

Increasing river alkalinity slows ocean acidification in the northern Gulf of Mexico

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Introduction

The following figures and tables provide complementary information to the main manuscript.

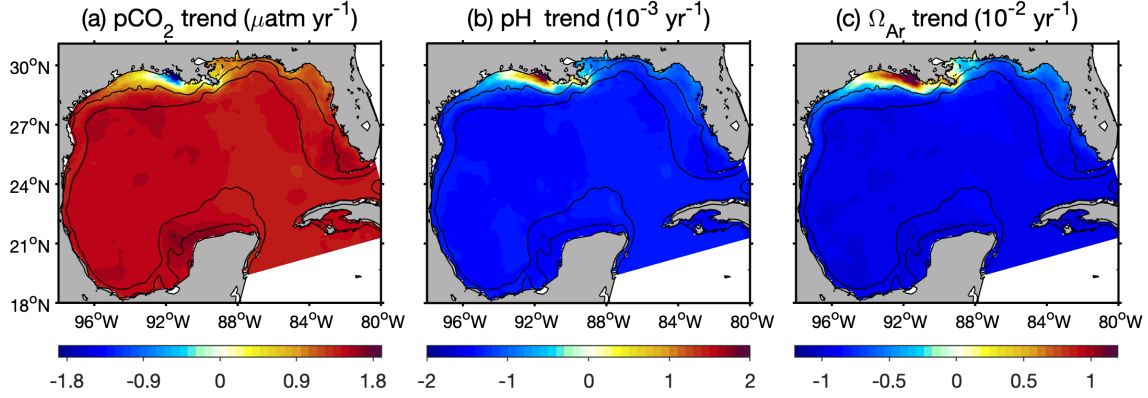


Figure S1. Trend patterns for (a) partial pressure of CO₂ (pCO₂), (b) pH, and (c) aragonite saturation state (Ω_{Ar}) after removing the salinity and temperature effect. Black contours depict the 25 and 200 m isobaths.

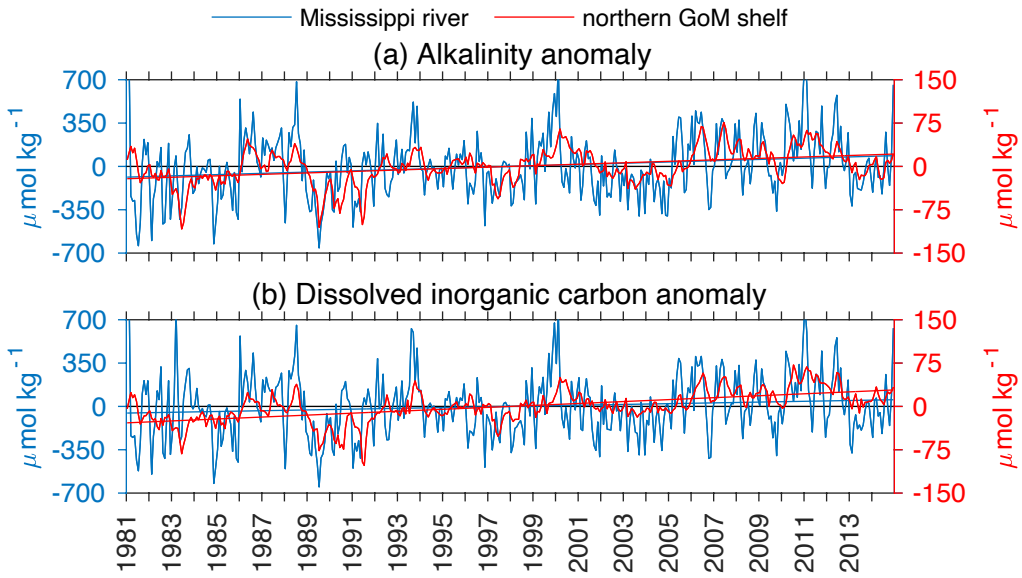


Figure S2. Mississippi river and northern GoM shelf patterns in carbonate chemistry. Low frequency patterns for (a) alkalinity and (b) dissolved inorganic carbon in the Mississippi river and the surface layer of the northern GoM shelf.

