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Supporting Information for

Long-term Strengthening of the CO₂ Sink and Spatiotemporal pCO₂ dynamics in the northern Gulf of Mexico: Insights from a 22-year Satellite-based Machine Learning Reconstruction

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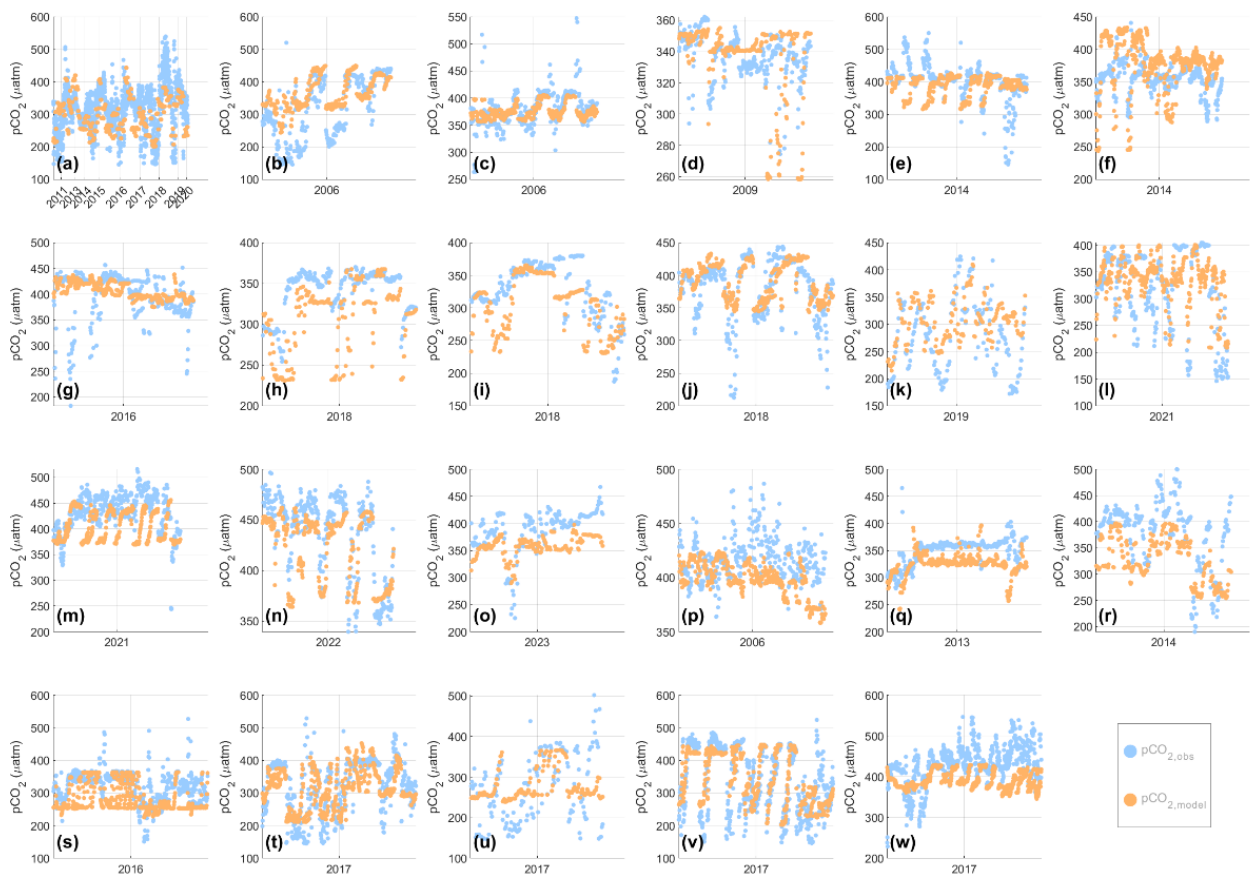
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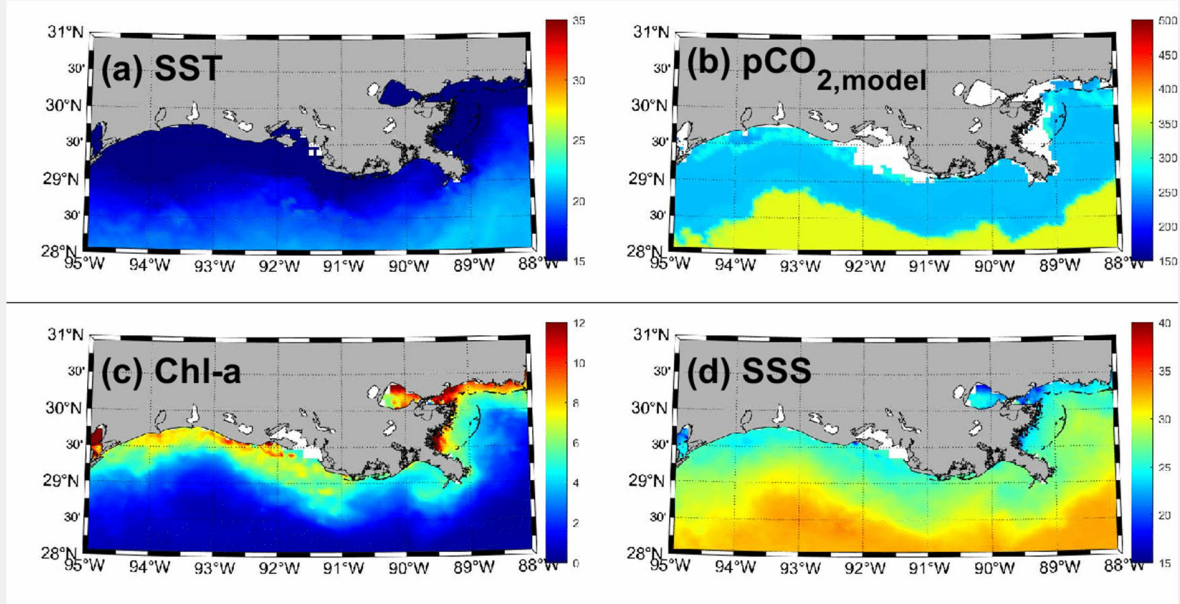
Figures S1 to S3

