

Controls on Sea-Air CO₂ Flux in EBUS

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Abstract

I am working to understand what controls historical variability in Sea-Air CO₂ Flux in Eastern Boundary Upwelling Systems. I use FG_CO2 output from the CESM Large Ensemble and correlate/regress it against various climate indices derived from model output (using Adam Phillip's CESM-LE CVDP output). In total, we have 34 ensemble members to work with, and treat them as independent time series.

1 Model Evaluation

Figure 1 compares 30-year annual climatologies of sea-air CO_2 flux (FGCO2) across the four upwelling systems (spanning 1982-2011). The top row is derived from the 30-year monthly resolution neural network by Landschützer et al. [2012]. The bottom row is the ensemble mean of 34 members of the CESM Large Ensemble spanning the same time period.

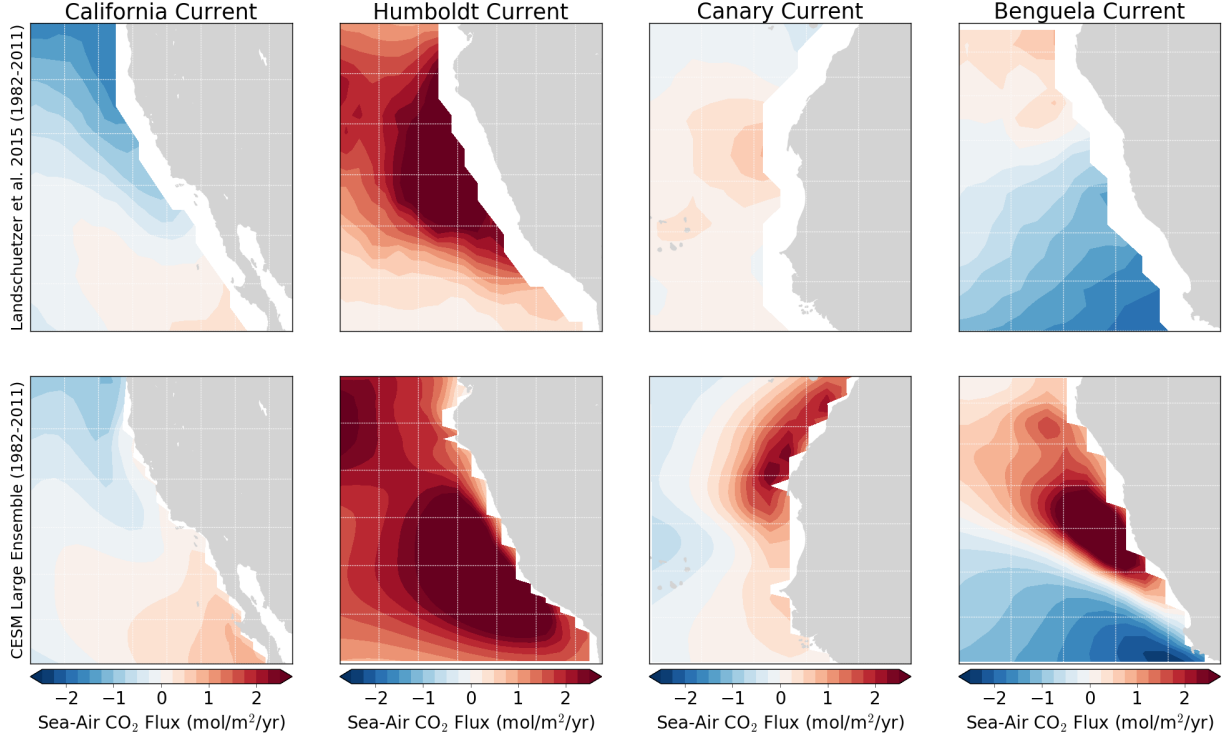


Figure 1: Annual averages of Sea-Air CO_2 flux over 1982-2011 for the four major eastern boundary upwelling systems. The top row is semi-observational data, while the bottom row is the ensemble mean from the CESM Large Ensemble.

2 Study Sites

For simplicity, I am using the latitudinal bounds set up by Chavez and Messié [2009], which dictates the ten degrees of most active upwelling via satellite wind stress climatology. I then constrain the offshore region to within 800km (via cell width output from the model).

