-2010 (Argo)	40
SOCAT + Argo South (3°x3°)	OSSE 6	2001-2010 (SOCAT) + 2008-2010 (Argo South)	195
SOCAT + Argo 25% South (3°x3°)	OSSE 7	2001-2010 (SOCAT) + 2008-2010 (Argo South)	48
SOCAT + Argo 10% South (3°x3°)	OSSE 8	2001-2010 (SOCAT) + 2008-2010 (Argo South)	19
SOCAT + Argo S + Moorings	OSSE 9	2001-2010 (SOCAT) + 2008-2010 (Argo South, Moorings)	195
SOCAT + Argo S 25% + Moorings	OSSE 10	2001-2010 (SOCAT) + 2008-2010 (Argo South, Moorings)	48
SOCAT + Argo S 10% + Moorings	OSSE 11	2001-2010 (SOCAT) + 2008-2010 (Argo South, Moorings)	19

Method

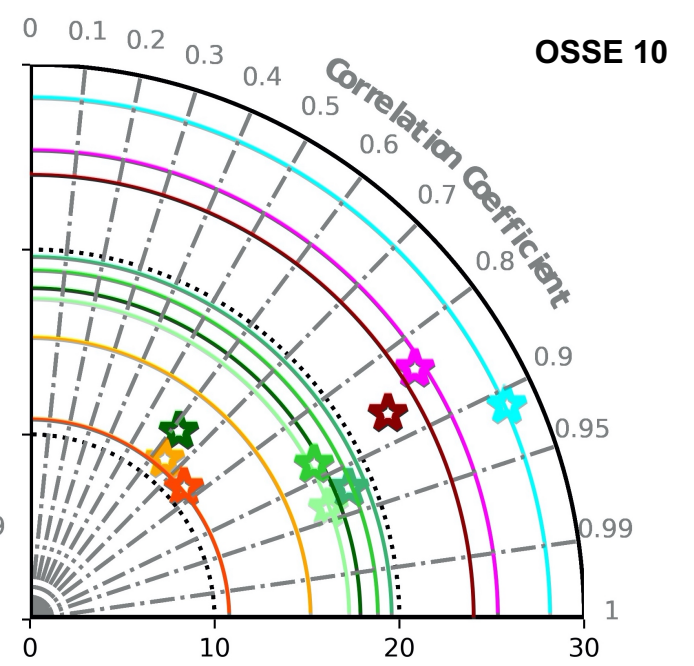
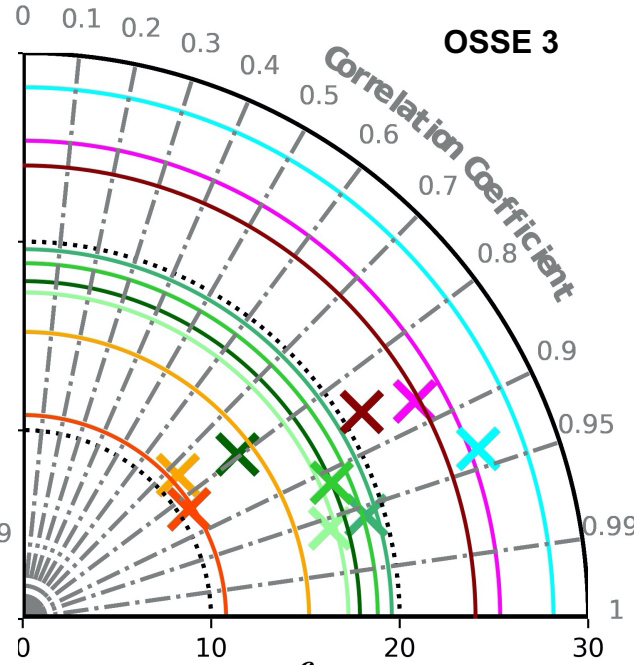
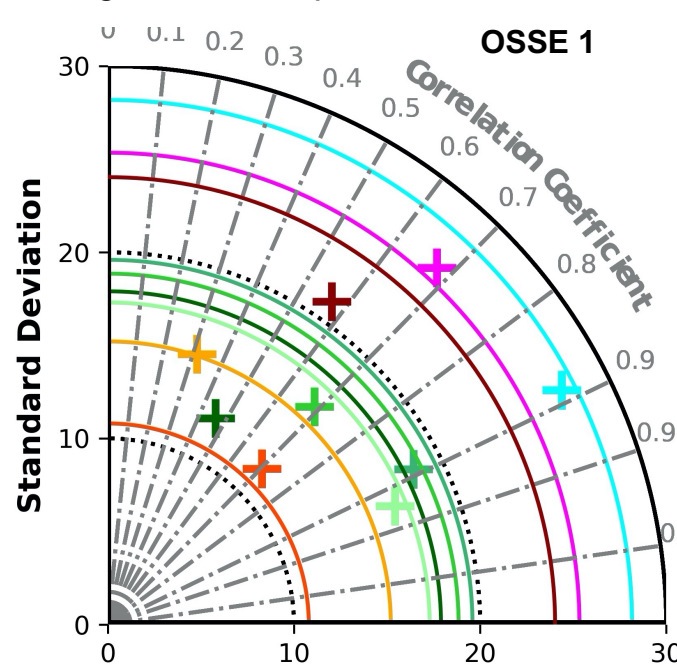
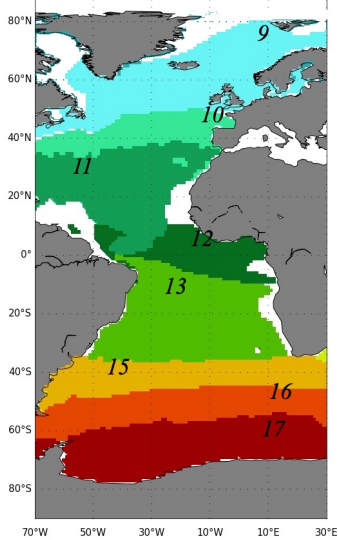
- Feed-Forward Neural Network to reconstruct $p\text{CO}_2$

