

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 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).

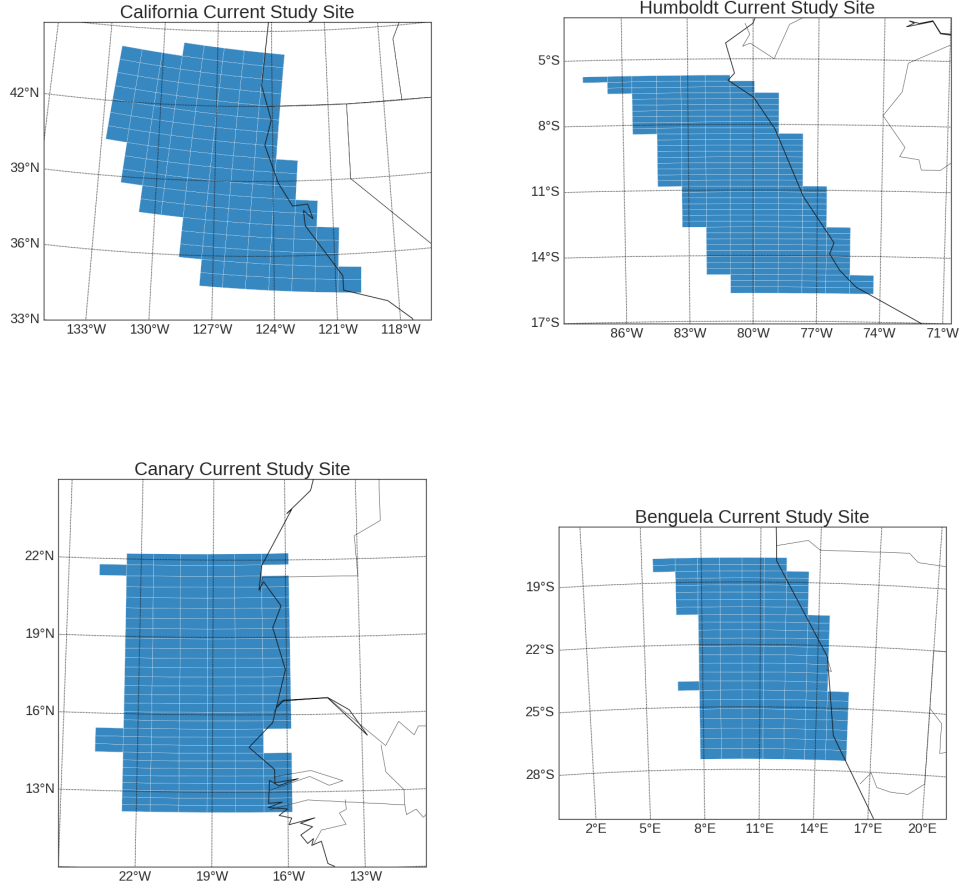


Figure 1: Nearshore regions for each EBUS over which area-weighted FGCO₂ is computed. The latitude is constrained by the 10 degree bounds of most active upwelling (per Chavez and Messié [2009]). The longitude is constrained to 800km offshore to standardize region sizes across different latitudes.

2 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 2, 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.