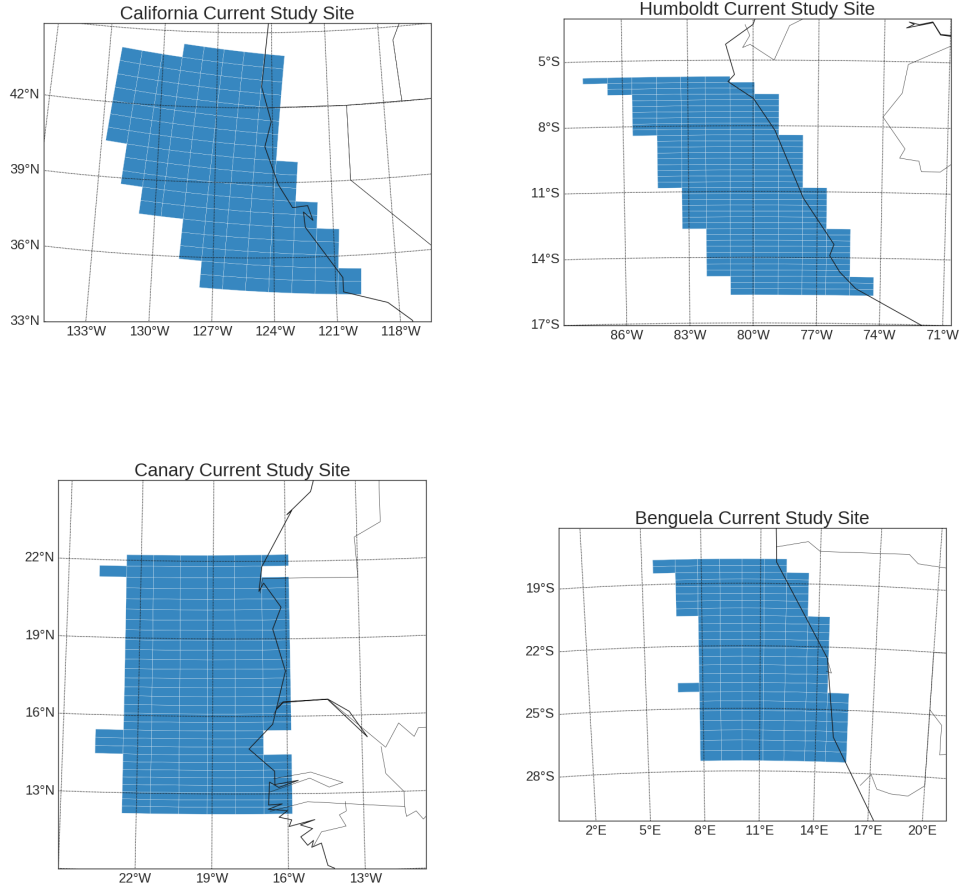


Figure 2: Nearshore regions for each EBUS over which area-weighted FGCO₂ is computed. The latitude is constrained by the 10 degree bounds of most active upwelling (per Chavez and Messié [2009]). The longitude is constrained to 800km offshore to standardize region sizes across different latitudes.

3 General Methodology

We use 34 CESM-LENS members, which can be treated as entirely independent time series, spanning 1920-2100 at monthly resolution. We focus, however, on the 1920-2015 period, since we are trying to understand the historical controls on FGCO₂ variability (and as Adam Phillip’s CVDP package covers this same period). The area-weighted mean (using TAREA) of FGCO₂ is computed for each EBUS, generating a 34x1152 time series matrix.

First, we subtract the ensemble mean time series from each individual simulation. This de-trends the data, leaving us with 34 independent anomaly time series, which we can think of as the *natural* flux of CO₂ into and out of the coastal ocean. We then load in climate

index time series (Nino3.4, PDO, AMO, NAO, SAM) for the same ensemble members, and remove the linear trend from each to similarly produce anomaly time series.

We apply a 12-month (annual) rolling mean to all FGCO2 anomaly time series, as we find the raw time series to be much too noisy for meaningful correlations. See Figure 3, which demonstrated raw (color) time series for simulation 001 for each EBUS and the smoothed time series overlaid in black. This is defensible, as an FFT of these raw time series shows roughly red noise.

Lastly, we regress the smoothed FGCO2 anomalies onto the four main predictors: Nino3.4, PDO, AMO, and SAM.

