2nd Ocean Carbon from Space workshop

24-26 November 2025 Online

Towards an Explainable AI Framework for Quantifying Air-Sea CO_2 Fluxes

Multi-Sensor Satellite Data Fusion with Knowledge Graph Representation

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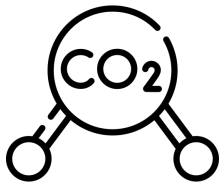
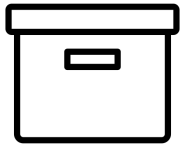
Why This Matters



Carbon Uncertainty
Oceans absorb ~25% of anthropogenic CO_2, but storage and distribution remain uncertain



Regional Variability
Strong regional variability (marine heatwaves, blooms, winds) complicates estimates



Data Sparsity
Air-sea CO_2 fluxes remain uncertain due to sparse in-situ measurements

Need for transparent, explainable, satellite-based monitoring

Data & Study Region

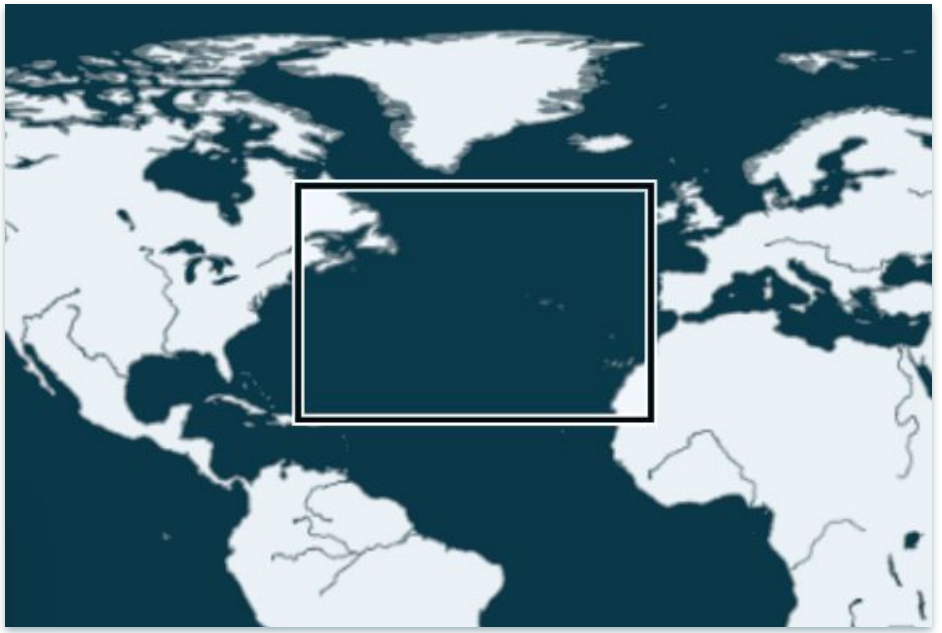


Fig. 1: North Atlantic regional test case

Variable	Sensor	Platform
Chl-a	OLCI	Sentinel-3
SST	SLSTR	Sentinel-3
SSH	SRAL/altimetry	Sentinel-3
Wind speed	ASCAT	MetOp
pCO_2	In-situ	SOCAT