$$p\text{CO}_{2,n} = f(SSS_n, SST_n, SSH_n, Chl_n, MLD_n, p\text{CO}_{2,atm,n}, SSS_{anom,n}, SST_{anom,n}, SSH_{anom,n}, Chl_{anom,n}, MLD_{anom,n}, p\text{CO}_{2,atm,anom,n}, lat_n, long_{1,n}, long_{2,n}) \quad (1)$$

- Target $p\text{CO}_2$ and predictors were normalized before their application that correspond to the subscript “n”. “anom” is for anomalies of corresponding variable.
- The FFNN is applied separately to each month.
- A K-fold cross-validation with K=4 was used to evaluate and validate the FFNN architecture. 25 % of independent data are chosen for validation. In each of the 4 cases the 25% of data are different and there is no overlap. Thereby, each run has 4 outputs.
- We present further the averaged values of 4 outputs for each OSSE. The shadows in figures of $p\text{CO}_2$ and $fg\text{CO}_2$ time series correspond to the maximum and minimum values of these 4 outputs.
- The observing systems used in this study either already perform measurements to estimate $p\text{CO}_2$ or have the possibility to be equipped with new sensors to provide biogeochemical measurements. We use their information on geographical.

Taylor diagrams

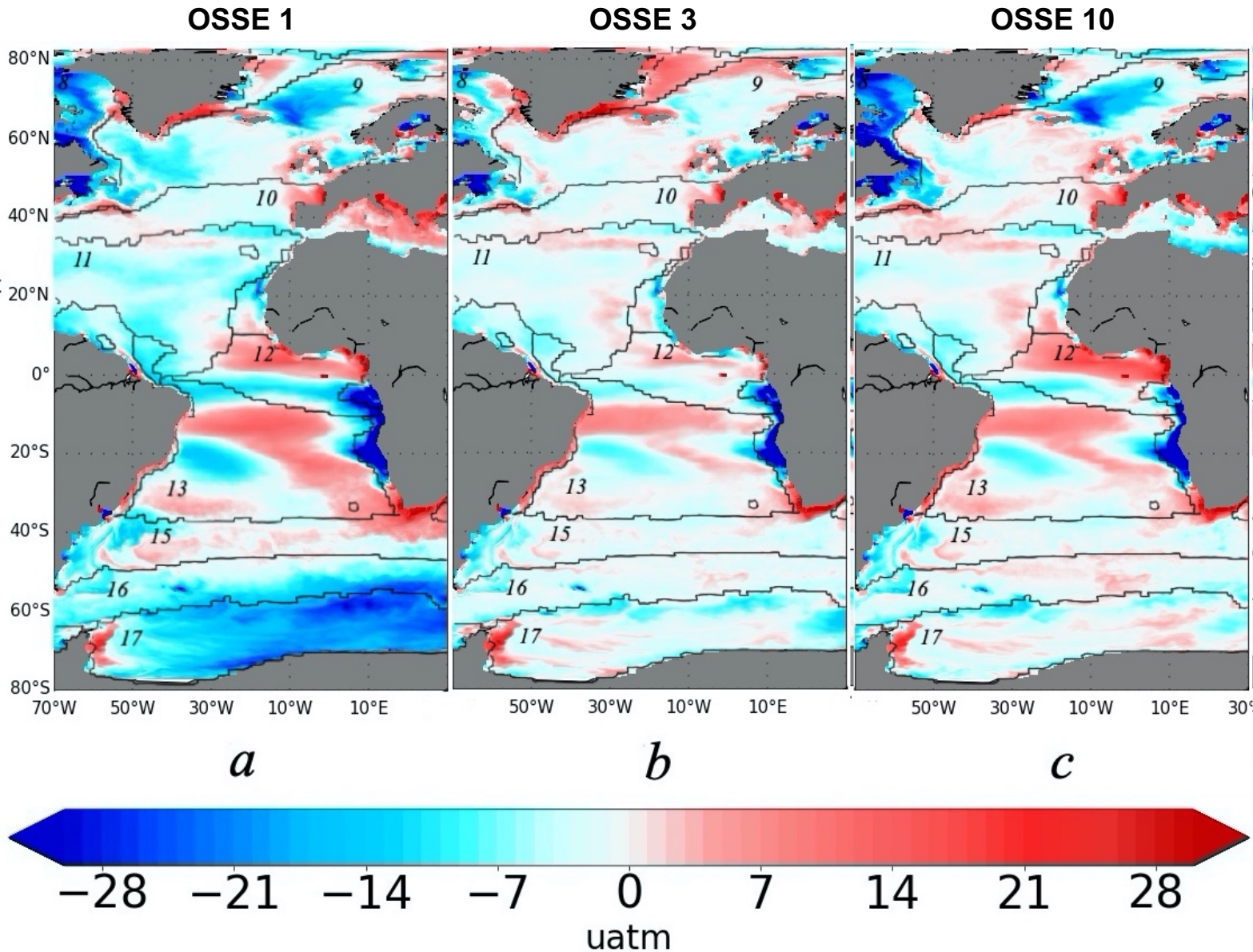
Biomes (after Rödenbeck et al., 2015; Fay and McKinley, 2014). Colors in Taylor diagrams correspond to biomes.



- Over 8 biomes (pink color) OSSE 1: STD = 26.08 μatm
R = 0.67
- OSSE 10 shows results close to the benchmark OSSE 3: STD = 23.79 μatm
R = 0.87
- OSSE 3: STD = 24.89 μatm
R = 0.85
- NEMO/PISCES STD = 25.34 μatm