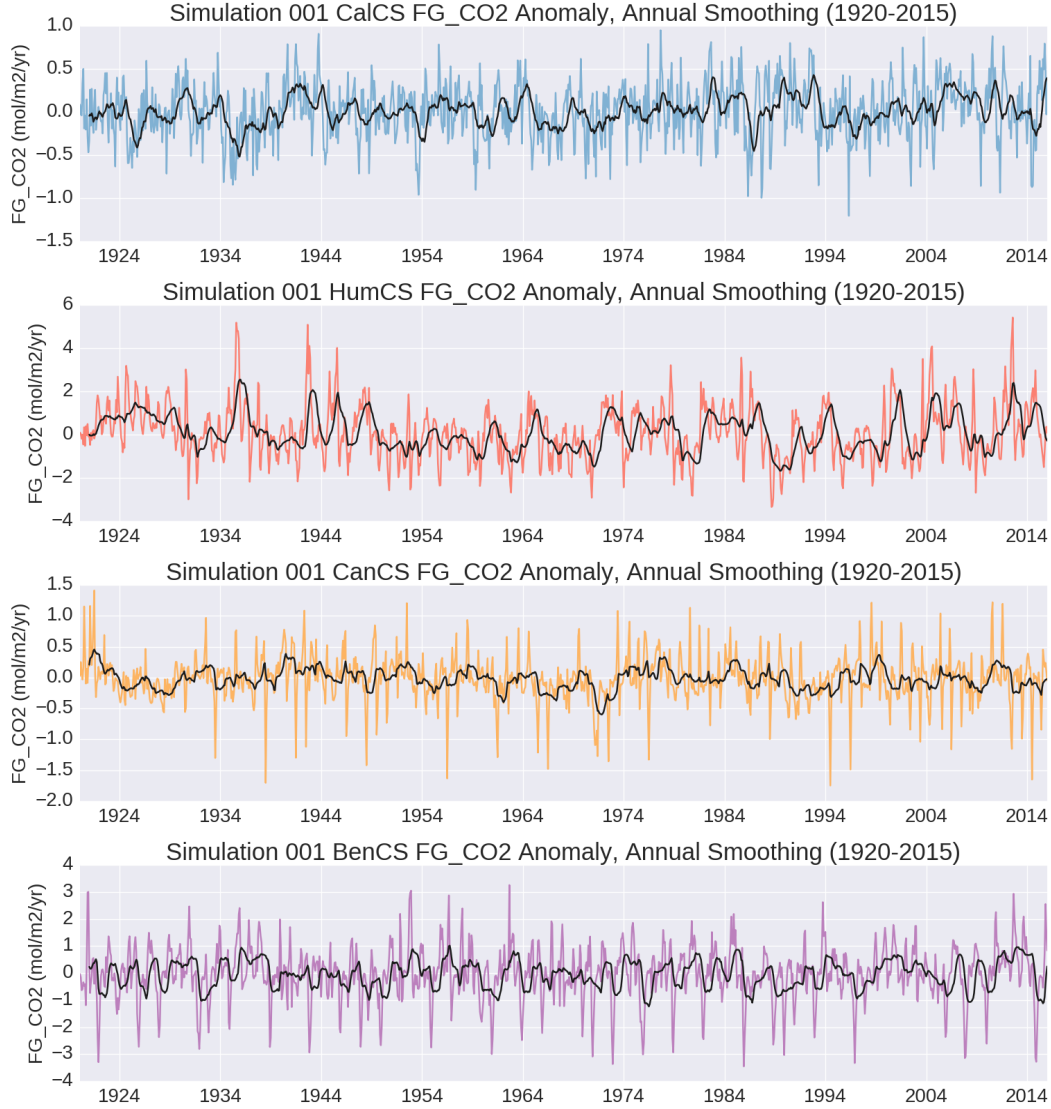


Figure 3: FGCO2 anomalies for arbitrary simulation 001 in color with their annual smoothing counterpart overlaid in black.

4 Climate Correlations

I have split the analysis into the two major ocean basins that house our four EBUS. This is because (1) it eases the viewing and interpretation of statistical tests, and (2) we might glean some similarities and differences between the two basins.

4.1 Pacific Sector

Figure 4 displays the results of using four climate indices (Nino3.4, PDO, AMO, and SAM) as predictors for CalCS and HumCS natural CO₂ fluxes over the 1920-2015 period. We find

that ENSO and PDO have the largest influence on natural CO_2 flux variability, and have inverse impacts on the two systems.

During an El Niño event, more CO_2 fluxes out of the CalCS, while more CO_2 is taken up by the HumCS. Perhaps this illuminates the dependency of CalCS FGCO_2 on SST variability, which would alter the solubility of pCO_2 ; during a warm event, low pCO_2 solubility would force carbon out of the CalCS. On the other hand, SSTs might be more stable in the more tropical HumCS, so FGCO_2 variability could be more dependent on DIC delivery from depth. During El Niño events, upwelling of high-DIC water would be suppressed, leading to an influx of carbon. These ideas can be tested by using Takahashi formulae to separate temperature-dependent pCO_2 effects from non-temperature-dependent effects. These arguments might also hold for the PDO, since it has a large impact on Pacific Ocean SST patterns. Raw values for the regression slope, r-value, and r^2 can be found in Table 1 (Nino3.4) and Table 2 (PDO).

An interesting result is that AMO has a small, but discernible correlation with CalCS CO_2 flux, but hovers around an r-value of zero for the HumCS. Perhaps atmospheric teleconnections between the North Atlantic and North Pacific play a role here.

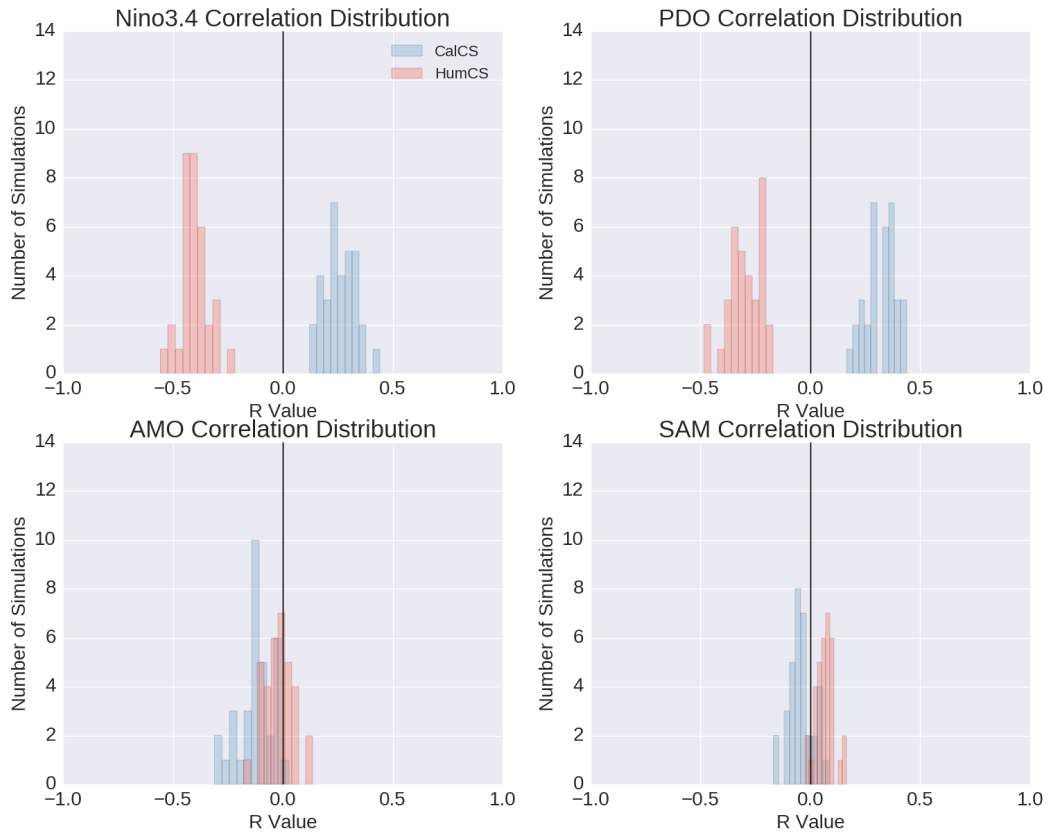


Figure 4: *R* values for annually smoothed FGCO2 anomalies in the CalCS and HumCS compared to four major climate indices. Correlations with $p > 0.05$ were not included.

