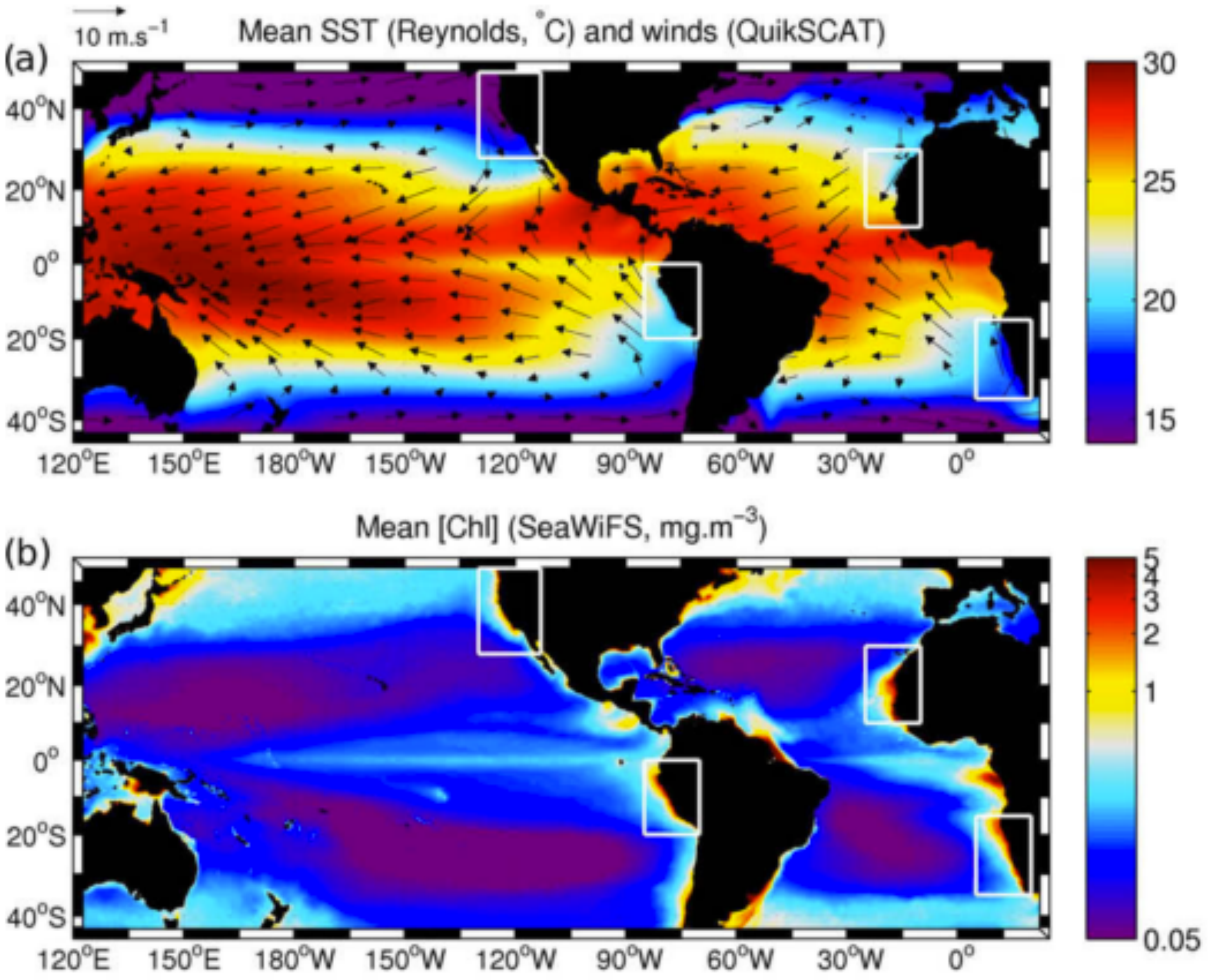
CO_2 Flux Variability in Eastern Boundary Upwelling Systems

Eastern Boundary Upwelling Systems are highly productive regions characterized by wind-driven surface divergence and subsequent upwelling of nutrient-rich waters.



Chavez & Messié 2009

Question: What natural factors control historical variability in CO_2 flux in eastern boundary upwelling systems?

CO_2 flux is complex and is driven by a myriad of factors, involving ocean state, circulation, biology, and chemistry.

$$F_{CO2} = k \cdot S_{CO2} \cdot \Delta pCO_2$$

"Piston Velocity"

- Temperature
- Salinity
- 10m Wind Speed

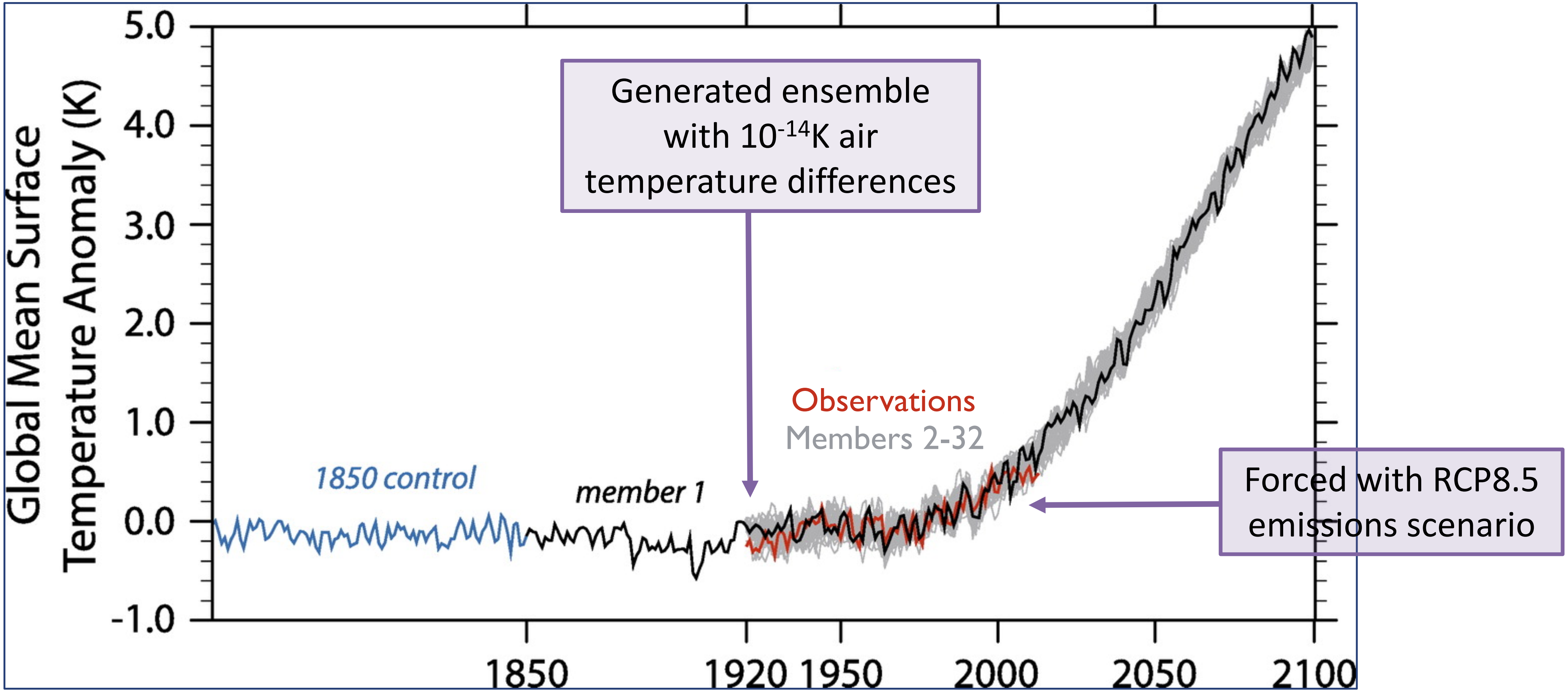
CO_2 Solubility

- Temperature
- Salinity

pCO_2 Anomaly

- Temperature
- Salinity
- DIC
- Alkalinity

The CESM-LENS generates an ensemble of independent climate simulations, which each have a unique representation of internal climate variability.