Tables S1 to S3



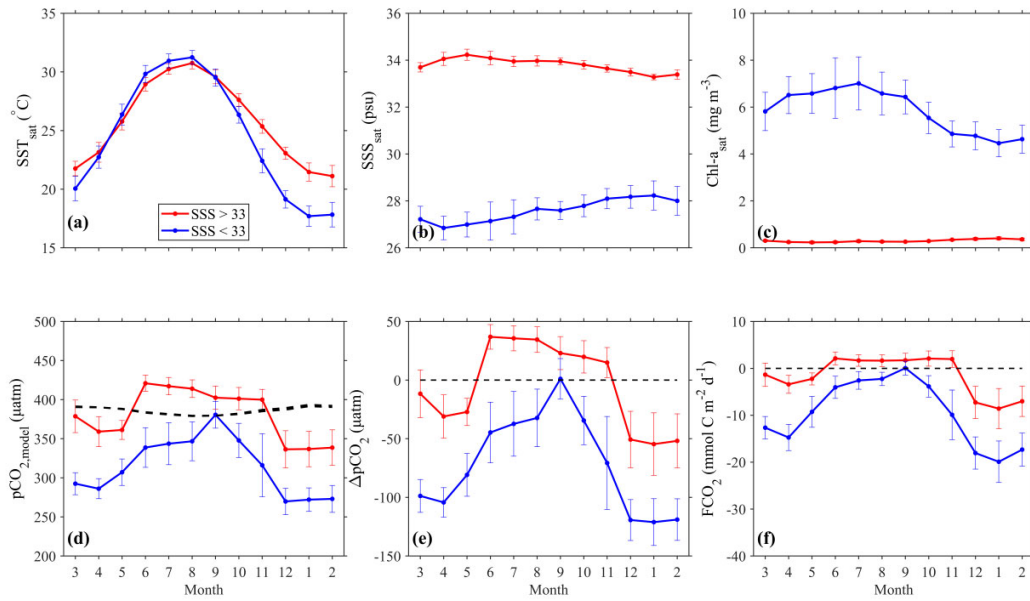
18 **Figure S1.** Independent verification of sea surface $p\text{CO}_2$ from the season-specific random forest
 19 model ($p\text{CO}_{2,\text{model}}$) against underway measurements ($p\text{CO}_{2,\text{obs}}$) from individual cruises.

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2003-1

23 **Figure S2.** Animated monthly variations of (a) sea surface temperature (SST), (b) sea surface pCO_2
 24 from the season-specific random forest model ($pCO_{2,model}$), (c) chlorophyll a (Chl-a), and (d) salinity
 25 in the northern Gulf of Mexico over the period 2003–2024.
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Figure S3. Seasonal variations of key surface water variables in the river-influenced coastal water (SSS<33, blue solid lines) and the open Gulf water (SSS>33, red solid lines) in the northern Gulf of Mexico: satellite-derived (a) sea surface temperature (SST_{sat}), (b) salinity (SSS_{sat}), and (c) chlorophyll a ($Chl-a_{sat}$); (d) sea surface pCO_2 from the season-specific random forest model ($pCO_{2,model}$); (e) air-sea pCO_2 difference (ΔpCO_2 , seawater minus atmosphere); (f) sea-to-air CO_2 flux (F_{CO_2}), where negative values refer to oceanic CO_2 uptake. Solid points represent the climatological regional monthly averages, with error bars indicating the standard deviation arising from spatial heterogeneity. The black dotted line in panel (d) shows the atmospheric pCO_2 . The black dashed lines in panels (e) and (f) mark the zero reference (pCO_2 equilibrium and zero flux, respectively).