Table 1: Results for regressing FGCO2 anomalies onto Nino3.4 time series for the two Pacific upwelling systems. Results with $p > 0.05$ are excluded.

Simulation	CalCS			HumCS		
	Slope ^a	R	R ²	Slope ^a	R	R ²
001	0.04	0.30	0.09	-0.20	-0.29	0.08
002	0.06	0.33	0.11	-0.31	-0.35	0.12
009	0.03	0.18	0.03	-0.24	-0.31	0.10
010	0.04	0.22	0.05	-0.33	-0.44	0.19
011	-	-	-	-0.28	-0.39	0.15
012	0.05	0.28	0.08	-0.31	-0.43	0.19
013	0.06	0.33	0.11	-0.33	-0.42	0.17
014	0.05	0.35	0.12	-0.30	-0.44	0.19
015	0.05	0.29	0.08	-0.34	-0.44	0.20
016	0.04	0.22	0.05	-0.32	-0.38	0.14
017	0.04	0.27	0.07	-0.26	-0.45	0.20
018	0.05	0.29	0.08	-0.33	-0.40	0.16
019	0.04	0.21	0.04	-0.35	-0.43	0.19
020	0.05	0.30	0.09	-0.22	-0.36	0.13
021	0.03	0.18	0.03	-0.28	-0.36	0.13
022	0.04	0.24	0.06	-0.37	-0.46	0.22
023	0.03	0.22	0.05	-0.31	-0.37	0.14
024	0.06	0.33	0.11	-0.33	-0.44	0.19
025	0.05	0.34	0.12	-0.29	-0.40	0.16
026	0.04	0.25	0.06	-0.32	-0.39	0.15
027	0.04	0.28	0.08	-0.22	-0.30	0.09
028	0.03	0.17	0.03	-0.26	-0.38	0.15
029	0.05	0.33	0.11	-0.39	-0.46	0.21
030	0.03	0.19	0.04	-0.30	-0.42	0.17
031	0.04	0.24	0.06	-0.34	-0.42	0.18
032	0.04	0.20	0.04	-0.39	-0.51	0.26
033	0.02	0.14	0.02	-0.14	-0.22	0.05
034	0.06	0.31	0.10	-0.25	-0.32	0.10
035	0.03	0.17	0.03	-0.31	-0.42	0.18
101	0.07	0.44	0.20	-0.28	-0.41	0.17
102	0.04	0.26	0.07	-0.24	-0.40	0.16
103	0.04	0.22	0.05	-0.29	-0.40	0.16
104	0.05	0.35	0.12	-0.41	-0.56	0.31
105	0.02	0.12	0.01	-0.45	-0.49	0.24
Mean	0.04	0.26	0.07	-0.30	-0.40	0.17
Std	0.01	0.07	0.04	0.06	0.06	0.05

^a mol/m²/yr/degC

Table 2: Results for regressing FGCO2 anomalies onto PDO time series for the two Pacific upwelling systems. Results with $p > 0.05$ are excluded.

Simulation	CalCS			HumCS		
	Slope ^a	R	R ²	Slope ^a	R	R ²
001	0.06	0.38	0.14	-0.23	-0.28	0.08
002	0.06	0.35	0.12	-0.20	-0.24	0.06
009	0.06	0.36	0.13	-0.17	-0.22	0.05
010	0.06	0.35	0.12	-0.27	-0.36	0.13
011	0.03	0.17	0.03	-0.29	-0.38	0.14
012	0.07	0.38	0.15	-0.20	-0.25	0.06
013	0.04	0.25	0.06	-0.22	-0.30	0.09
014	0.06	0.34	0.11	-0.25	-0.30	0.09
015	0.05	0.29	0.09	-0.17	-0.23	0.05
016	0.05	0.28	0.08	-0.18	-0.22	0.05
017	0.06	0.37	0.14	-0.23	-0.34	0.11
018	0.05	0.28	0.08	-0.14	-0.17	0.03
019	0.07	0.36	0.13	-0.26	-0.32	0.10
020	0.06	0.37	0.14	-0.26	-0.38	0.15
021	0.04	0.26	0.07	-0.27	-0.35	0.12
022	0.07	0.40	0.16	-0.29	-0.35	0.12
023	0.05	0.37	0.14	-0.16	-0.19	0.04
024	0.08	0.44	0.19	-0.26	-0.34	0.12
025	0.07	0.41	0.17	-0.25	-0.30	0.09
026	0.05	0.33	0.11	-0.17	-0.21	0.04
027	0.03	0.19	0.04	-0.24	-0.29	0.08
028	0.07	0.43	0.19	-0.20	-0.31	0.09
029	0.03	0.22	0.05	-0.26	-0.27	0.07
030	0.05	0.27	0.07	-0.17	-0.23	0.05
031	0.05	0.30	0.09	-0.24	-0.29	0.08
032	0.05	0.29	0.09	-0.35	-0.48	0.23
033	0.05	0.34	0.11	-0.15	-0.21	0.04
034	0.04	0.23	0.05	-0.16	-0.21	0.04
035	0.04	0.23	0.05	-0.17	-0.23	0.05
101	0.05	0.29	0.08	-0.27	-0.35	0.12
102	0.07	0.39	0.15	-0.28	-0.39	0.15
103	0.06	0.34	0.11	-0.25	-0.35	0.12
104	0.06	0.39	0.15	-0.42	-0.48	0.23
105	0.05	0.30	0.09	-0.24	-0.26	0.07
Mean	0.05	0.32	0.11	-0.23	-0.30	0.09
Std	0.01	0.07	0.04	0.06	0.08	0.05

^a mol/m²/yr/degC

4.2 Atlantic Sector

Figure 5 displays distributions of correlation tests between FGCO₂ anomalies in the two Atlantic Ocean EBUS (Canary and Benguela) and the same four climate indices. At first glance, the results are much weaker than that of the Pacific systems. I find it surprising that the SAM has virtually no impact on the BenCS, when it is the only EBUS that interfaces directly with the Southern Ocean.