Modified from Kay et al. 2015

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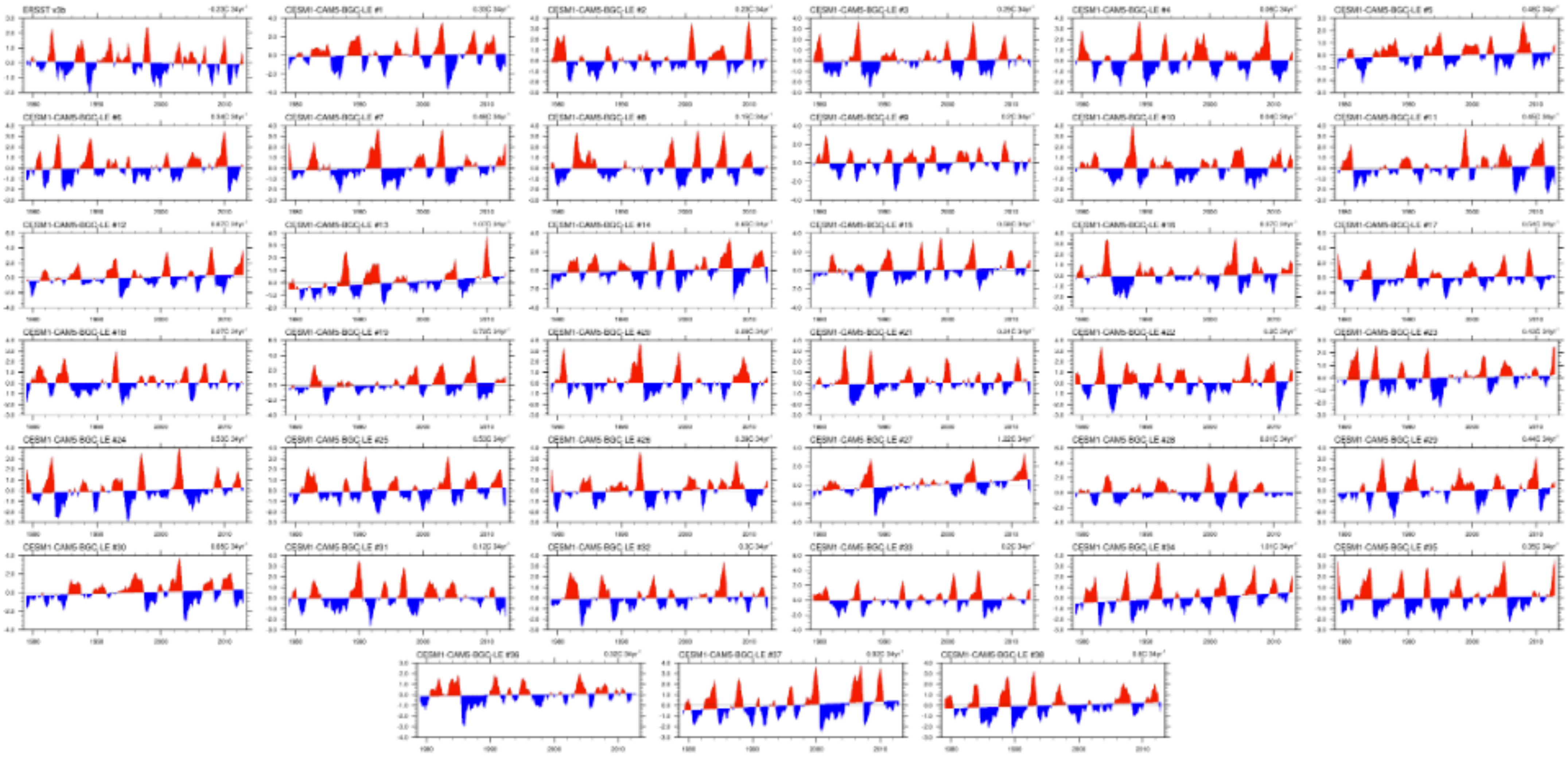
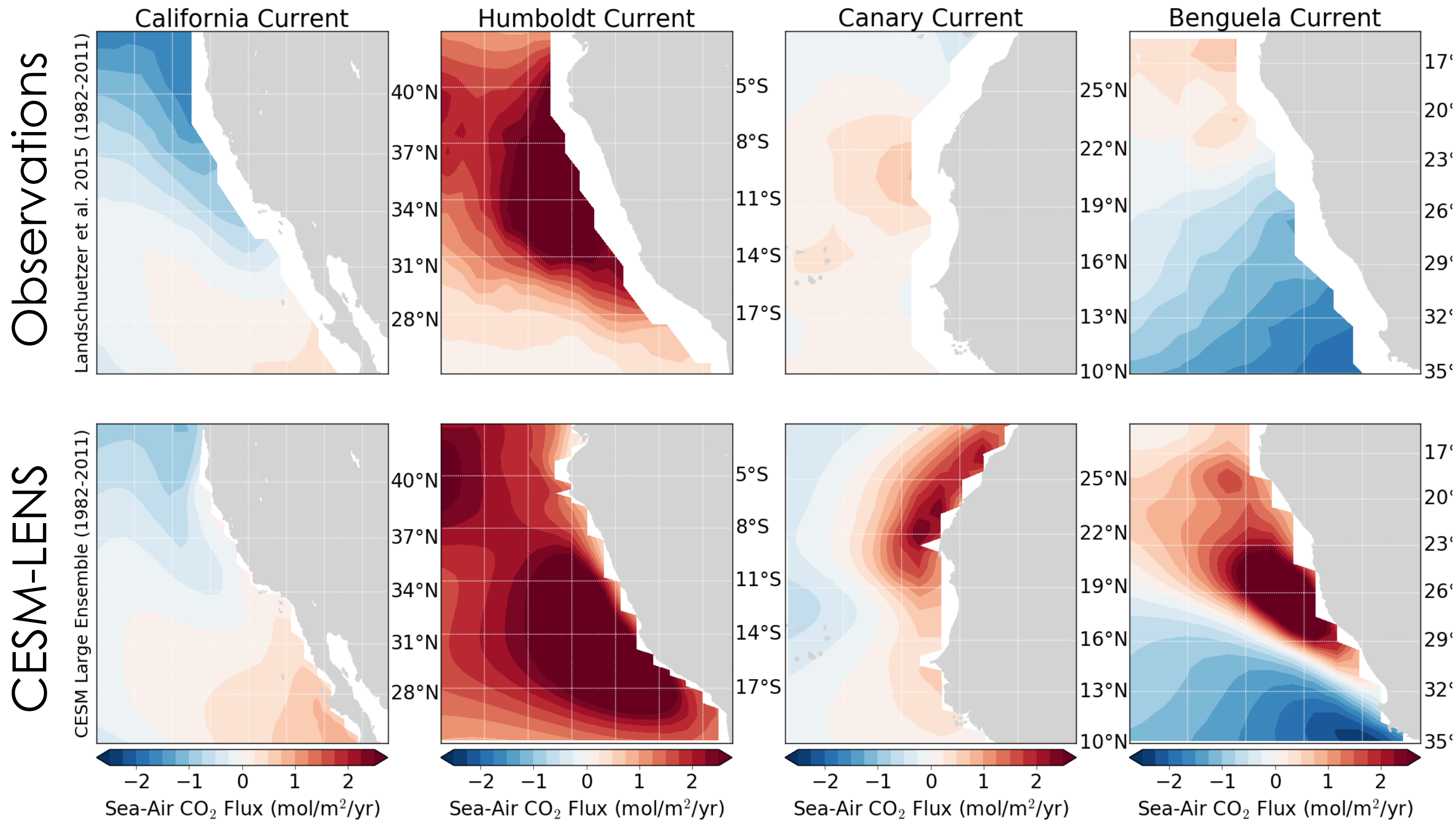
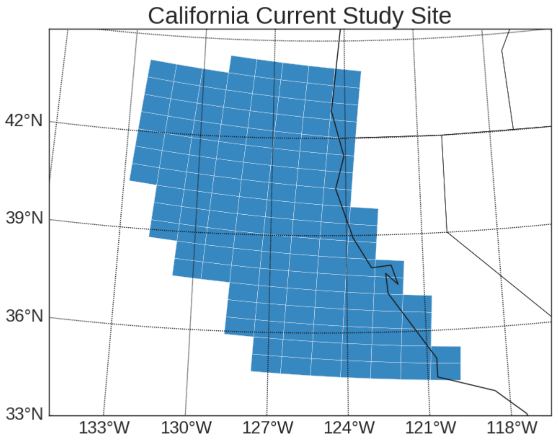


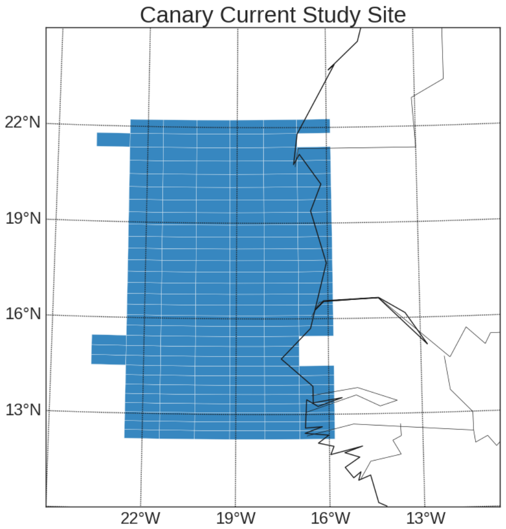
Courtesy of Adam Phillips

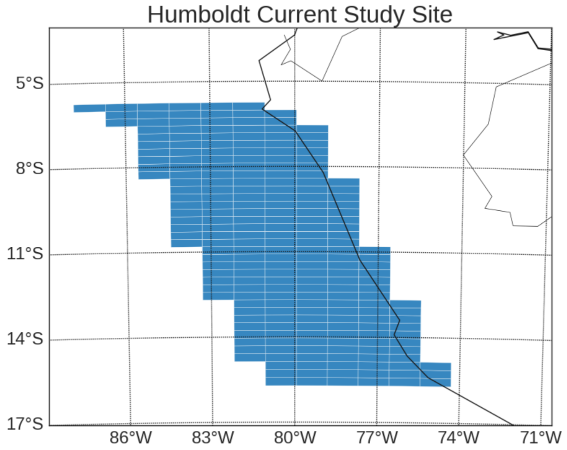
The CESM-LENS captures general characteristics of historical CO_2 flux in EBUS.