Table S1. Summary statistics of environmental variables used for model training.

Time period data number	Full-season 18648		Spring 3649		Summer 4291		Autumn 7966		Winter 2742	
Statistics Variables	Mean \pm SD	Range	Mean \pm SD	Range	Mean \pm SD	Range	Mean \pm SD	Range	Mean \pm SD	Range
$p\text{CO}_{2,\text{obs}}$ (μatm)	358.25 \pm 65.67	145.44-549.93	333.76 \pm 68.19	145.10-542.15	352.99 \pm 81.90	145.44-549.21	384.59 \pm 48.13	145.97-549.93	322.52 \pm 42.27	146.86-526.98
Chl- a_{sat} (mg/m^3)	0.18 \pm 0.05	0.05-0.75	0.16 \pm 0.03	0.05-0.35	0.17 \pm 0.04	0.06-0.32	0.18 \pm 0.06	0.05-0.75	0.17 \pm 0.04	0.09-0.39
SST $_{\text{sat}}$ ($^{\circ}\text{C}$)	26.26 \pm 4.10	20.65-29.43	23.40 \pm 2.54	24.48-29.43	29.78 \pm 1.05	22.63-28.55	27.97 \pm 2.19	20.65-28.08	19.61 \pm 2.62	21.51-27.98
SSS $_{\text{sat}}$	31.65 \pm 4.84	10.91-38.13	31.36 \pm 5.61	18.54-36.63	29.54 \pm 5.40	4.68-38.13	32.40 \pm 3.77	22.33-36.62	33.17 \pm 4.39	17.73-35.62
$p\text{CO}_{2,\text{air}}$ (μatm)	386.90 \pm 11.16	361.87-408.58	394.30 \pm 8.02	375.13-408.58	382.42 \pm 10.55	363.93-405.53	383.72 \pm 11.03	357.13-401.64	393.27 \pm 7.68	377.47-408.25

Table S2. Performance comparison between the full-season model and the season-specific model. The evaluation metrics include coefficient of determination (R^2), root mean square error (RMSE), mean absolute error (MAE), mean relative error (MRE), and mean ratio (MR).

	Full-season model		Season-specific model			
		Spring	Summer	Autumn	Winter	Overall
R^2	0.65	0.76	0.82	0.78	0.70	0.81
RMSE (μatm)	40.80	32.40	34.38	22.31	22.12	27.60
MAD (μatm)	21.42	19.81	22.93	13.54	12.20	16.73
MRD (%)	1.58	1.25	1.66	0.52	0.48	0.92
MR	1.02	1.01	1.02	1.00	1.00	1.00

Table S3. Climatological averages (referenced to year 2013) and decadal changing rates of environmental variables in the northern Gulf of Mexico. Asterisks indicate significance levels: ** $p < 0.001$, * $p < 0.05$.

Variables	Climatological average					Decadal rate
	Annual	Spring	Summer	Autumn	Winter	
SST (°C)	25.09±1.52	23.73±1.88	31.22±1.61	26.41±1.49	18.76±2.60	0.05**
SSS	28.47±4.86	28.57±4.7	28.50±4.45	29.09±4.98	28.73±4.37	-0.01
Chl-a (mg/m ³)	5.47±6.81	5.24±5.96	6.01±7.51	4.83±7.24	4.51±5.53	0.04*
Wind speed (m/s)	4.82±1.67	5.00±1.49	3.72±1.22	4.94±1.74	5.60±1.81	0.003
Discharge (*10 ³ m ³ /s)	24.68±5.87	28.36±7.98	23.85±8.01	16.33±4.17	22.92±9.05	0.30
TN (10 ³ tons)	35.28±8.62	48.35±12.53	33.74±15.71	15.11±9.67	33.75±11.29	-0.07
$p\text{CO}_{2,\text{air}}$ (µatm)	383.01 ± ±1.51	386.02±0.61	377.87±0.80	379.92±0.82	387.28±1.36	2.13**
$p\text{CO}_2$ (µatm)	325.54±38.86	306.80±50.76	351.78±52.43	357.59±29.32	285.77±36.92	0.5*
F_{CO_2} (mmol C m ⁻² d ⁻¹)	-7.55±5.03	-9.57±6.91	-2.02±3.43	-3.04±3.65	-14.88±6.03	-0.41**