Interestingly, CanCS gas flux has a reasonable relationship with ENSO and the PDO. As much as 15% of FGCO₂ variability in the CanCS can be explained by ENSO in some simulations (Table 3). We find a similar situation with regards to the PDO (Table 4). There is a slight relationship between FGCO₂ anomalies in the CanCS and the AMO, but it isn't even as strong as the correlation with ENSO and PDO. Overall, the BenCS is not well-explained by any major climate index.

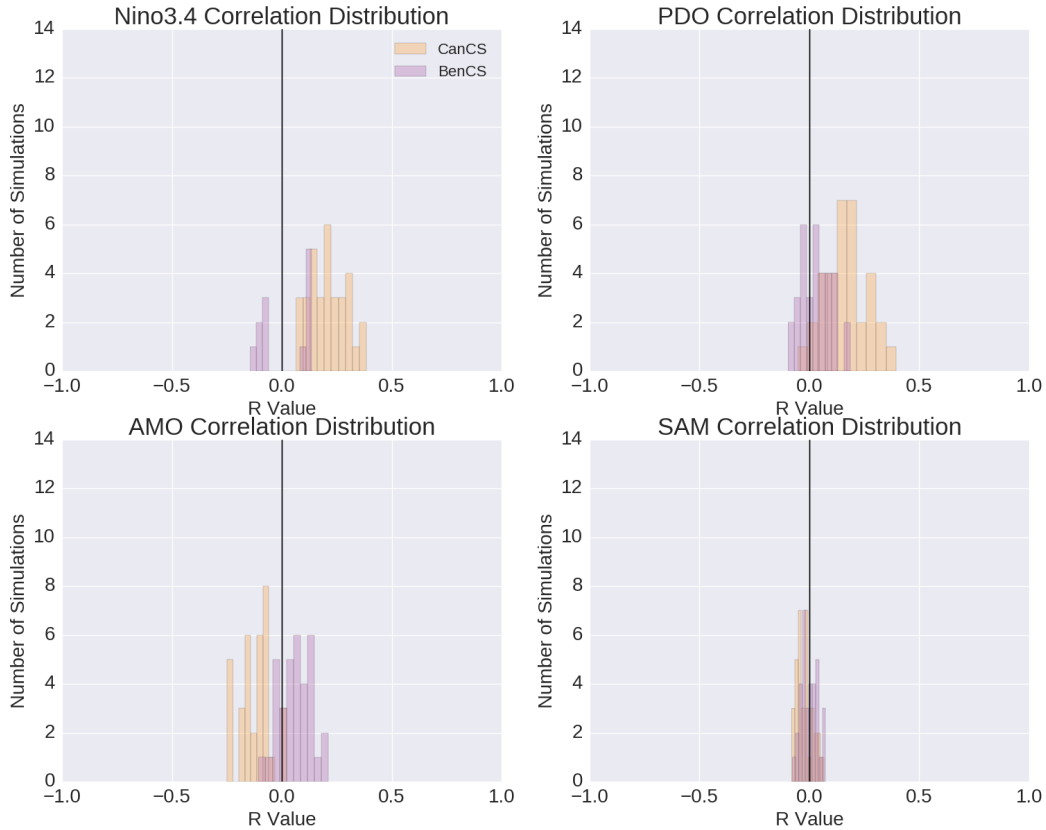


Figure 5: *R* values for annually smoothed FGCO₂ anomalies in the CalCS and HumCS compared to four major climate indices. Correlations with $p > 0.05$ were not included.

Table 3: Results for regressing FGCO2 anomalies onto ENSO time series for the two Atlantic upwelling systems. Results with $p > 0.05$ are excluded.

Simulation	CanCS			BenCS		
	Slope ^a	R	R ²	Slope ^a	R	R ²
001	0.04	0.28	0.08	-	-	-
002	0.06	0.31	0.10	-	-	-
009	0.03	0.18	0.03	-	-	-
010	0.05	0.29	0.08	-	-	-
011	0.04	0.25	0.06	0.05	0.13	0.02
012	0.04	0.28	0.08	-0.05	-0.11	0.01
013	0.04	0.22	0.05	-	-	-
014	0.05	0.34	0.12	-	-	-
015	0.03	0.16	0.03	-	-	-
016	0.02	0.10	0.01	-	-	-
017	0.05	0.38	0.15	-	-	-
018	0.03	0.17	0.03	-0.07	-0.14	0.02
019	0.02	0.11	0.01	0.04	0.09	0.01
020	0.05	0.32	0.10	-	-	-
021	0.02	0.12	0.01	-	-	-
022	0.02	0.15	0.02	0.06	0.12	0.01
023	0.04	0.22	0.05	-	-	-
024	0.04	0.25	0.06	0.06	0.13	0.02
025	0.01	0.08	0.01	-	-	-
026	0.05	0.27	0.07	-0.04	-0.09	0.01
027	0.03	0.20	0.04	0.07	0.14	0.02
028	0.01	0.07	0.00	0.06	0.13	0.02
029	0.05	0.31	0.10	-	-	-
031	0.02	0.15	0.02	-	-	-
032	0.03	0.15	0.02	-	-	-
033	0.03	0.21	0.04	-0.03	-0.08	0.01
034	0.03	0.17	0.03	-0.05	-0.11	0.01
035	0.01	0.07	0.00	-0.03	-0.07	0.00
101	0.03	0.22	0.05	-	-	-
102	0.03	0.19	0.04	-	-	-
103	0.07	0.39	0.15	-	-	-
104	0.03	0.23	0.05	-	-	-
105	0.02	0.13	0.02	-	-	-
Mean	0.03	0.21	0.05	0.01	0.01	0.01
Std	0.01	0.09	0.04	0.05	0.11	0.01

^a mol/m²/yr/degC

Table 4: Results for regressing FGCO2 anomalies onto PDO time series for the two Atlantic upwelling systems. Results with $p > 0.05$ are excluded.