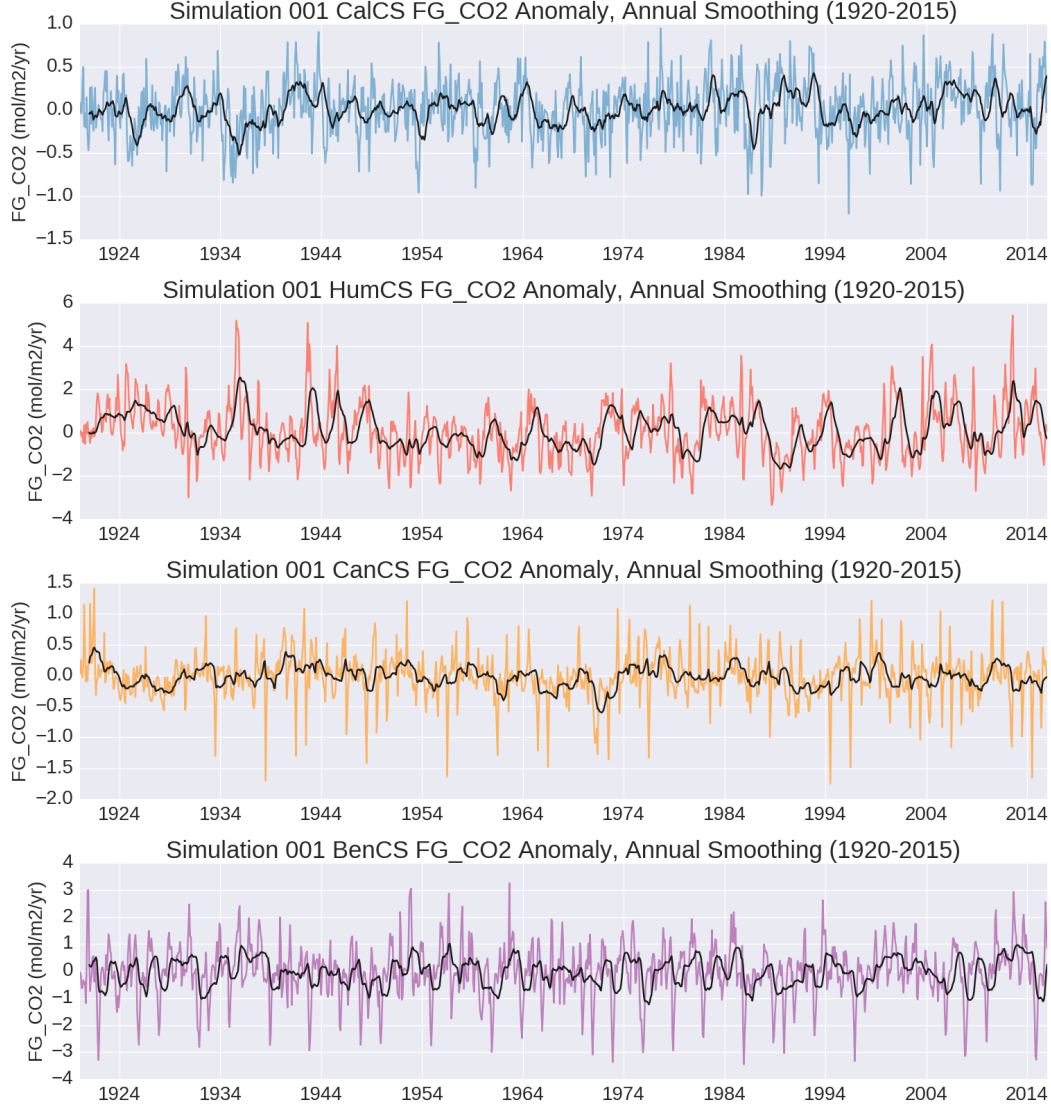


Figure 2: $FGCO_2$ anomalies for arbitrary simulation 001 in color with their annual smoothing counterpart overlaid in black.

3 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.

3.1 Pacific Sector

Figure 3 displays the results of using four climate indices (Nino3.4, PDO, AMO, and SAM) as predictors for CalCS and HumCS natural CO_2 fluxes over the 1920-2015 period. We find

that ENSO and PDO have the largest influence on natural CO₂ flux variability, and have inverse impacts on the two systems.

During an El Niño event, more CO₂ fluxes out of the CalCS, while more CO₂ is taken up by the HumCS. Perhaps this illuminates the dependency of CalCS FGCO₂ on SST variability, which would alter the solubility of pCO₂; during a warm event, low pCO₂ solubility would force carbon out of the CalCS. On the other hand, SSTs might be more stable in the more tropical HumCS, so FGCO₂ 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 pCO₂ 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 r² 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 CO₂ 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.