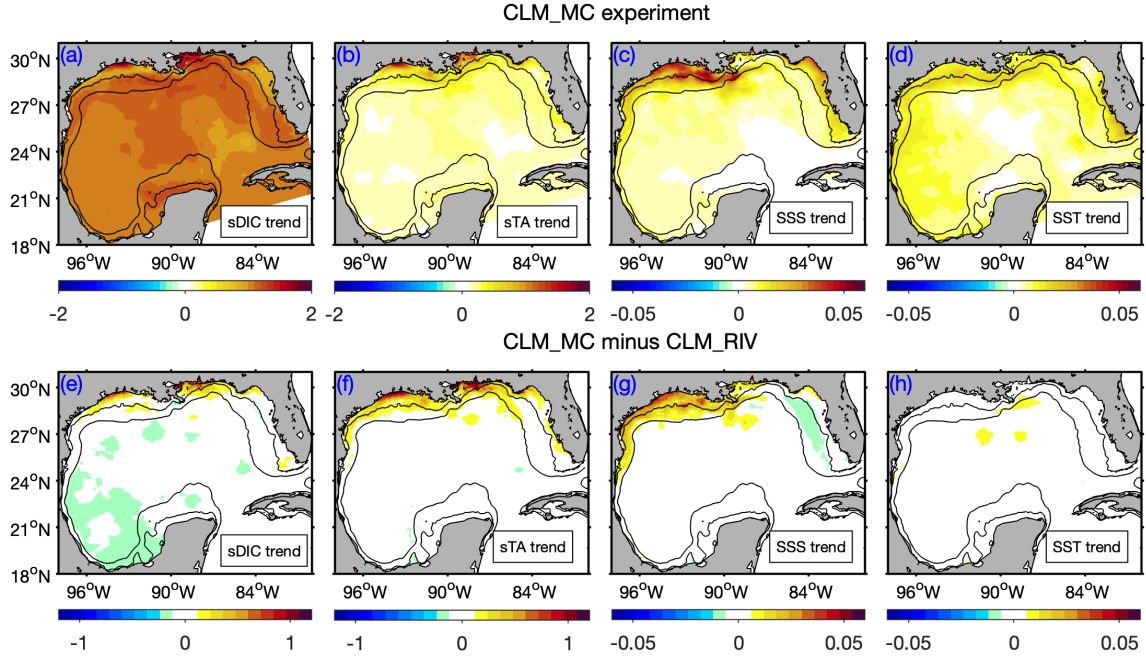


Figure S3. (a–d) Trend patterns for surface dissolved inorganic carbon (sDIC), surface total alkalinity (sTA), sea surface salinity (SSS), and sea surface temperature (SST) derived from climatological MARS chemistry experiment (CLM_MC); (e–h) Differences between trend patterns from CLM_MC and climatological river experiment (CLM_RIV). Trends for sDIC and sTA are in $\mu\text{mol kg}^{-1} \text{yr}^{-1}$, for SSS in yr^{-1} , and for SST in $^{\circ}\text{C yr}^{-1}$. Black contours depict the 25 and 200 m isobaths.

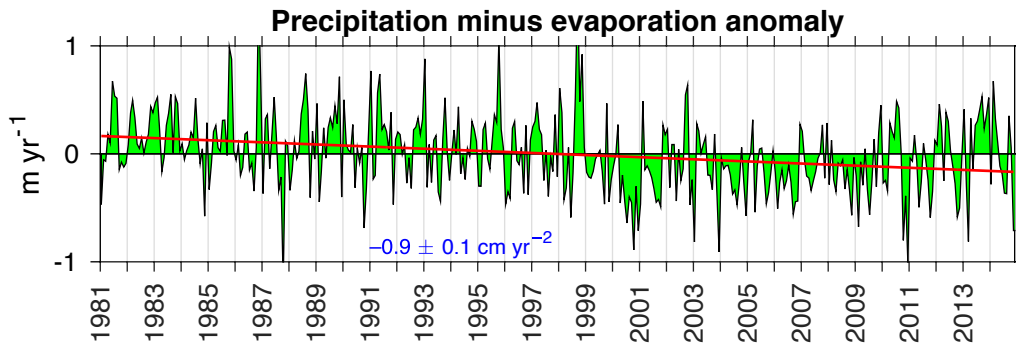


Figure S4. Average time series of precipitation minus evaporation anomaly across the Gulf of Mexico. Red line depicts the linear regression for 1981–2014. Long-term trend is indicated in blue.