Combined multi-sensor + in-situ dataset for pCO_2 prediction

→ THE EUROPEAN SPACE AGENCY

Model & Explainability

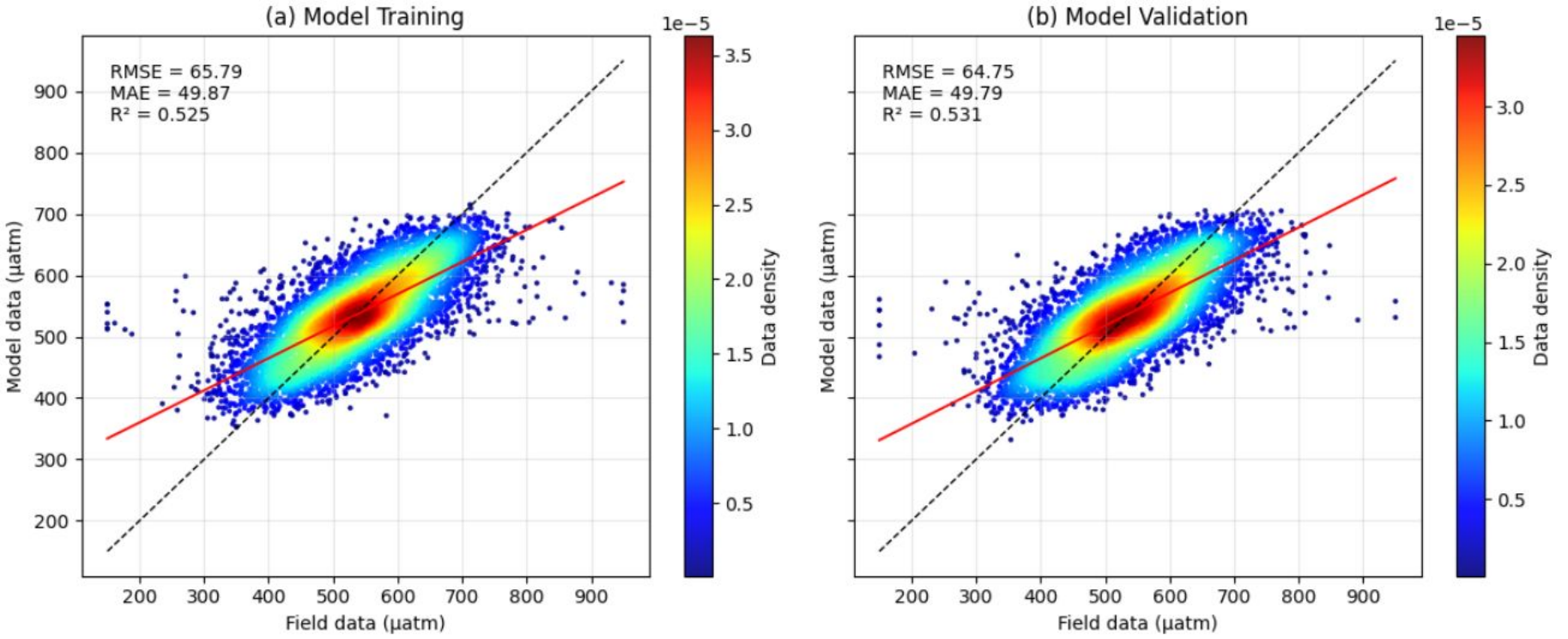
- **XGBoost** utilized for predicting surface pCO_2
- Model generalization: *No overfitting*
- Bulk CO_2 formulation that computes flux ***(ocean ⟷ air)***

Revealed strongest link between flux:

- **sst_anom**
- **co2_air**
- **chl-a**

CKG

Air-sea CO_2 exchange reports that global attempts at modelling and synthesis still carry substantial *uncertainty* and *variability*