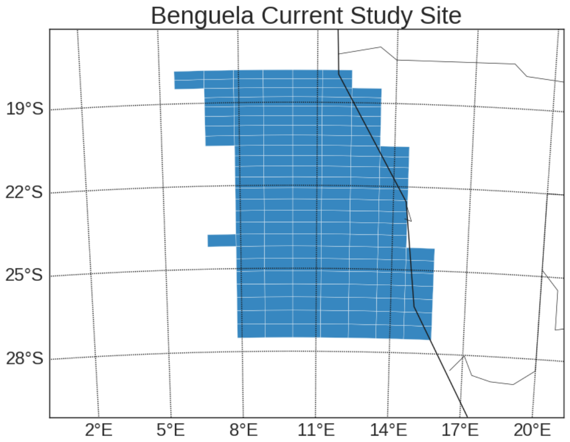


Our study sites are standardized across the ten degrees latitude of most active historical upwelling and confined to 800km offshore.

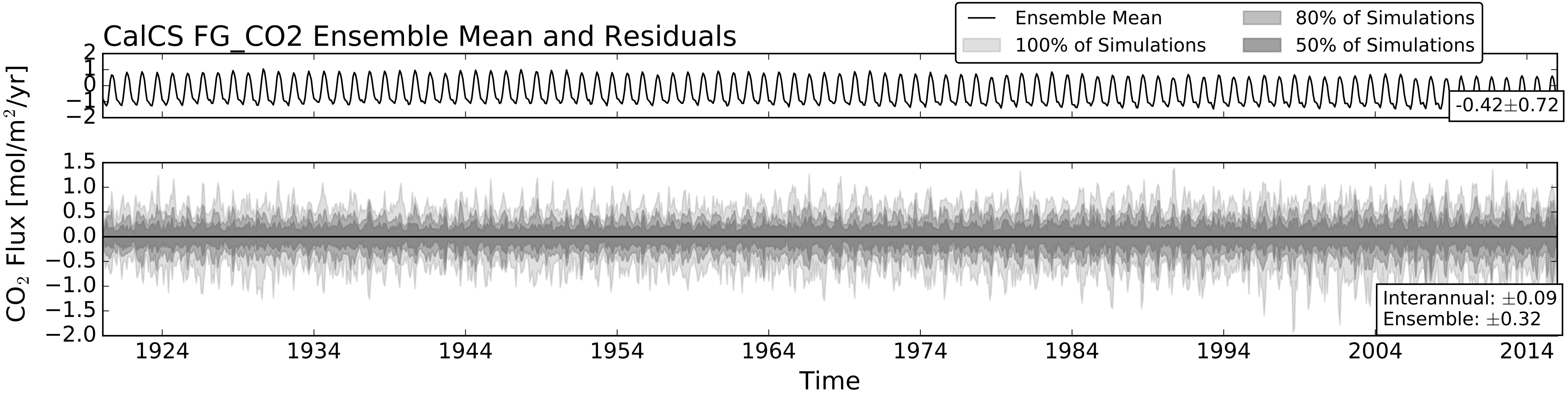




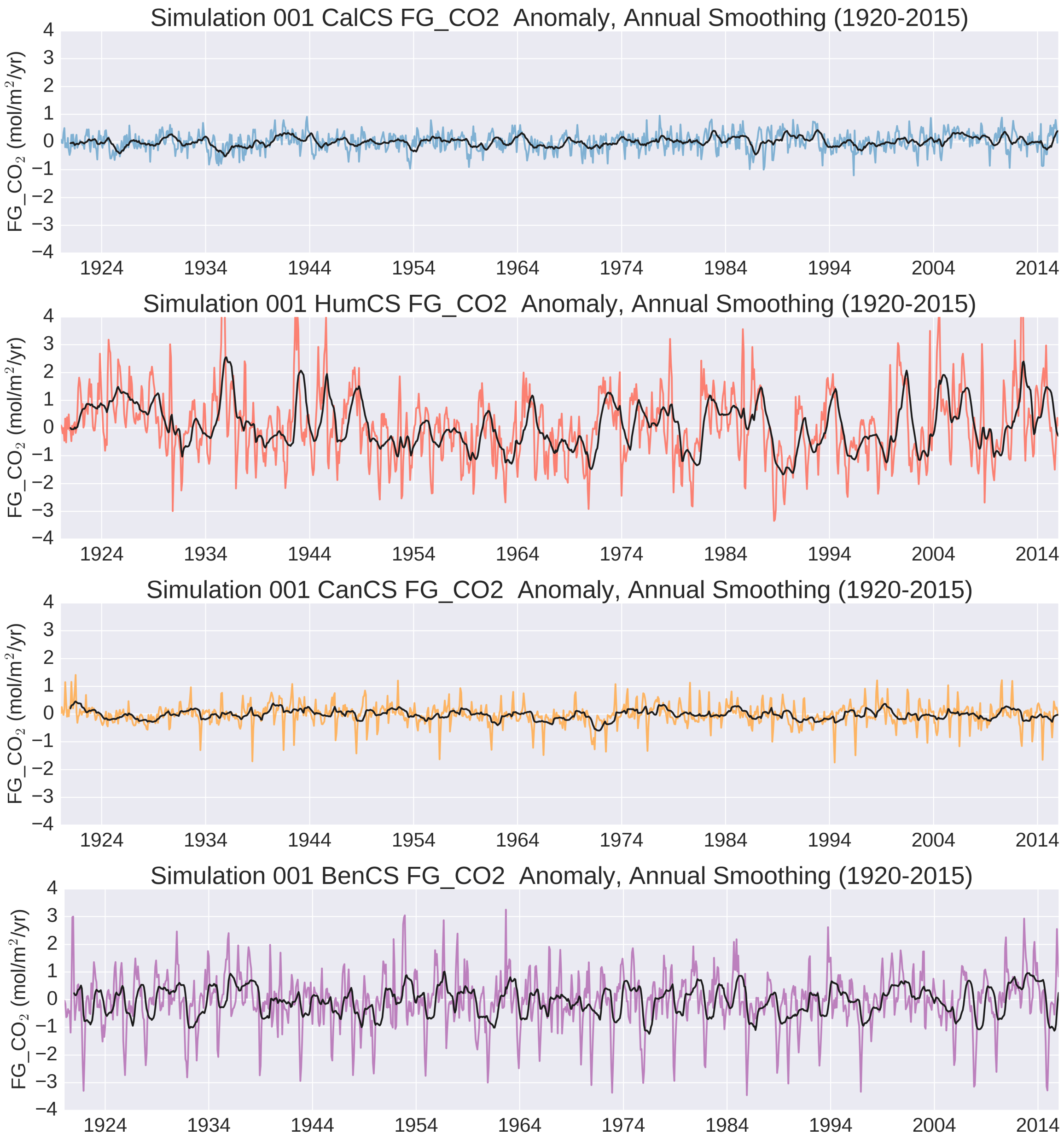




The CESM-LENS allows us to confidently remove the seasonal and forced signal from every ensemble member.

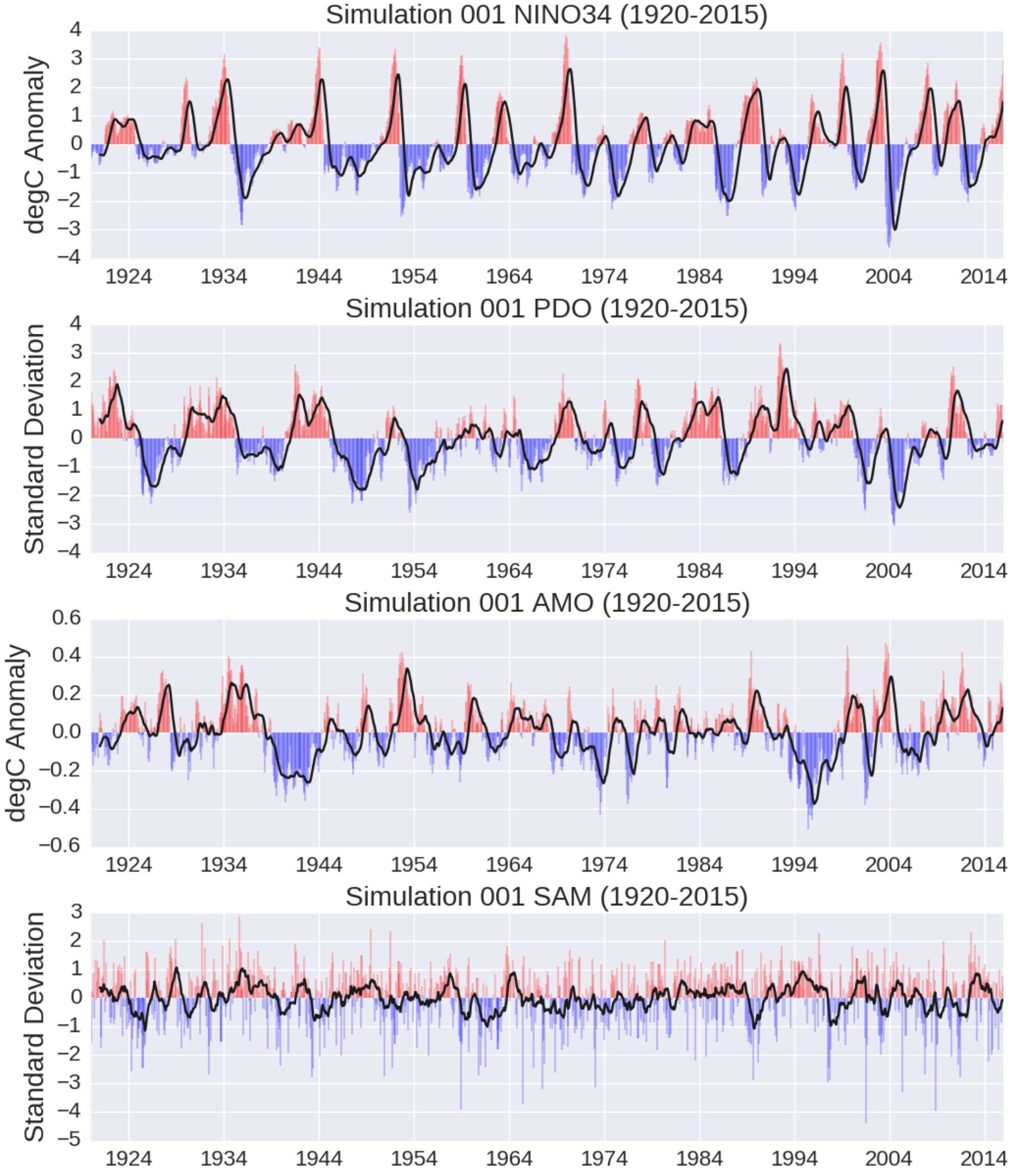


We apply a 12-month moving average to the area-weighted mean residuals of each region.