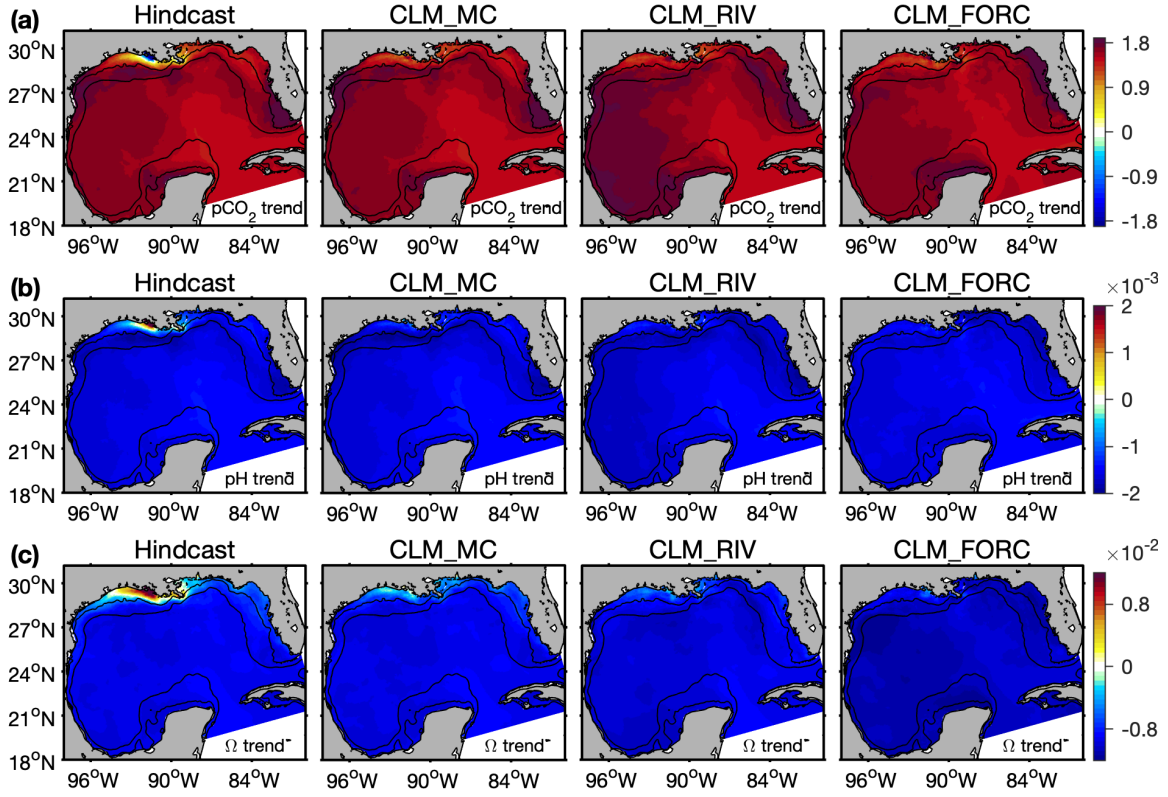


Figure S5. Sensitivity analysis for the simulated ocean acidification indicator's trends: (a) partial pressure of CO₂ trend ($\mu\text{atm yr}^{-1}$), (b) pH trend (yr^{-1}), and (c) aragonite saturation state trend (yr^{-1}) derived from the model hindcast, climatological MARS chemistry experiment (CLM_MC), climatological rivers experiment (CLM_RIV), and climatological forcing experiment (CLM_FORC). Black contours depict the 25 and 200 m isobaths.