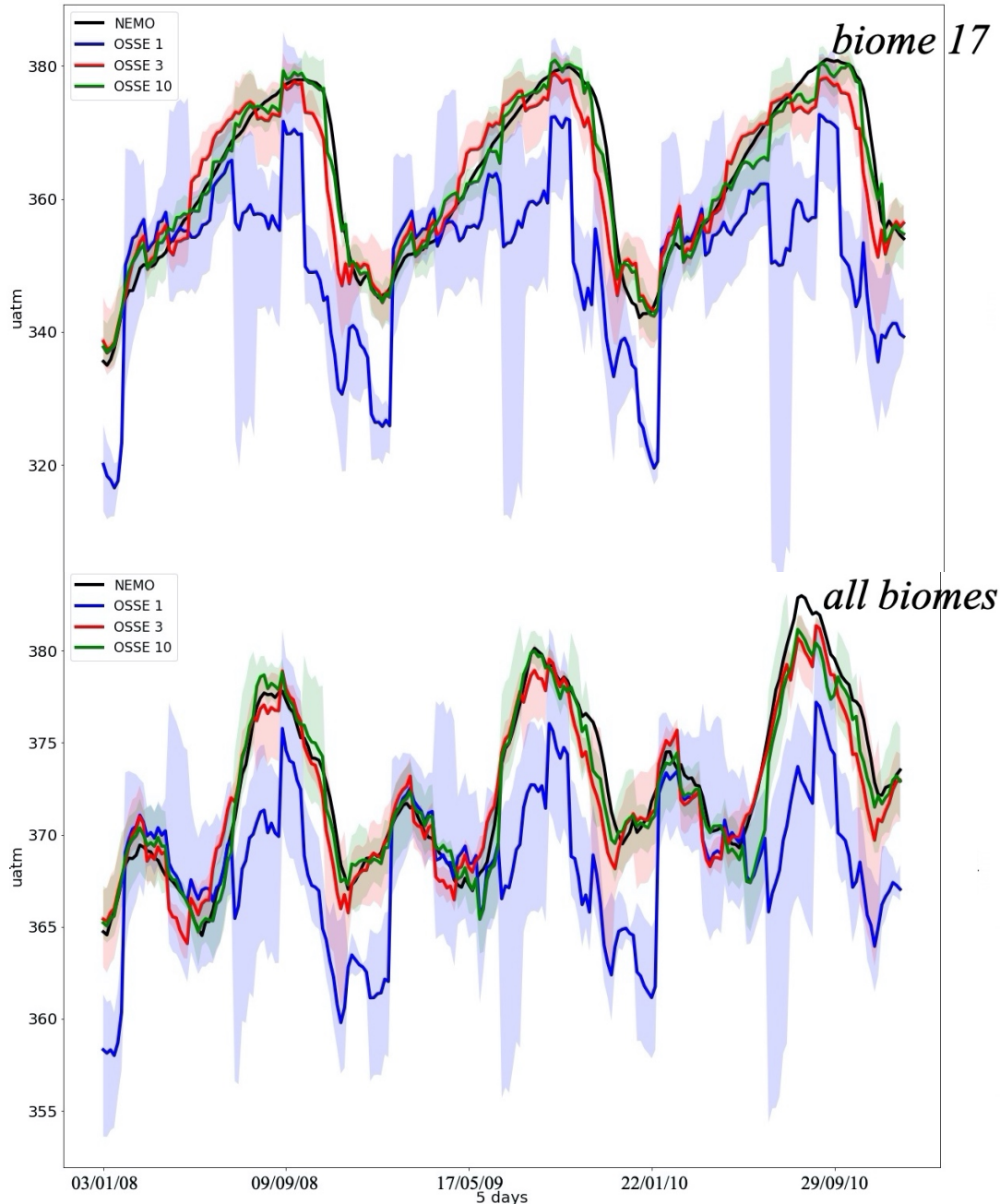
- Significant improvement in biomes 13, 15, 16, 17 that are less covered by SOCAT
- OSSE 1: STD = 16.11/15.28/11.76/21.11 μatm
R = 0.68/0.31/0.7/0.57
- OSSE 3: STD = 17.91/11.21/10.55/21.06 μatm
R = 0.91/0.73/0.83/0.85
- OSSE 10: STD = 17.36/11.35/11.01/22.25 μatm
R = 0.88/0.65/0.78/0.89
- NEMO/PISCES STD = 18.84/15.20/10.79/24.03 μatm