Correlate to:
Nino3.4
PDO
AMO
SAM

These area-weighted smoothed means are correlated with four major climate indices.

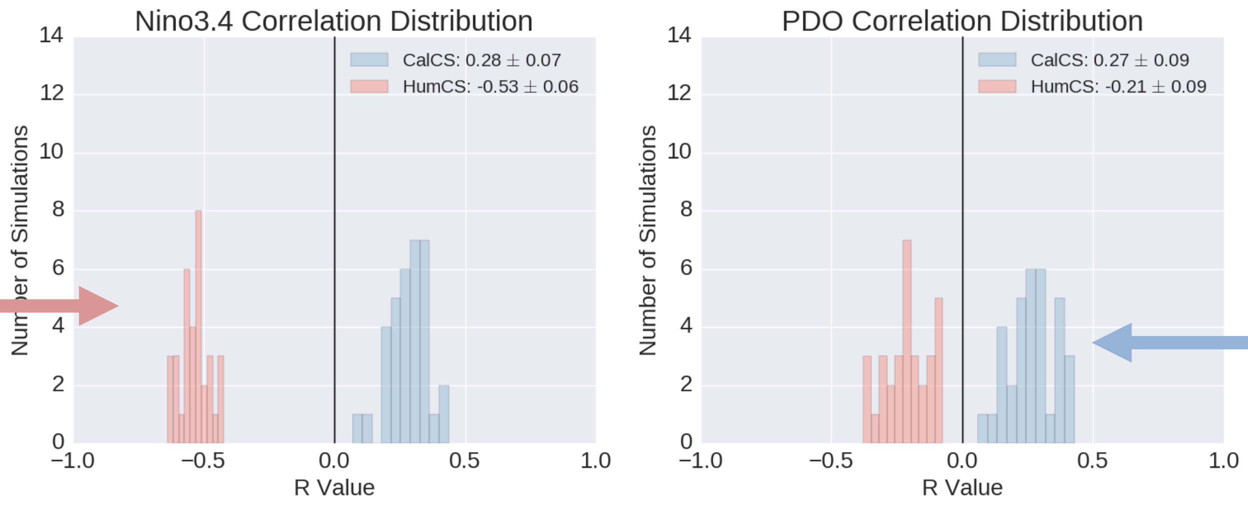


Section 1: Detecting climate indices that have the strongest influence on CO_2 flux anomalies

Pacific ocean upwelling systems are mainly controlled by ENSO and PDO, which have opposing impacts on flux anomalies.

Sea-Air CO_2 Flux Anomaly Correlations

Anomalous **uptake** in a climatological outgassing site.



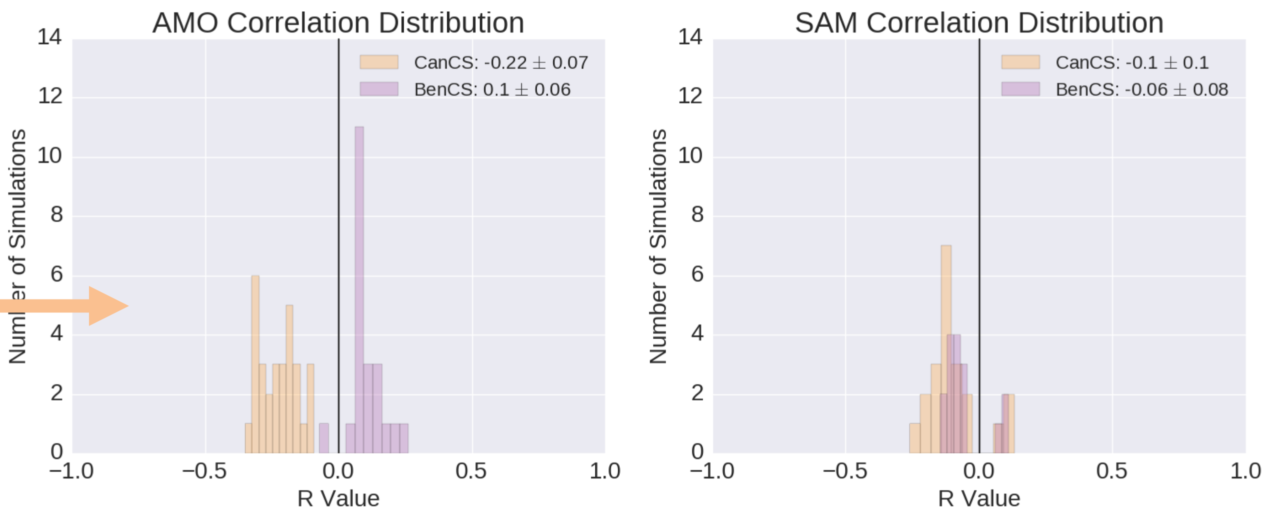
Anomalous **outgassing** in a climatological uptake site.

Hypothesis: The CalCS is a solubility-driven system, while the HumCS is a circulation-driven system.

The Canary Current is best explained by AMO, while the Benguela Current is not well-correlated with any major climate index.

Sea-Air CO_2 Flux Anomaly Correlations

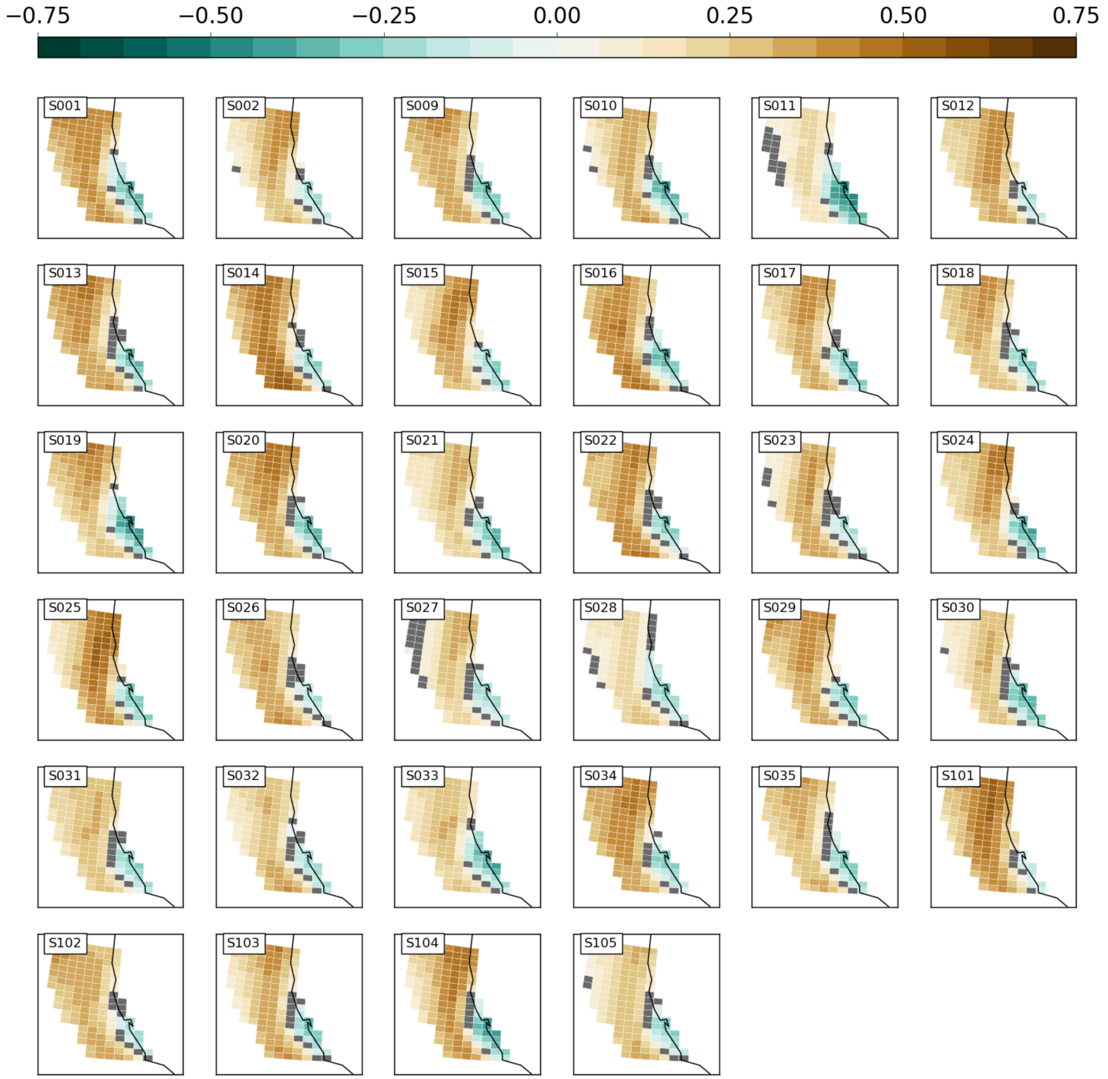
Anomalous **uptake** in a climatological outgassing site.