	SST trend	SSS trend	sTA trend	sDIC trend	pCO ₂ trend	pH trend	Ω _{Ar} trend	CO ₂ flux trend
	[10 ⁻³ °C yr ⁻¹]	[10 ⁻³ yr ⁻¹]	[μmol kg ⁻¹ yr ⁻¹]	[μmol kg ⁻¹ yr ⁻¹]	[μatm yr ⁻¹]	[10 ⁻³ yr ⁻¹]	[10 ⁻³ yr ⁻¹]	[mmol m ⁻² yr ⁻²]
GoM basin	7.93 (2.02)	6.63 (0.90)	0.31 (0.02)	1.16 (0.02)	1.57 (0.03)	-1.53 (0.03)	-8.66 (0.15)	-3.68 (0.95)
1. Northern GoM shelf	13.98 (3.42)	22.09 (4.66)	1.26 (0.14)	1.67 (0.11)	1.31 (0.07)	-1.34 (0.08)	-4.18 (0.57)	-9.18 (2.74)
Inner shelf	13.92 (4.16)	27.32 (6.60)	1.90 (0.22)	1.97 (0.17)	0.93 (0.10)	-0.94 (0.11)	-0.26* (0.85)	-17.61 (2.79)
Outer shelf	14.02 (2.99)	18.05 (3.63)	0.76 (0.08)	1.45 (0.07)	1.61 (0.06)	-1.64 (0.07)	-7.18 (0.43)	-2.69* (1.80)
2. West Florida shelf	10.69 (3.73)	10.55 (1.91)	0.32 (0.03)	1.12 (0.02)	1.64 (0.05)	-1.59 (0.05)	-8.21 (0.29)	2.38* (1.51)
Inner shelf north 27°N	8.93 (5.02)	21.57 (3.74)	0.43 (0.06)	1.03 (0.04)	1.55 (0.08)	-1.48 (0.08)	-6.57 (0.40)	1.78* (1.92)
Inner shelf south 27°N	17.59 (4.56)	13.30 (2.09)	0.32 (0.09)	1.15 (0.03)	1.87 (0.07)	-1.78 (0.07)	-8.62 (0.46)	4.86 (1.48)
Outer shelf	9.32 (3.22)	5.75 (1.67)	0.31 (0.03)	1.14 (0.03)	1.61 (0.03)	-1.58 (0.04)	-8.69 (0.25)	1.88* (1.50)
3. Yucatan shelf	5.32 (2.19)	2.28 (0.57)	0.17 (0.02)	1.09 (0.02)	1.59 (0.03)	-1.51 (0.03)	-9.37 (0.16)	-3.53 (0.91)
Inner shelf	6.22 (2.64)	3.26 (0.87)	0.19 (0.02)	1.13 (0.02)	1.69 (0.04)	-1.57 (0.04)	-9.60 (0.18)	-1.16* (0.93)
Outer shelf	4.97 (2.06)	1.91 (0.52)	0.16 (0.02)	1.08 (0.02)	1.56 (0.03)	-1.49 (0.03)	-9.28 (0.15)	-4.43 (0.93)
4. Western GoM shelf	12.56 (2.44)	10.21 (2.83)	0.32 (0.05)	1.17 (0.03)	1.70 (0.04)	-1.67 (0.04)	-8.77 (0.27)	-0.96* (1.05)
5. Open GoM	6.85 (1.81)	4.27 (0.62)	0.19 (0.02)	1.10 (0.02)	1.59 (0.02)	-1.55 (0.02)	-9.30 (0.12)	-3.79 (0.89)

Table S1. Simulated trends for carbon system variables in the Gulf of Mexico (GoM) and sub-regions as derived from the hindcast experiment (1981-2014): sea surface temperature (SST), sea surface salinity (SSS), surface total alkalinity (sTA), surface dissolved inorganic carbon (sDIC), surface partial pressure of CO₂ (pCO₂), surface pH, surface aragonite saturation state (Ω_{Ar}), and air-sea CO₂ flux. Standard errors are indicated in parenthesis. Main subregions are depicted in Fig. 1c. The northern GoM, West Florida, and Yucatan shelves were divided in inner and outer part (bottom depths 0-25 m and 25-200 m, respectively). Florida inner shelf was further divided in a northern and a southern part. (*) Non-significant trend at the 95% confidence level.