Mean differences between OSSEs and NEMO/PISCES $p\text{CO}_2$



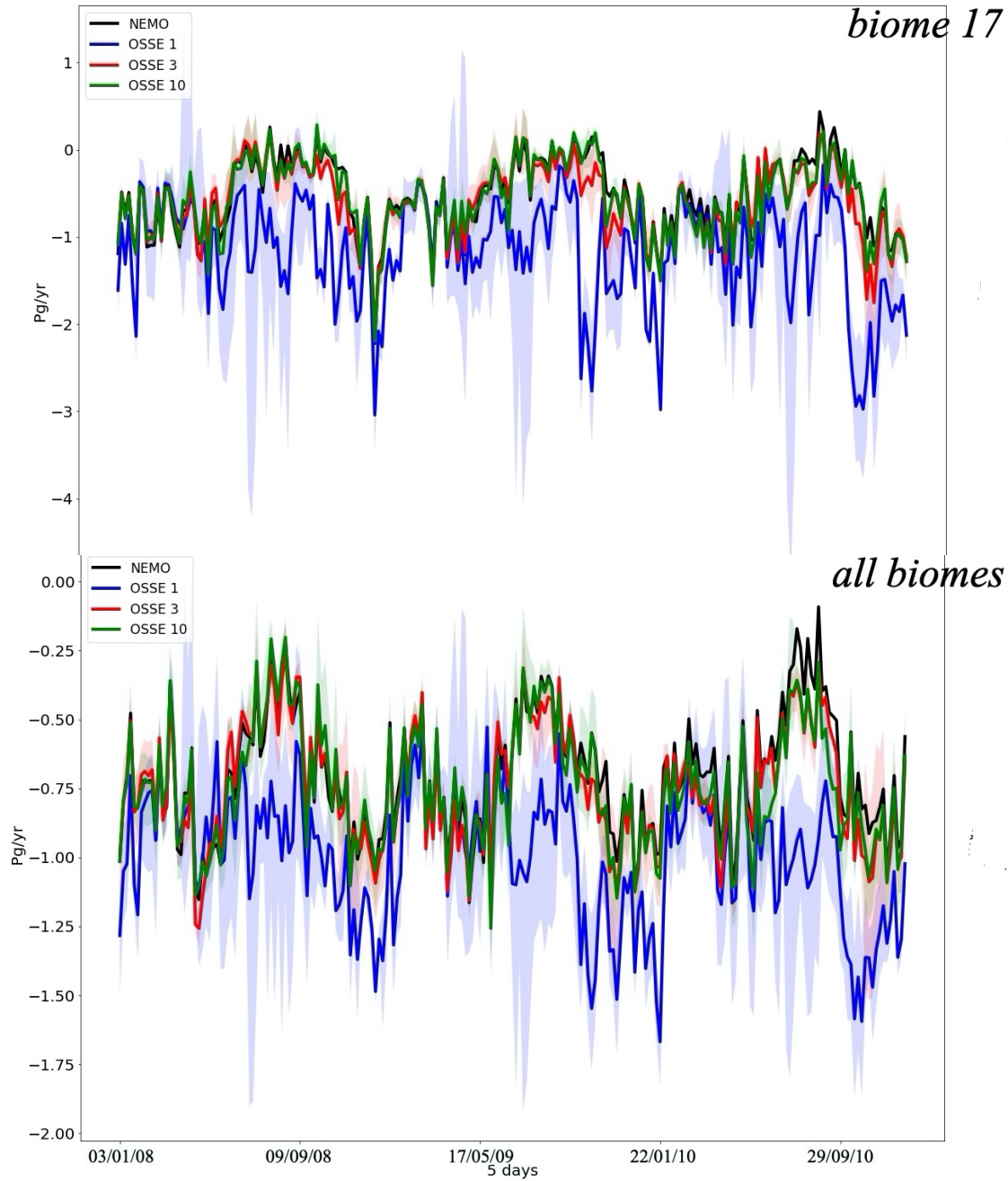
- Improvement in biomes 13, 15, 16, 17 for OSSEs 3 and 10 compare to OSSE 1.
- A lack of data in biomes 8 (was excluded from analysis due to the small amount of data) and 12 for OSSE 10.
- Need for data in costal areas.