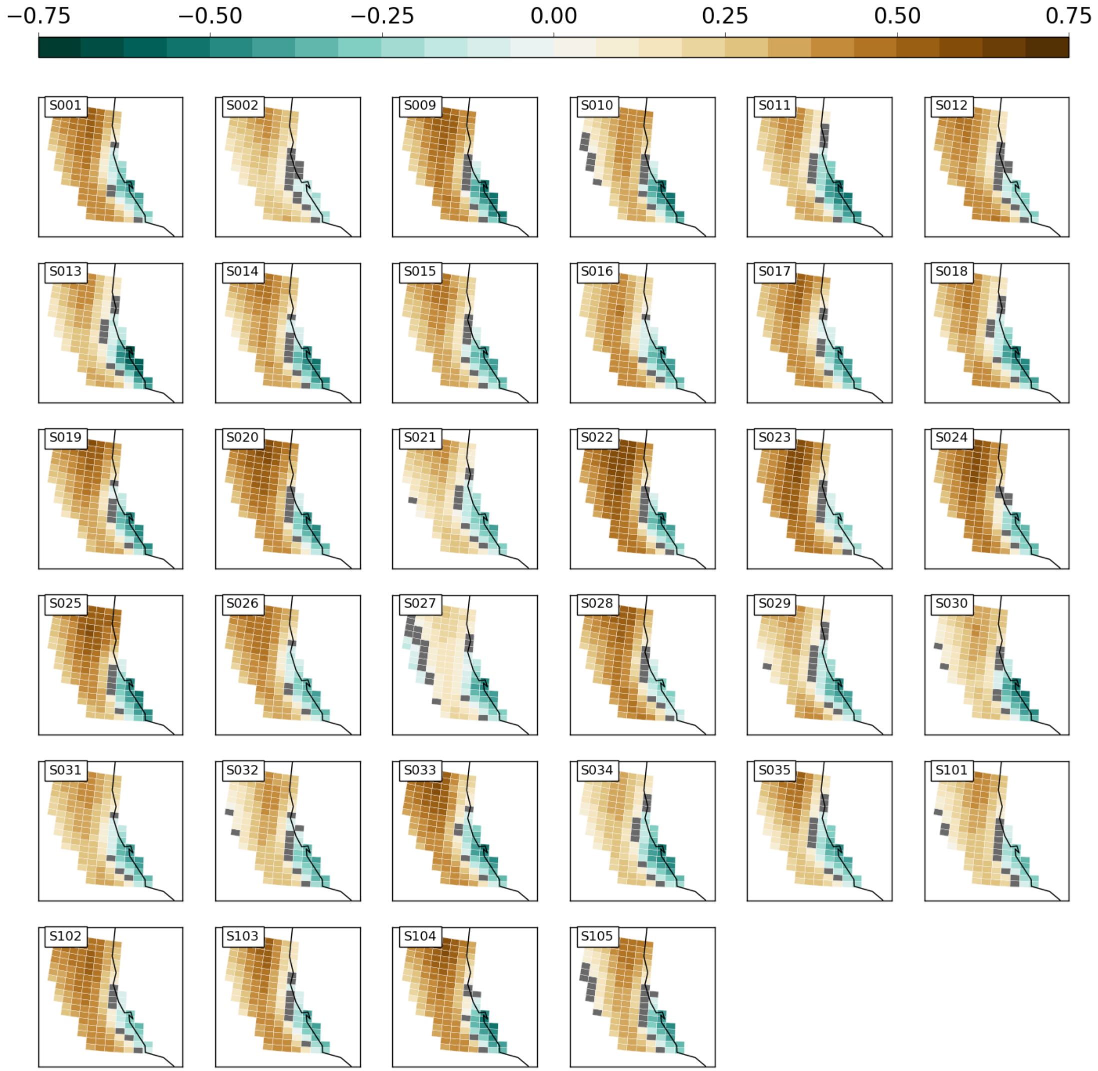
Hypothesis: The CanCS is also a circulation-driven system. The BenCS ???

The California Current exhibits finer spatial structure in its relationship between CO_2 flux anomalies and ENSO and PDO.

Sea-Air CO_2 Flux Anomaly Correlations with Nino3.4

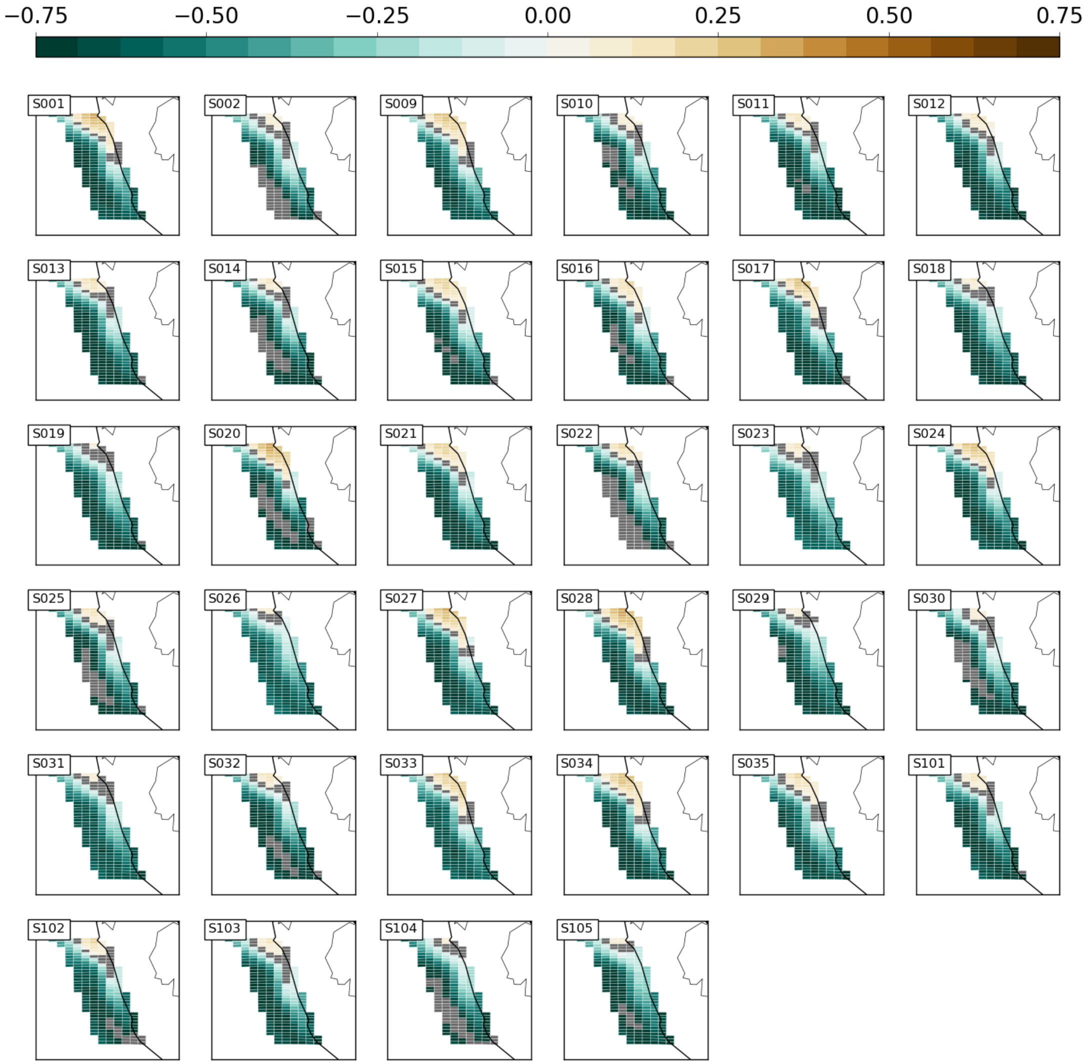


Sea-Air CO_2 Flux Anomaly Correlations with PDO



This spatial dipole is not characterized by every system.

Sea-Air CO_2 Flux Anomaly Correlations with Nino3.4



Sea-Air CO_2 Flux Anomaly Correlations with AMO

CO_2 Flux Summary

CO_2 flux variability in the Pacific upwelling systems is better explained by climate indices than the Atlantic systems.

The CalCS appears to be most sensitive to changes in solubility. The warming effect of ENSO leads to anomalous outgassing.