Simulation	CanCS			BenCS		
	Slope ^a	R	R ²	Slope ^a	R	R ²
001	0.05	0.30	0.09	-0.01	-0.02	0.00
002	0.07	0.39	0.15	-0.00	-0.00	0.00
009	0.02	0.11	0.01	-0.03	-0.05	0.00
010	0.05	0.28	0.08	-0.01	-0.01	0.00
011	0.03	0.17	0.03	0.01	0.02	0.00
012	0.02	0.11	0.01	0.02	0.04	0.00
013	0.03	0.21	0.04	0.02	0.03	0.00
014	0.05	0.27	0.07	-0.02	-0.04	0.00
015	0.02	0.11	0.01	0.03	0.07	0.01
016	0.02	0.14	0.02	0.04	0.07	0.01
017	0.04	0.22	0.05	-0.02	-0.05	0.00
018	0.01	0.08	0.01	-0.01	-0.01	0.00
019	0.01	0.06	0.00	0.09	0.19	0.03
020	0.02	0.13	0.02	-0.00	-0.01	0.00
021	0.01	0.06	0.00	0.06	0.13	0.02
022	0.03	0.16	0.03	0.09	0.18	0.03
023	-0.01	-0.05	0.00	-0.01	-0.02	0.00
024	0.02	0.11	0.01	0.04	0.08	0.01
025	0.03	0.17	0.03	-0.04	-0.08	0.01
026	0.02	0.13	0.02	0.02	0.05	0.00
027	0.03	0.19	0.03	0.06	0.10	0.01
028	0.02	0.13	0.02	0.05	0.11	0.01
029	0.06	0.33	0.11	0.06	0.12	0.01
030	0.01	0.05	0.00	0.05	0.10	0.01
031	0.00	0.02	0.00	-0.01	-0.02	0.00
032	0.03	0.20	0.04	-0.03	-0.06	0.00
033	0.03	0.22	0.05	0.01	0.02	0.00
034	0.03	0.14	0.02	-0.05	-0.10	0.01
035	0.02	0.15	0.02	0.02	0.04	0.00
101	0.01	0.04	0.00	0.03	0.05	0.00
102	0.03	0.19	0.03	0.00	0.01	0.00
103	0.05	0.31	0.09	0.06	0.12	0.01
104	0.04	0.27	0.07	0.02	0.03	0.00
105	0.03	0.19	0.04	0.02	0.05	0.00
Mean	0.03	0.16	0.04	0.02	0.03	0.01
Std	0.02	0.09	0.04	0.03	0.07	0.01

^a mol/m²/yr/degC

5 Cross Correlation

Perhaps we are underestimating the strength of relationship between some climate indices and EBU CO₂ flux, as we are not lagging/leading the correlations properly. Due to the physical mechanisms behind ENSO, there might be a sort of lag between a strong El Niño and an anomalous gas flux. Since we are trying to understand controls on CO₂ flux variability, it probably only makes sense to look at situations where the climate index leads the gas flux anomalies.

Figure 6 shows little consistency in enhanced correlations at any lead/lag. I would argue that there is little sense in correlating anything but lag zero in the case of CalCS and Nino3.4. However, turning our attention to the HumCS, we find a strong case to compute a lag correlation for ENSO, rather than a standard lag zero correlation (Figure 7). In 100% of the simulations, the correlation is stronger when leading FGCO2 anomalies by 4-5 months with the Nino3.4 index.

Table 5 displays the results of a regression analysis between HumCS FGCO2 anomalies and the Nino3.4 index with a 5-month lead. Without the lead, a 1 degree C El Niño event would explain 17% of the FGCO2 variability on average ($r = -0.40$) (Table 1). After applying a 5-month lead time to the Nino3.4 index, we find the same El Niño event would explain 26% of the FGCO2 variability ($r = -0.51$) (Table 5)). Across all systems and the four major climate index predictors, there is really only a strong argument to lead HumCS FGCO2 anomalies by a few months with ENSO.