$p\text{CO}_2$ time series



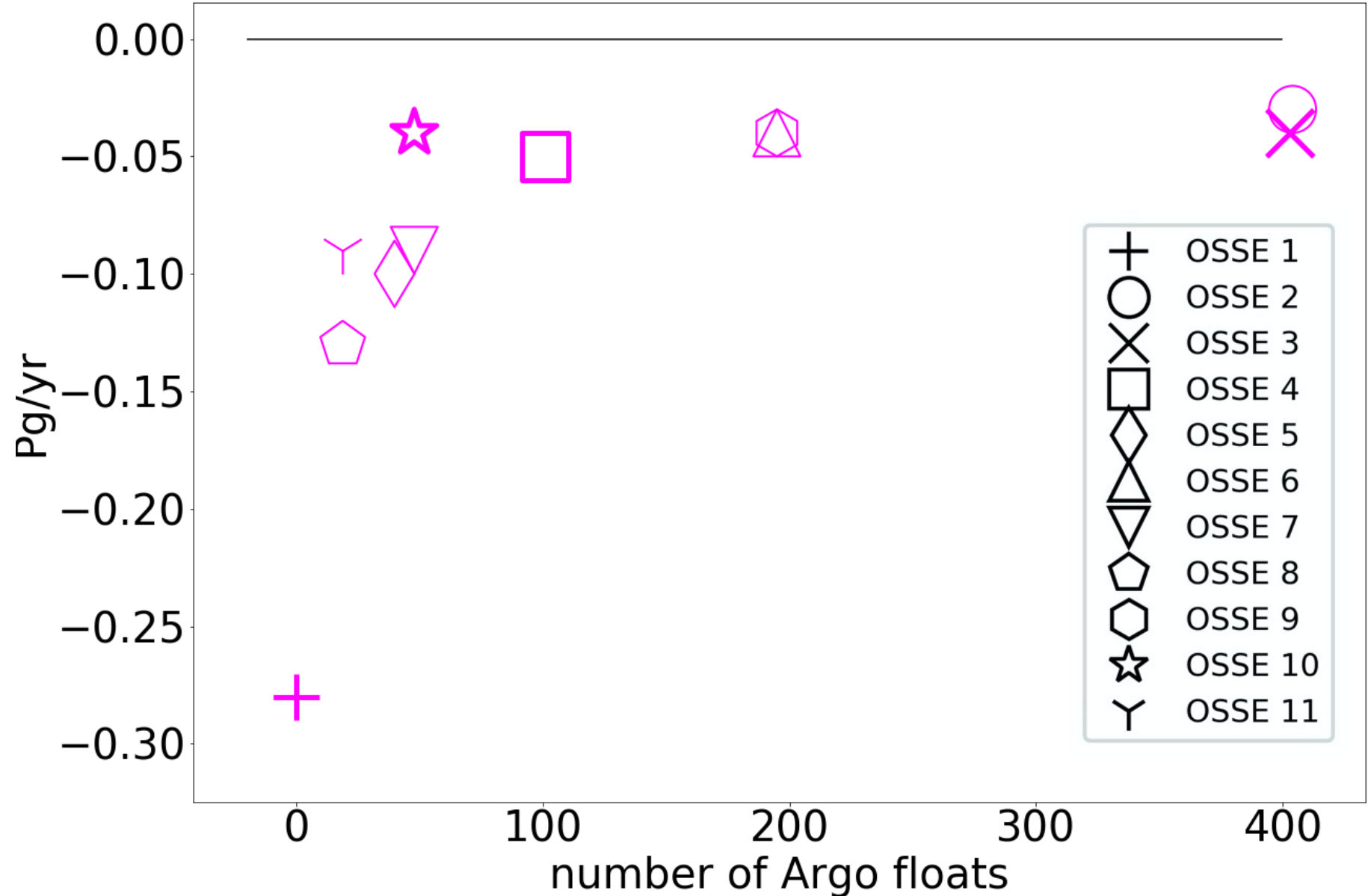
- Additional data from mooring stations and Argo floats in the South Hemisphere (**green curve**) provide significant improvement in reproduction of seasonal cycle in biome 17 (Southern Ocean Ice).
- The results over all biomes from **OSSE 10** are very close to the ones from **OSSE 3**.
- Averaged $p\text{CO}_2$ over biome 17 and over all biomes:
NEMO/PISCES: 363.08/372.65 μatm
OSSE 1: 351.44/368.39 μatm
OSSE 3: 362.42/372.18 μatm
OSSE 10: 362.87/372.26 μatm

Sea-air flux $fgCO_2$ time series



- **OSSE 10** also shows improvement in sea-air flux $fgCO_2$. Results from **OSSE 10** are close to the ones from **OSSE 3** and **NEMO/PISCES**.
- In biome 17 **OSSE 3** and **10** reproduce well the seasonal cycle of $fgCO_2$.
- Averaged $fgCO_2$ over biome 17 and over all biomes:
NEMO/PISCES: -0.52/-0.70 Pg/yr
OSSE 1: -1.17/-0.99 Pg/yr
OSSE 3: -0.59/-0.74 Pg/yr
OSSE 10: -0.56/-0.74 Pg/yr

Number of Argo profiles vs. averaged differences between OSSE and NEMO sea-air CO₂ flux



Conclusion

- Argo floats could significantly improve the accuracy of FFNN-based ocean $p\text{CO}_2$ reconstructions over the Atlantic Ocean and the Atlantic sector of the Southern Ocean
- Coverage of the southern Hemisphere with biogeochemical ARGO floats corresponding to at least 25% of the density of active floats can significantly improve a $p\text{CO}_2$ reconstruction.
- We demonstrate a potential reduction in bias of estimated sea-air CO_2 fluxes by 74%.
- Additional observations are required in coastal regions and shelf seas which are not accessible to floats, as well as in regions with a strong seasonal variability of $p\text{CO}_2$ and all predictors.
- Results are submitted and currently under review: Denvil-Sommer, A., Gehlen, M., and Vrac, M.: Observation System Simulation Experiments in the Atlantic Ocean for enhanced surface ocean $p\text{CO}_2$ reconstructions, Ocean Sci. Discuss. [preprint], <https://doi.org/10.5194/os-2021-17>, in review, 2021.