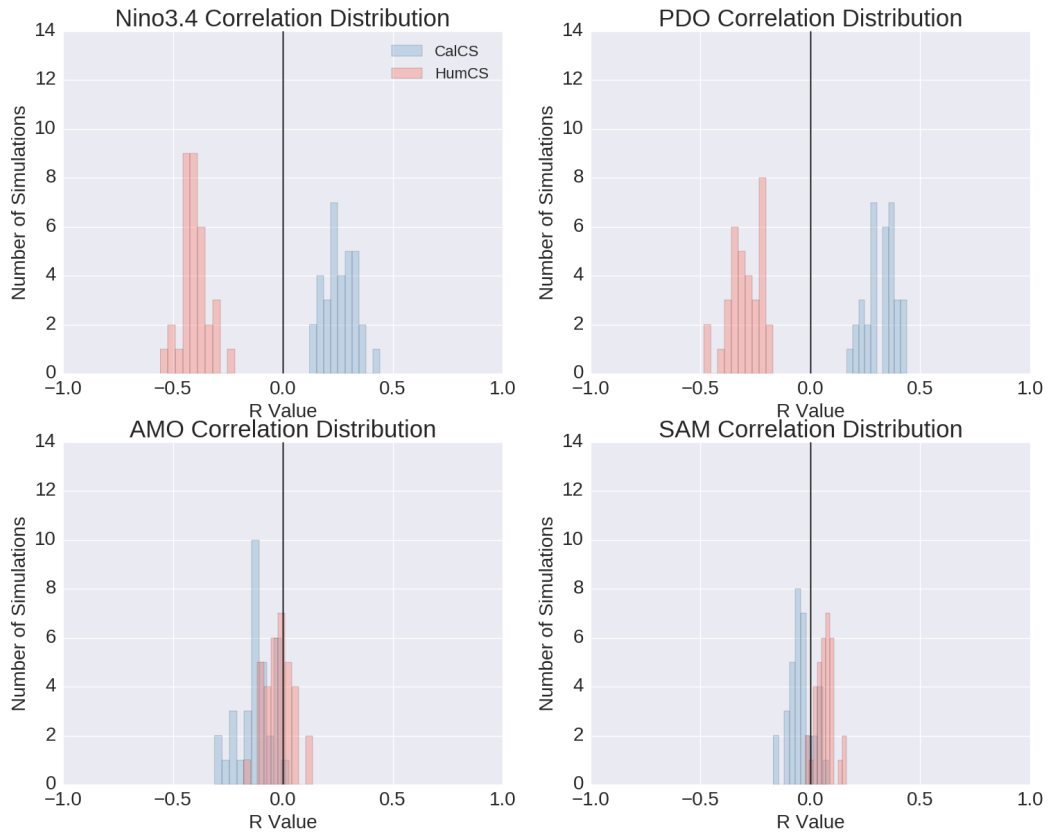


Figure 3: *R* values for annually smoothed FGCO2 anomalies in the CalCS and HumCS compared to four major climate indices. Correlations with $p > 0.05$ were not included.

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

3.2 Atlantic Sector

Figure 4 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.

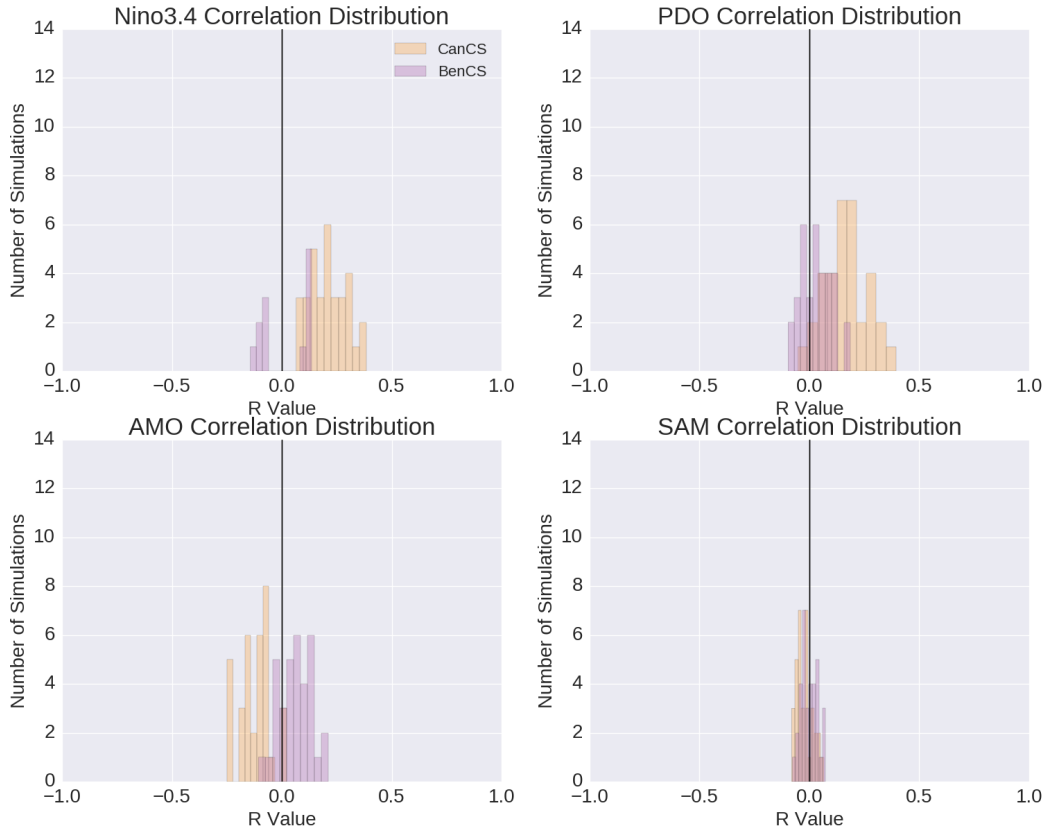


Figure 4: *R* values for annually smoothed FGCO₂ anomalies in the CalCS and HumCS compared to four major climate indices. Correlations with $p > 0.05$ were not included.