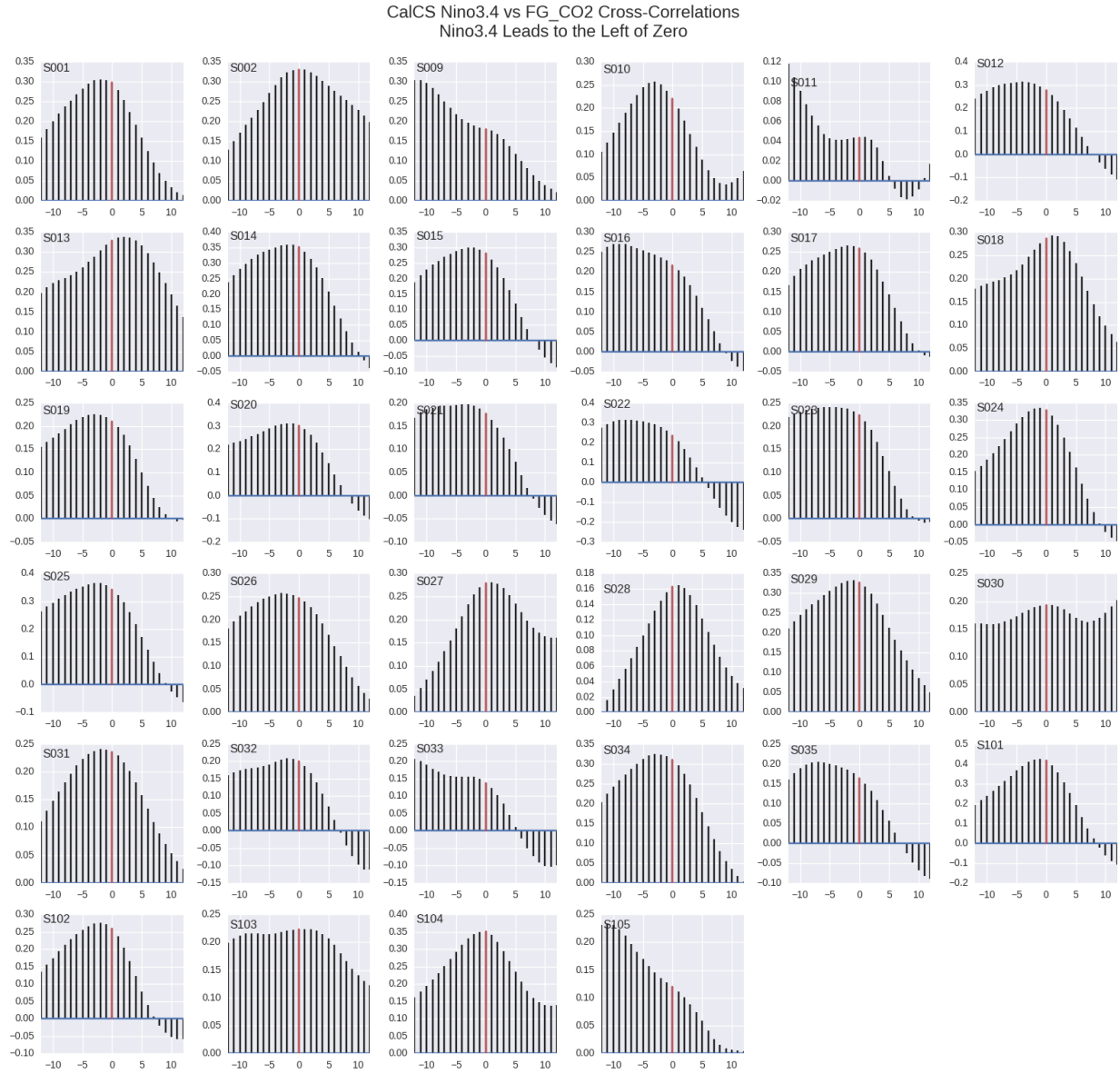


Figure 6: Cross correlations between CalCS FGCO2 and the Nino3.4 index. Negative values indicate ENSO leading FGCO2 in months. The red bar indicates no lag for reference.