	Mississippi	Atchafalaya
Mean values (1981-2014)		
DIC ($\mu\text{mol kg}^{-1}$)	2,301 (328)	2,019 (413)
TA ($\mu\text{mol kg}^{-1}$)	2,228 (333)	1,941 (426)
TA:DIC ratio	0.968 (0.029)	0.959 (0.046)
Linear trends (1981-2014)		
DIC trend ($\mu\text{mol kg}^{-1} \text{ yr}^{-1}$)	3.2 (1.3)	3.0 (1.6)
TA trend ($\mu\text{mol kg}^{-1} \text{ yr}^{-1}$)	5.1 (1.2)	5.6 (1.6)
TA:DIC ratio trend (yr^{-1})	0.88×10^{-3} (0.14×10^{-3})	1.37×10^{-3} (0.21×10^{-3})

Table S2. Long term patterns for the Mississippi and Atchafalaya carbon chemistry derived from the U.S. Geological Survey records. Standard errors of the mean values and trends are indicated in parenthesis.

	SST [10 ⁻³ °C yr ⁻¹]	SSS [10 ⁻³ yr ⁻¹]	sTA [μmol kg ⁻¹ yr ⁻¹]	sDIC [μmol kg ⁻¹ yr ⁻¹]	pCO ₂ [μatm yr ⁻¹]	pH [10 ⁻³ yr ⁻¹]	Ω _{Ar} [10 ⁻³ yr ⁻¹]
CLM_MC experiment							
GoM basin	7.9 (1.00)	6.6 (1.00)	0.20 (0.65)	1.09 (0.93)	1.60 (1.02)	-1.57 (1.03)	-9.11 (1.05)
Northern GoM shelf	14.0 (1.00)	22.1 (1.00)	0.49 (0.39)	1.14 (0.68)	1.56 (1.19)	-1.65 (1.23)	-7.28 (1.74)
West Florida shelf	10.7 (1.00)	10.6 (1.00)	0.24 (0.75)	1.07 (0.96)	1.66 (1.01)	-1.62 (1.02)	-8.55 (1.04)
Yucatan shelf	5.3 (1.00)	2.3 (1.00)	0.17 (1.00)	1.09 (1.00)	1.59 (1.00)	-1.51 (1.00)	-9.39 (1.00)
Western GoM shelf	12.6 (1.00)	10.2 (1.00)	0.19 (0.59)	1.07 (0.91)	1.71 (1.01)	-1.71 (1.02)	-9.23 (1.05)
Open GoM	6.9 (1.00)	4.3 (1.00)	0.16 (0.84)	1.08 (0.98)	1.59 (1.00)	-1.56 (1.01)	-9.41 (1.01)
CLM_RIV experiment							
GoM basin	7.4 (0.93)	4.9 (0.74)	0.18 (0.58)	1.11 (0.96)	1.65 (1.05)	-1.62 (1.05)	-9.57 (1.11)
Northern GoM shelf	13.7 (0.98)	7.5 (0.34)	0.20 (0.16)	1.00 (0.60)	1.57 (1.20)	-1.66 (1.23)	-8.41 (2.01)
West Florida shelf	11.8 (1.10)	14.3 (1.34)	0.20 (0.62)	1.04 (0.93)	1.74 (1.06)	-1.71 (1.08)	-8.94 (1.08)
Yucatan shelf	4.0 (0.75)	2.7 (1.17)	0.21 (1.23)	1.17 (1.07)	1.67 (1.05)	-1.57 (1.04)	-9.87 (1.05)
Western GoM shelf	11.8 (0.95)	4.1 (0.40)	0.16 (0.50)	1.14 (0.97)	1.79 (1.05)	-1.76 (1.05)	-9.98 (1.14)
Open GoM	6.2 (0.89)	3.7 (0.87)	0.17 (0.89)	1.13 (1.03)	1.64 (1.03)	-1.60 (1.03)	-9.78 (1.05)
CLM_FORC experiment							
GoM basin	0.1 (0.01)	0.6 (0.09)	0.04 (0.13)	1.06 (0.91)	1.61 (1.03)	-1.57 (1.03)	-10.66 (1.23)
Northern GoM shelf	1.5 (0.11)	2.7 (0.12)	0.10 (0.08)	1.03 (0.62)	1.51 (1.15)	-1.61 (1.20)	-9.90 (2.37)
West Florida shelf	1.3 (0.12)	2.4 (0.23)	-0.01 (-0.03)	1.03 (0.91)	1.72 (1.05)	-1.67 (1.05)	-10.68 (1.30)
Yucatan shelf	-0.1 (-0.02)	0.5 (0.22)	0.03 (0.17)	1.10 (1.00)	1.68 (1.06)	-1.60 (1.06)	-11.05 (1.18)
Western GoM shelf	0.2 (0.02)	-2.8 (0.27)	0.03 (0.09)	1.12 (0.96)	1.69 (0.99)	-1.63 (0.98)	-11.17 (1.27)
Open GoM	-0.3 (-0.04)	0.3 (0.07)	0.03 (0.16)	1.07 (0.97)	1.59 (1.00)	-1.55 (1.00)	-10.69 (1.15)