SHAP Insights

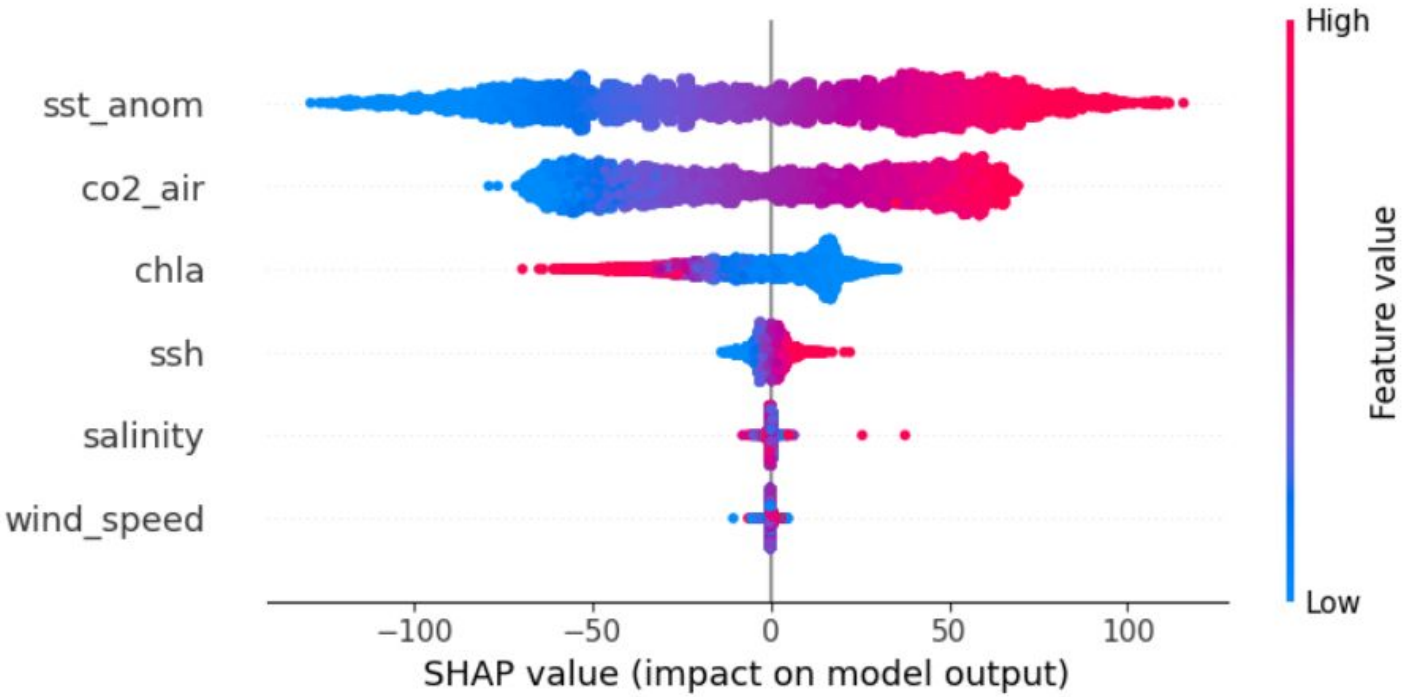
SHAP quantifies driver importance → XAI

SST anomaly
dominant driver

Chlorophyll-a
seasonal events (sharpness in graph)

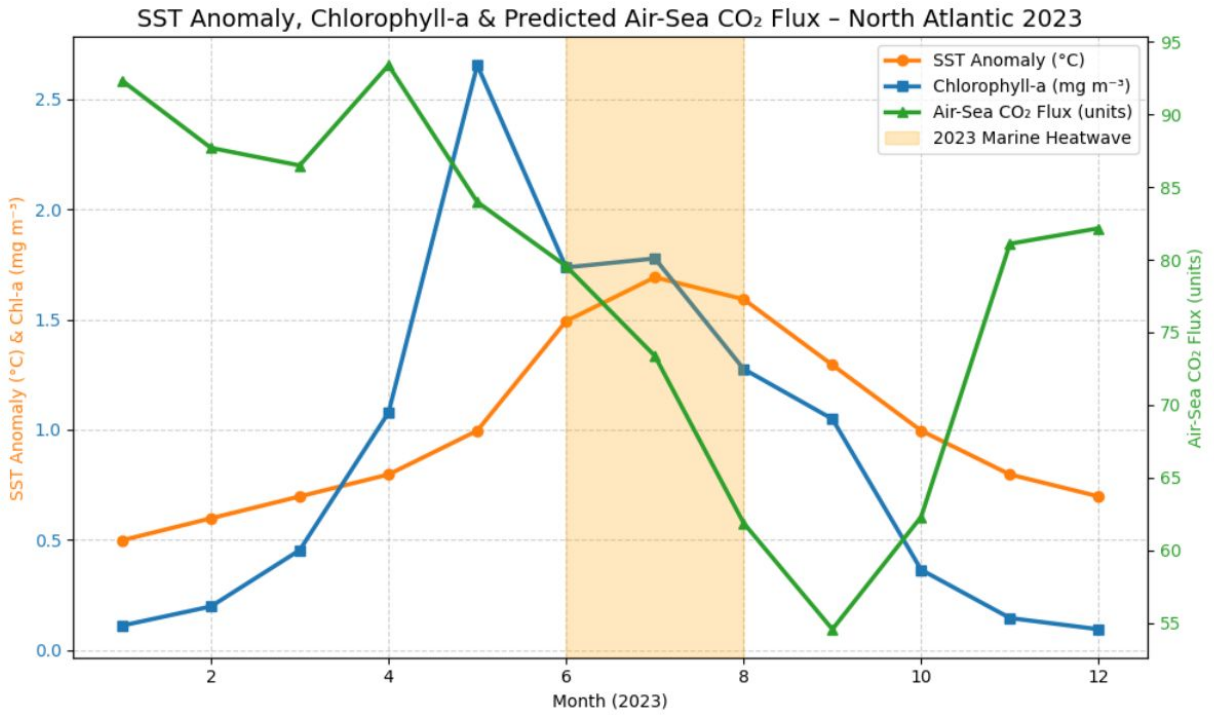
Winds
secondary driver in flux magnitude