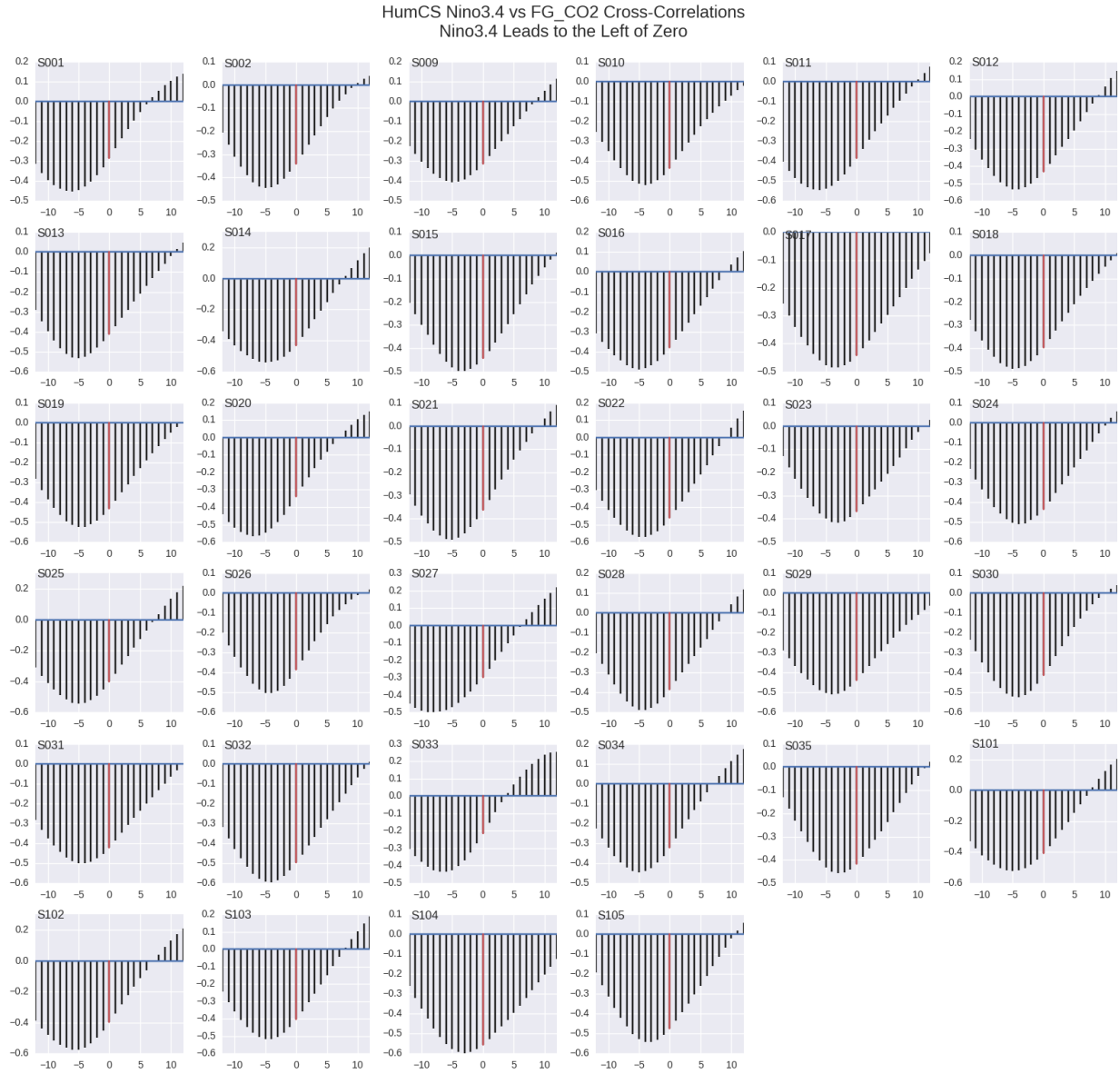


Figure 7: Cross correlations between HumCS FGCO2 and the Nino3.4 index. Negative values indicate ENSO leading FGCO2 in months. The red bar indicates no lag for reference.

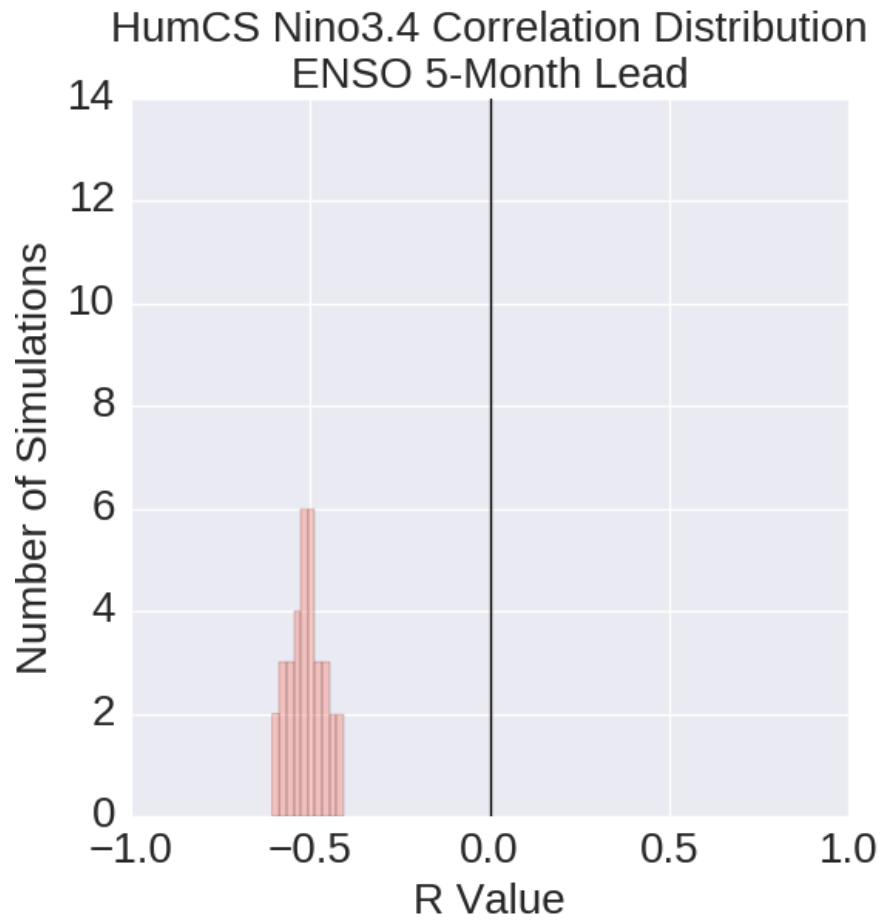


Figure 8: Distribution of r values for a correlation between HumCS FGCO₂ anomalies and the Nino3.4 index with a 5-month lead time.

Table 5: Results for regressing HumCS FGCO2 anomalies onto Nino3.4 time series with a 5-month lead. Results with $p > 0.05$ are excluded.

Simulation	Slope ^a	R	R ²
0	-0.31	-0.45	0.20
1	-0.41	-0.46	0.21
2	-0.31	-0.41	0.17
3	-0.40	-0.52	0.27
4	-0.40	-0.55	0.30
5	-0.39	-0.54	0.29
6	-0.43	-0.54	0.29
7	-0.38	-0.56	0.31
8	-0.38	-0.49	0.24
9	-0.41	-0.49	0.24
10	-0.28	-0.48	0.23
11	-0.41	-0.49	0.24
12	-0.43	-0.53	0.28
13	-0.35	-0.58	0.34
14	-0.38	-0.49	0.24
15	-0.45	-0.57	0.33
16	-0.34	-0.41	0.17
17	-0.38	-0.51	0.26
18	-0.40	-0.55	0.30
19	-0.41	-0.50	0.25
20	-0.35	-0.47	0.22
21	-0.33	-0.49	0.24
22	-0.45	-0.52	0.27
23	-0.37	-0.52	0.27
24	-0.41	-0.50	0.25
25	-0.46	-0.61	0.37
26	-0.29	-0.43	0.19
27	-0.34	-0.45	0.20
28	-0.32	-0.43	0.19
29	-0.36	-0.53	0.28
30	-0.35	-0.58	0.34
31	-0.37	-0.52	0.27
32	-0.44	-0.59	0.34
33	-0.50	-0.55	0.30
Mean	-0.38	-0.51	0.26
Std	0.05	0.05	0.05

^a mol/m²/yr/degC

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