Table S3. Simulated surface trends (1981–2014) for sea surface temperature (SST), sea surface salinity (SSS), surface total alkalinity (sTA), surface dissolved inorganic carbon (sDIC), partial pressure of CO₂ (pCO₂), pH, and aragonite saturation state (Ω_{Ar}) derived from the climatological experiments. The ratio between the climatological and hindcast trends is reported in parenthesis.

X :	SST	SSS	sTA	sDIC
$\partial p\text{CO}_2/\partial X$	12.9219	8.7166	-1.2253	1.5264
$\partial \text{pH}/\partial X$	-0.0150	-0.0130	0.0015	-0.0016
$\partial \Omega/\partial X$	0.0233	-0.0438	0.0112	-0.0106

Table S4. Partial derivatives of partial pressure of CO_2 (CO_2), pH, and aragonite saturation state (Ω_{Ar}) for an average surface condition on the northern GoM shelf during 1981-2014: sea surface temperature (SST) = 24.4°C; sea surface salinity (SSS) = 32.2; surface dissolved inorganic carbon (sDIC) = 1,987 $\mu\text{mol kg}^{-1}$; surface total alkalinity (sTA) = 2,311 $\mu\text{mol kg}^{-1}$.

	Region	Period	pCO ₂ trend ($\mu\text{atm yr}^{-1}$)	pH trend (10^{-3} yr^{-1})	Ω_{Ar} trend (10^{-3} yr^{-1})
Open ocean:					
Present study	Open GoM	1981-2014	1.59 ± 0.02	-1.6 ± 0.0	-9.3 ± 0.1
Kealoha et al. (2020)	Open GoM	1996-2018	Ranging from -0.21 ± 0.67 to 1.70 ± 0.14		
Xu et al. (2020)	Offshore South Atlantic Bight	1981-2011	1.38 ± 0.04	-1.3 ± 0.5	-7.3 ± 1.1
Lauvset et al. (2015)	Stratified Subtropical North Atlantic	1991-2011	1.44 ± 0.12	-1.1 ± 0.2	
		1981-2011	1.42 ± 0.12		
Bates et al. (2014)	BATS	1983-2014	1.69 ± 0.11	-1.7 ± 0.1	-9.5 ± 0.7
Bates & Johnson (2020)	BATS	1983-2020	1.92 ± 0.08	-1.9 ± 0.1	-9 ± 1
Wanninkhof et al. (2019)	Caribbean Sea	2002-2018	1.30 ± 0.03		
Gledhill et al. (2008)	Caribbean Sea	1996-2006			-12 ± 1
Coastal regions:					
Present study	GoM shelves	1981-2014	Ranging from 1.31 ± 0.07 to 1.70 ± 0.04	Ranging from -1.3 ± 0.1 to -1.7 ± 0.0	Ranging from -4.2 ± 0.6 to -9.4 ± 0.2
Kealoha et al. (2020)	GoM shelves	1996-2018	Ranging from 0.08 ± 1.66 to 3.20 ± 1.47		
Robbins et al. (2018)	West Florida	1996-2016	4.37		
Xu et al. (2020)	South Atlantic Bight shelf	1981-2011	1.40 ± 0.09	-1.3 ± 0.1	-6.3 ± 1.5
	Mid Atlantic Bight shelf	1981-2011	1.77 ± 0.07	-1.9 ± 0.1	-10.3 ± 1.0