SSH (altimetry)
minor contribution overall



SST × winds × biology → fluxes are difficult to model globally

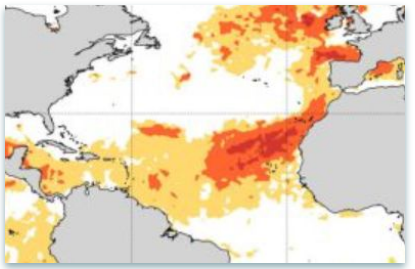
2023 Marine Heatwave Signal



Some parts of the eastern North Atlantic exceeded +2 °C anomalies in June (England et al., 2025).

In summer 2023, North Atlantic MWH → record high SST anomalies:

- **SST anomaly** peaks in June-August, aligning with the heatwave
- **CO_2 flux** drops at SST peak → *temperature-driven*
- Chl-a drops during peak warming *(50-60%, Mercator Ocean International)*
- Post-summer recovery *(SST cools, CO_2 flux rises)*



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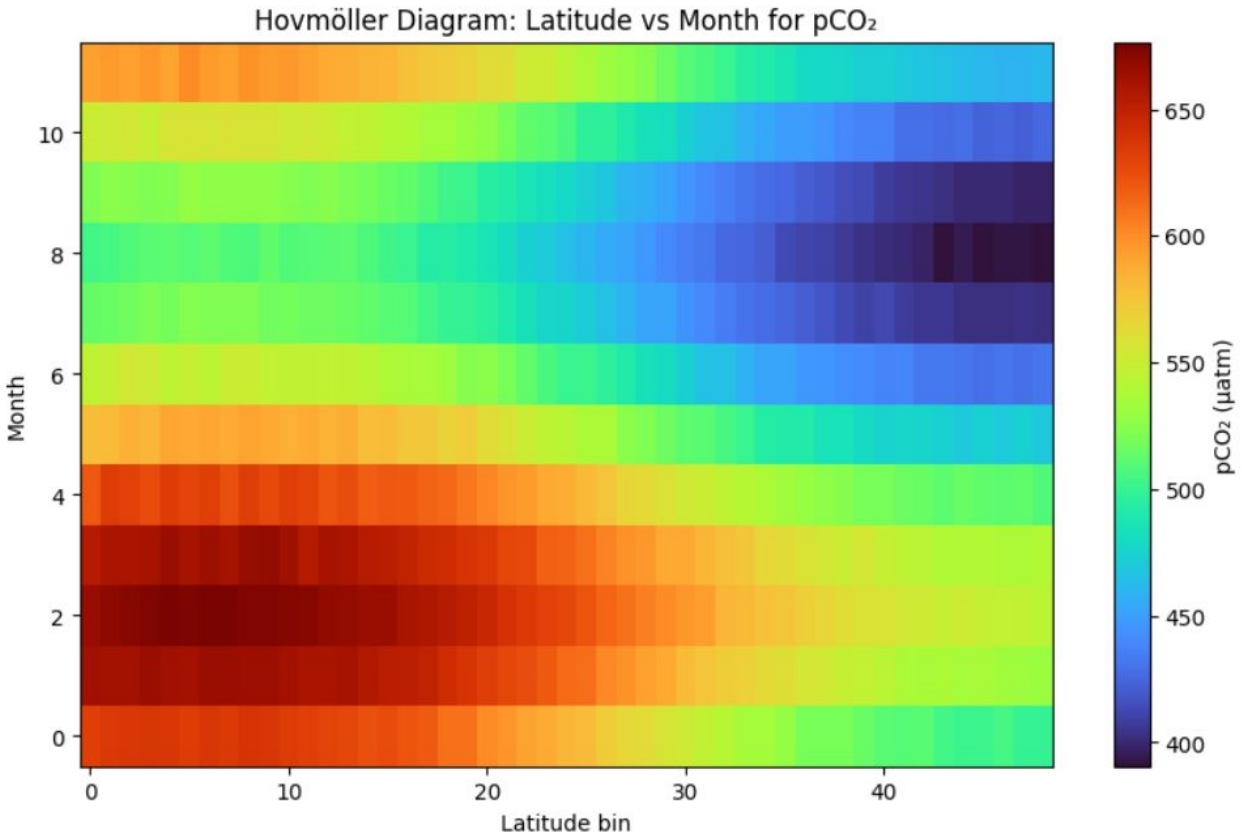