Table 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

4 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.

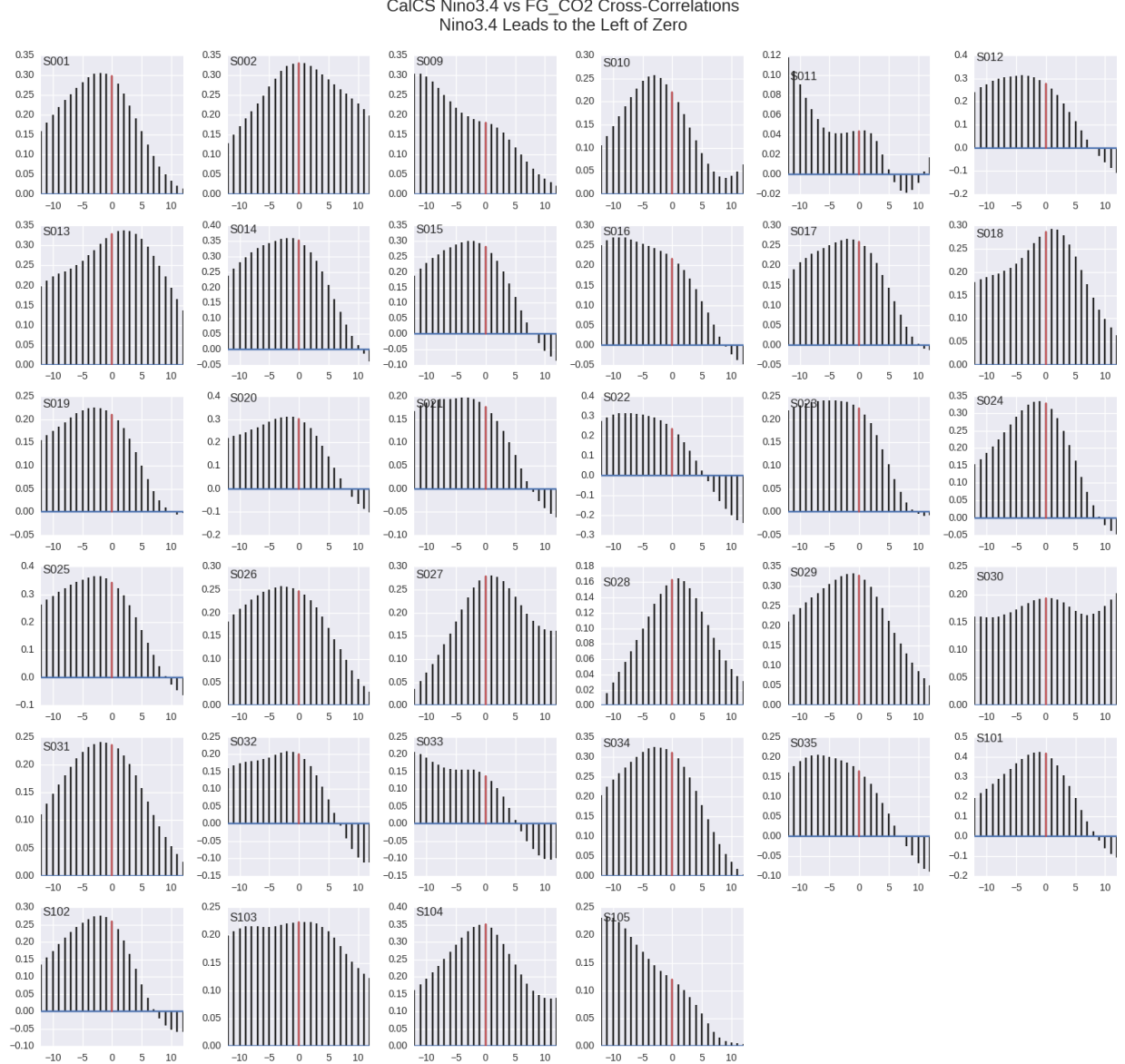


Figure 5: R values for annually smoothed FGCO2 anomalies in the CalCS and HumCS compared to four major climate indices. Correlations with $p > 0.05$ were not included.

References

- Francisco P Chavez and Monique Messié. A comparison of eastern boundary upwelling ecosystems. *Progress in Oceanography*, 83(1):80–96, 2009.
- G. Turi, Z. Lachkar, and N. Gruber. Spatiotemporal variability and drivers of pCO_2 and air-sea CO_2 fluxes in the california current system: an eddy-resolving modeling study. *Biogeosciences*, 11(3):671–690, 2014. doi: 10.5194/bg-11-671-2014. URL <http://www.biogeosciences.net/11/671/2014/>.