Table S5. Simulated trends and reported trend values for partial pressure of CO₂ (pCO₂), pH, and aragonite saturation state (Ω_{Ar}) in open ocean and coastal regions from the north Atlantic.

Datasets S1 to S7:

Datasets S1 to S7 contain the monthly outputs (January 1981 to December 2014) of sea surface temperature, sea surface salinity, surface alkalinity, surface dissolved inorganic carbon, surface partial pressure of CO₂, surface pH, and surface aragonite saturation state derived from the model hindcast experiment. Each file contains a 3-dimension array (longitude, latitude, time). The horizontal model grid (longitude, latitude) is provided in Dataset S29.

	Variable	Array name	Units
Dataset S1	Sea surface temperature	SST	°C
Dataset S2	Sea surface salinity	SSS	Unitless
Dataset S3	Surface alkalinity	ALK	μmol kg ⁻¹
Dataset S4	Surface dissolved inorganic carbon	DIC	μmol kg ⁻¹
Dataset S5	Surface partial pressure of CO ₂	PCO2	μatm
Dataset S6	Surface pH	pH	Unitless
Dataset S7	Surface aragonite saturation state	OMar	Unitless

Datasets S8 to S14:

As Datasets S1-S7 but for the climatological river experiment.

	Variable	Array name	Units
Dataset S8	Sea surface temperature	SST	°C
Dataset S9	Sea surface salinity	SSS	Unitless
Dataset S10	Surface alkalinity	ALK	μmol kg ⁻¹
Dataset S11	Surface dissolved inorganic carbon	DIC	μmol kg ⁻¹
Dataset S12	Surface partial pressure of CO ₂	PCO2	μatm
Dataset S13	Surface pH	pH	Unitless
Dataset S14	Surface aragonite saturation state	OMar	Unitless

Datasets S15 to S21:

As Datasets S1-S7 but for the climatological MARS chemistry experiment.

	Variable	Array name	Units
Dataset S15	Sea surface temperature	SST	°C
Dataset S16	Sea surface salinity	SSS	Unitless
Dataset S17	Surface alkalinity	ALK	$\mu\text{mol kg}^{-1}$
Dataset S18	Surface dissolved inorganic carbon	DIC	$\mu\text{mol kg}^{-1}$
Dataset S19	Surface partial pressure of CO ₂	PCO2	μatm
Dataset S20	Surface pH	pH	Unitless
Dataset S21	Surface aragonite saturation state	OMar	Unitless

Datasets S22 to S28:

As Datasets S1-S7 but for the climatological forcing experiment.

	Variable	Array name	Units
Dataset S22	Sea surface temperature	SST	°C
Dataset S23	Sea surface salinity	SSS	Unitless
Dataset S24	Surface alkalinity	ALK	$\mu\text{mol kg}^{-1}$
Dataset S25	Surface dissolved inorganic carbon	DIC	$\mu\text{mol kg}^{-1}$
Dataset S26	Surface partial pressure of CO ₂	PCO2	μatm
Dataset S27	Surface pH	pH	Unitless
Dataset S28	Surface aragonite saturation state	OMar	Unitless

Dataset S29. Horizontal model grid (longitude, latitude)