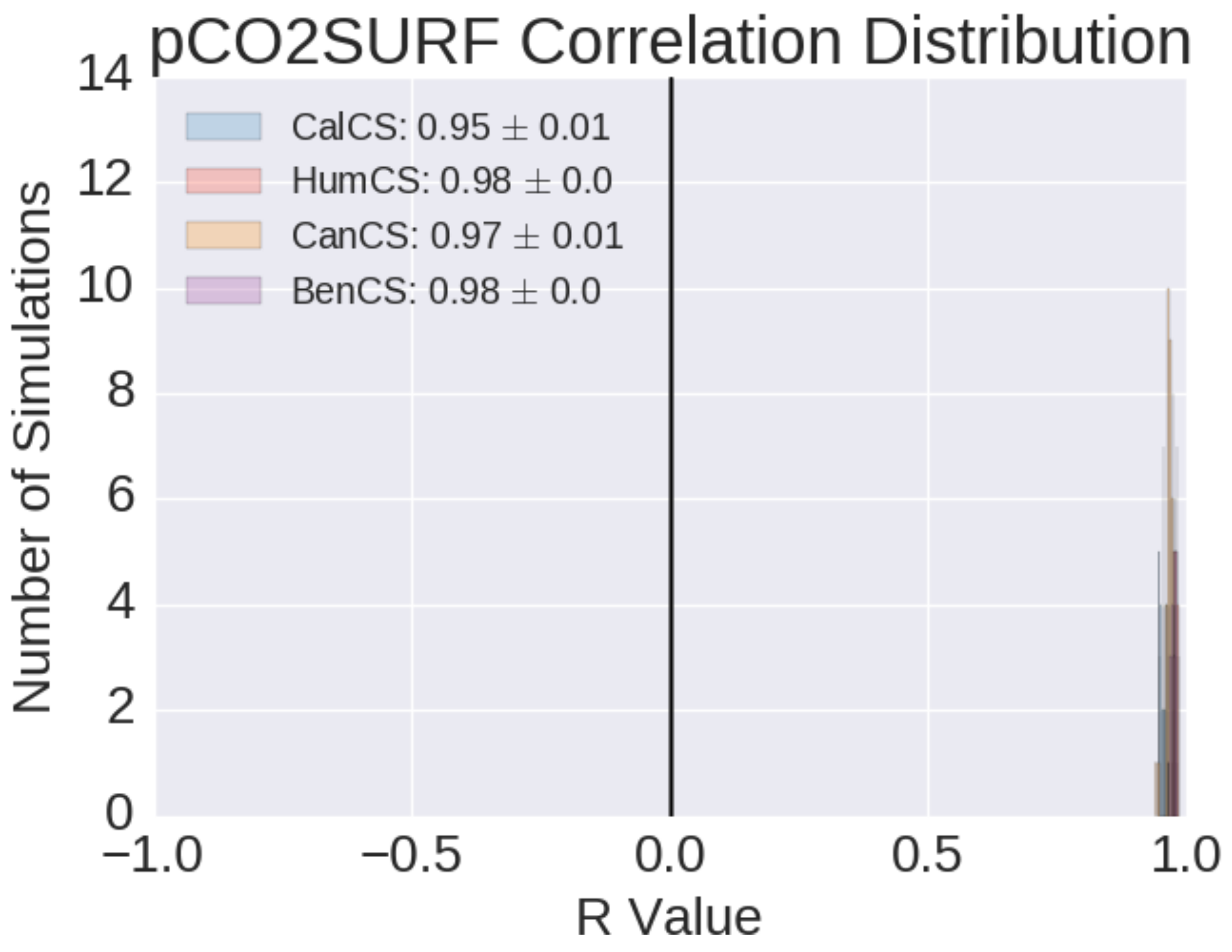
The HumCS and CanCS appear to be most sensitive to changes in circulation. Suppression of upwelling by ENSO/AMO leads to anomalous uptake.

CO_2 flux anomalies in the BenCS are not well-explained by *any* of the four investigated climate indices.

A spatial perspective of correlations reveals a dipole in the CalCS between a circulation-driven coastline and solubility-driven offshore region. This is not replicated by the other systems.

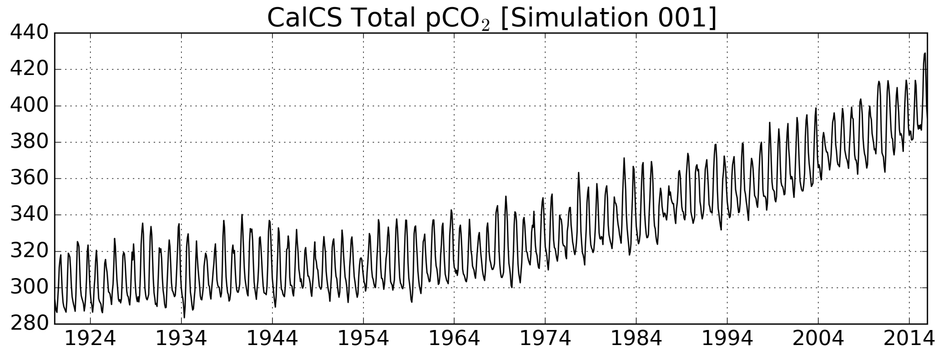
Section 2: Diagnosing the individual contributions to surface pCO_2 variability

Anomalies in surface ocean pCO_2 explain almost all of the CO_2 flux variability. The model works like it should!



We can decompose the pCO_2 anomalies into temperature and non-temperature dependent components.

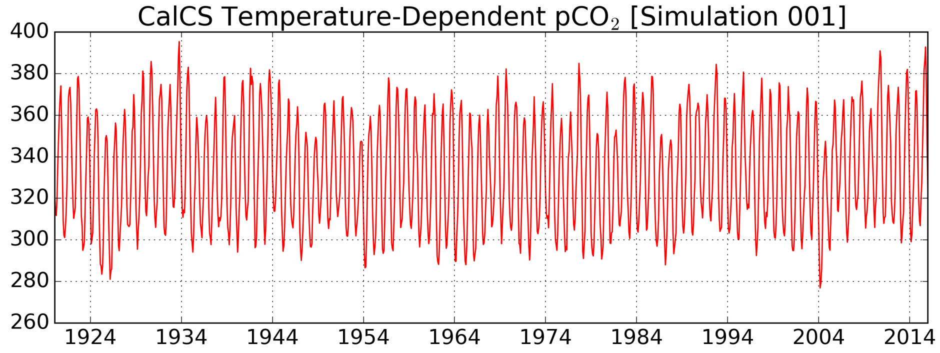
Total pCO2:
The partial pressure of CO2 in the surface ocean, determined by SST, DIC, alkalinity, and sea surface temperature.



pCO2-T =

$$\overline{pCO_2} \cdot exp[0.0423 \cdot (T_{obs} - \overline{T})]$$

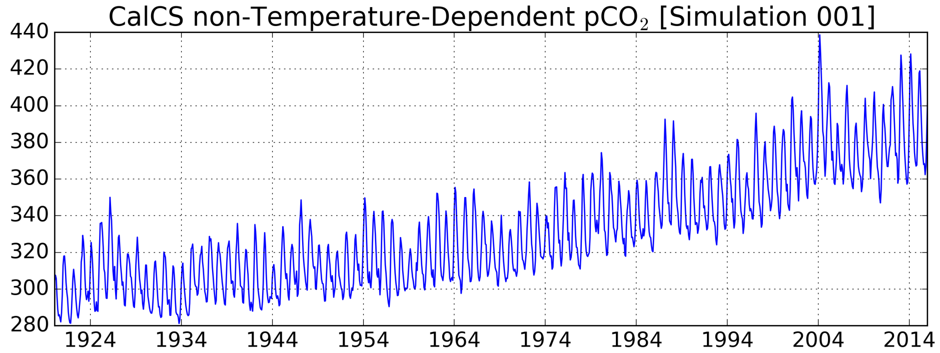
Keep a fixed pCO2 value and observe how SST residuals influence its magnitude.



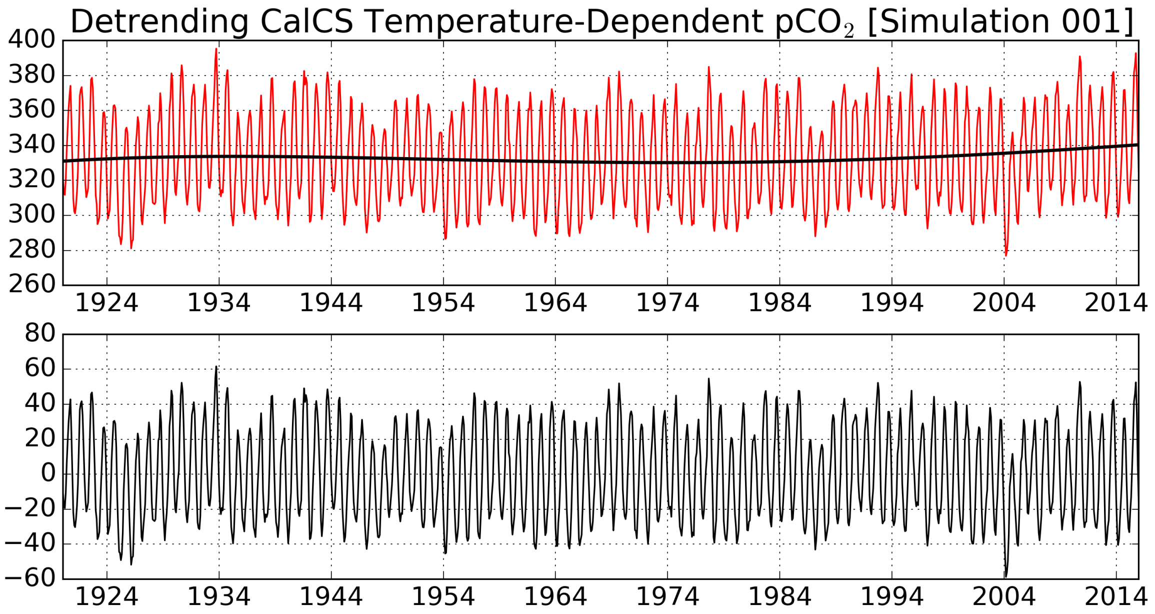
pCO2-nonT:

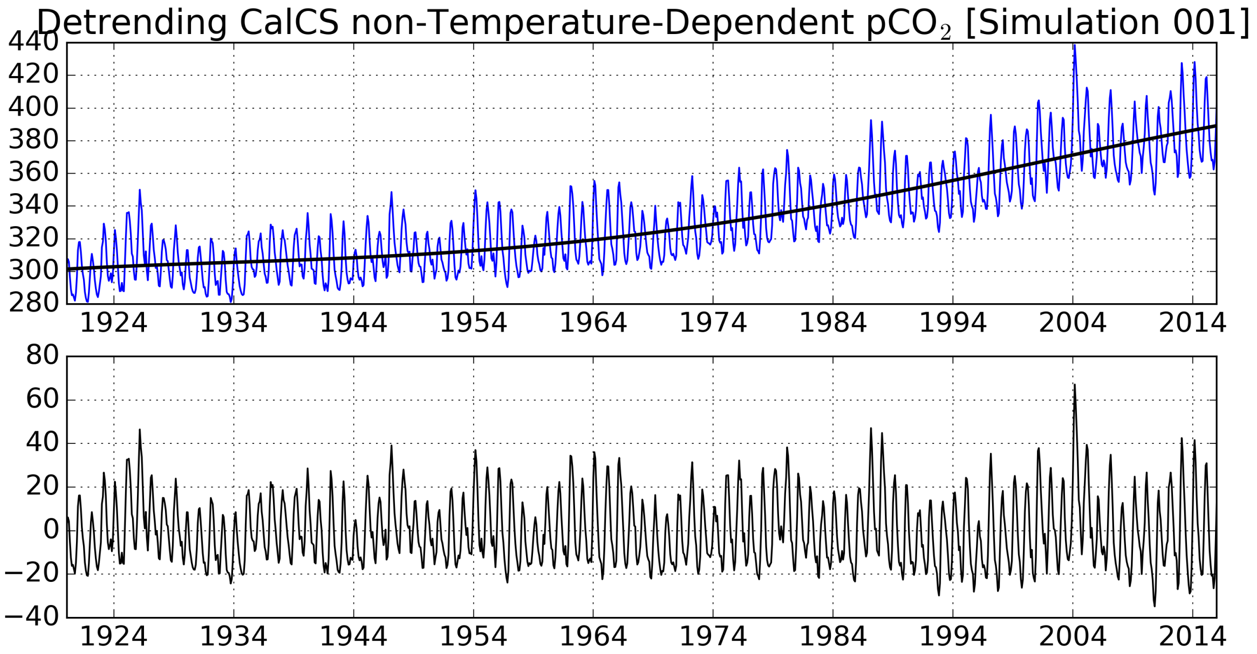
$$pCO2_{obs} \cdot exp[0.0423 \cdot (\overline{T} - T_{obs})]$$

Normalize the observed pCO2 to the mean temperature from the time series, removing the influence of temperature. Variability includes SSS, Alk, and TCO2.



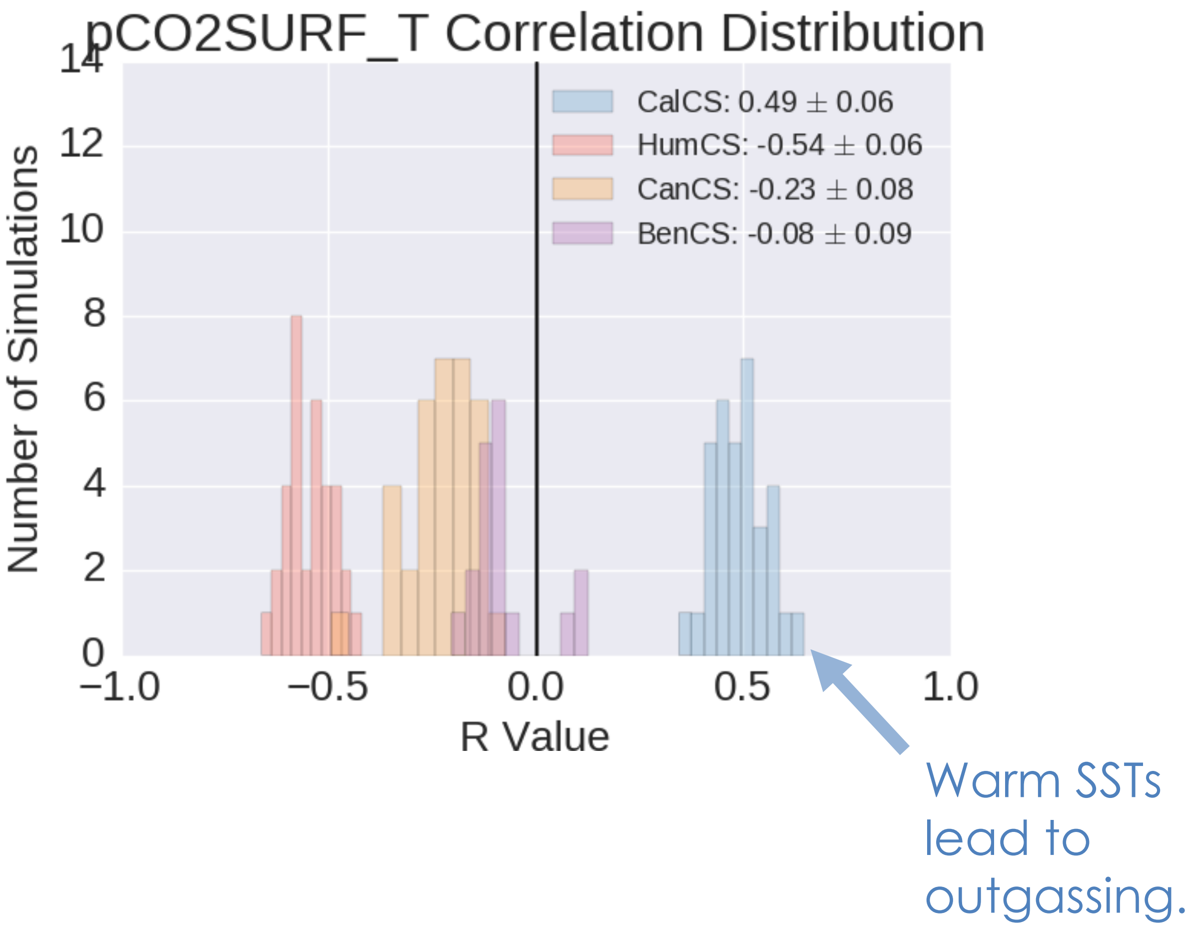
We then de-trend these time series with a 4th order polynomial to avoid the detection of secular trends in correlation analyses.



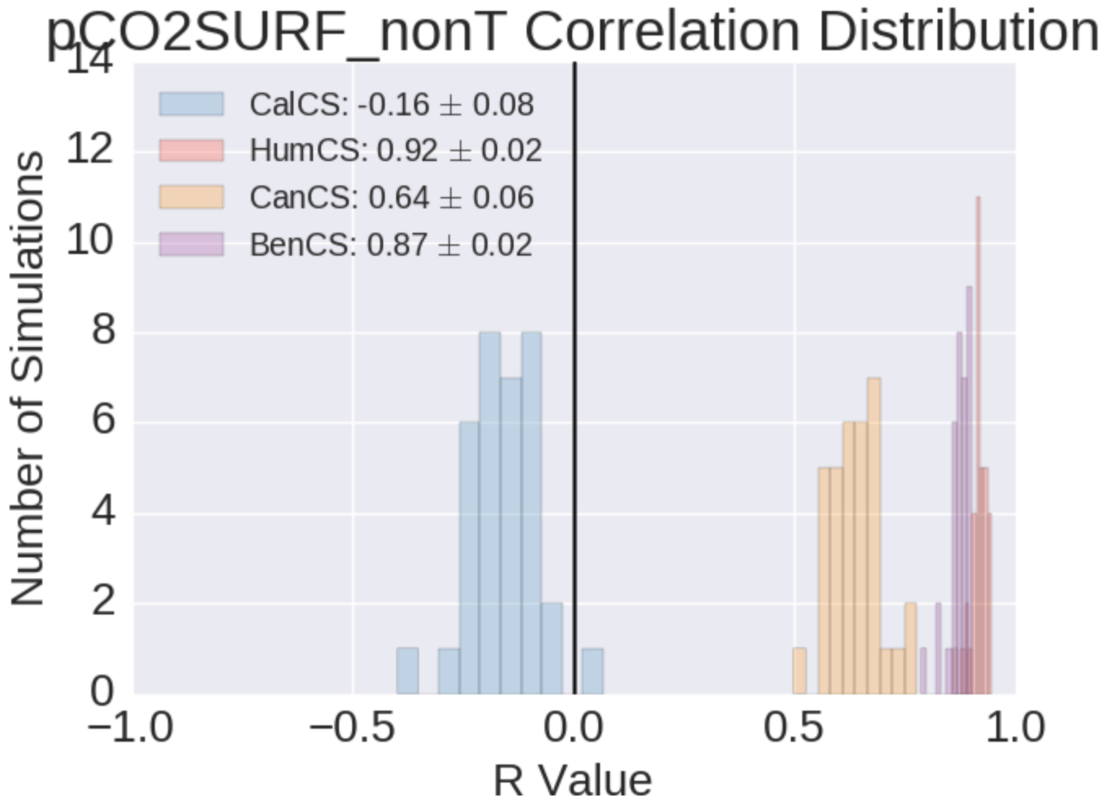


The California Current emerges as a unique solubility-driven system. The other three systems are likely driven by other factors.