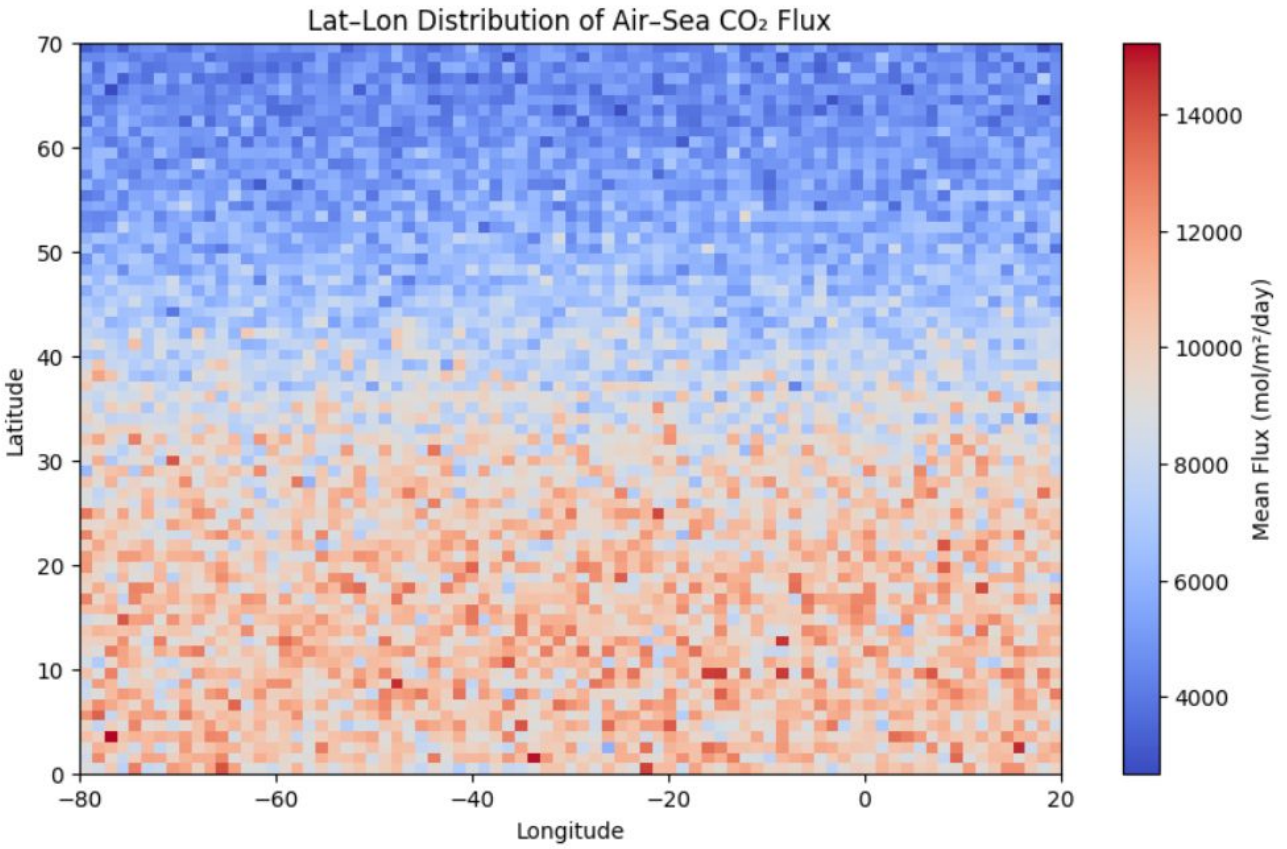
Additional Seasonal and Spatial Patterns





Conclusions & Outlook

Knowledge Gaps

- Limited coverage of pCO_2
- **Sparse** in-situ + satellite in **extreme events** *(e.g. heatwaves)*
- **Carbon-cycle XAI**

1-Year Priorities

- Benchmark **XAI for ML models** *(e.g. XGBoost, RF, neural nets)*

5-Year Priorities

- Develop open **Carbon Knowledge Graph** frameworks
- Add **ML-estimated pCO_2** into **ocean carbon models**

10-Year Priorities

- **ML-XAI** + full Earth-system models ***(ESMs)***
- Carbon cycle **digital twin**

Conclusion:

XAI + multi-sensor Earth observation → transparent, policy-relevant monitoring of air-sea CO_2 fluxes