Temperature Component



Non-Temperature Component



A linear Taylor expansion allows us to directly attribute pCO_2 variability during a natural climate event to individual factors.

$$\Delta pCO_2 = \frac{\partial pCO_2}{\partial DIC}\Delta DIC + \frac{\partial pCO_2}{\partial ALK}\Delta ALK + \frac{\partial pCO_2}{\partial SST}\Delta SST + \frac{\partial pCO_2}{\partial SALT}\Delta SALT$$

Regression of pCO_2 onto the climate index.

How much did pCO_2 actually change during this climate event?

Sensitivity of pCO_2 to changes in Alk. Empirically-driven.

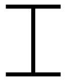
How much does pCO_2 change per unit alkalinity?

Regression of SST anomalies onto the climate index.

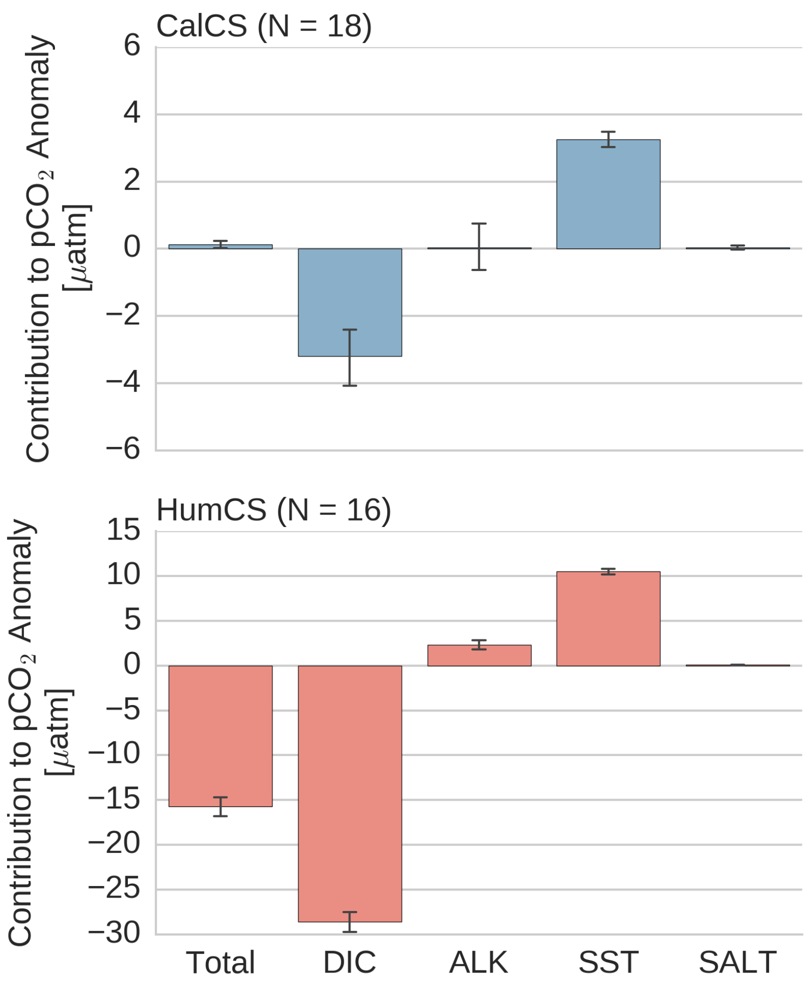
How much did SSTs actually change during this climate event?

During an El Nino, solubility changes drive the California Current and circulation changes drive the Humboldt Current.

Linear Taylor Expansion for 1°C El Nino



95% of the ensemble spans these bounds.

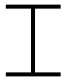


Slight outgassing occurs during an El Nino, since solubility impacts just outweigh circulation impacts.

Uptake occurs during an El Nino since circulation suppression greatly outweighs solubility changes.

During a positive AMO phase, the Canary Current behaves similar to the Humboldt Current.

Linear Taylor Expansion for 1°C AMO



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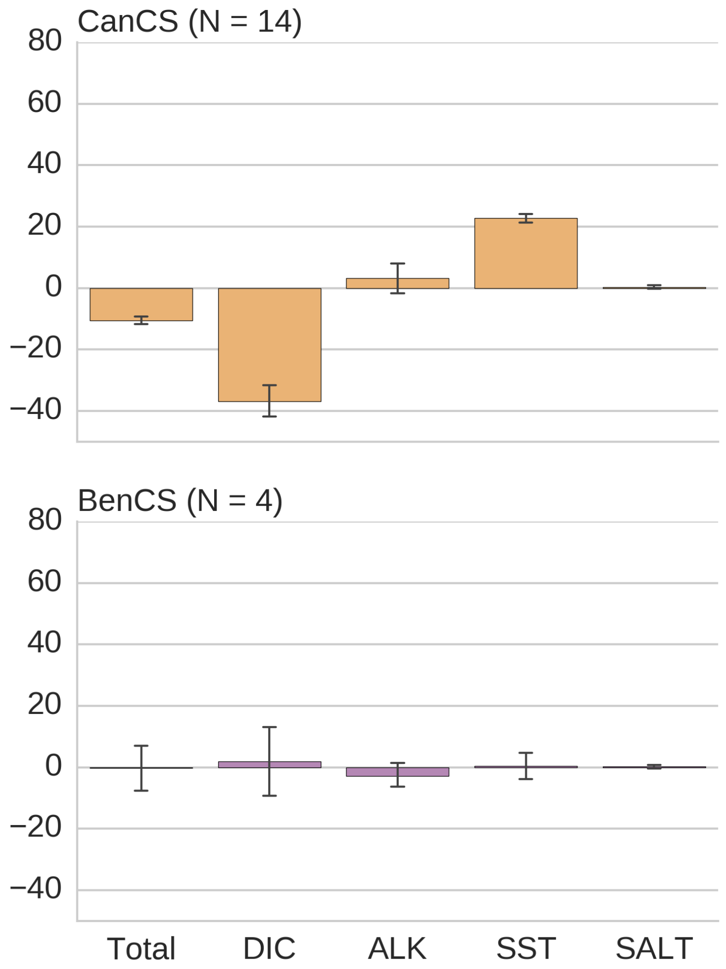
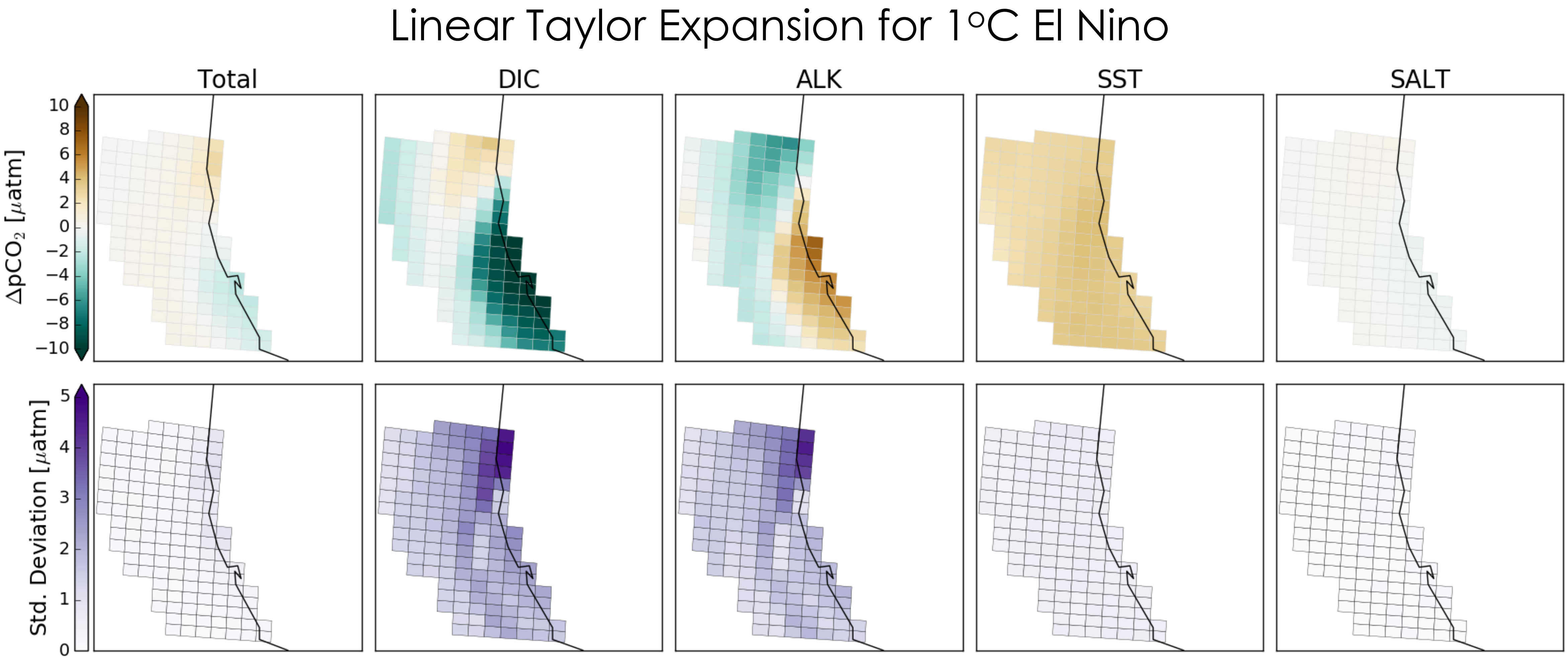


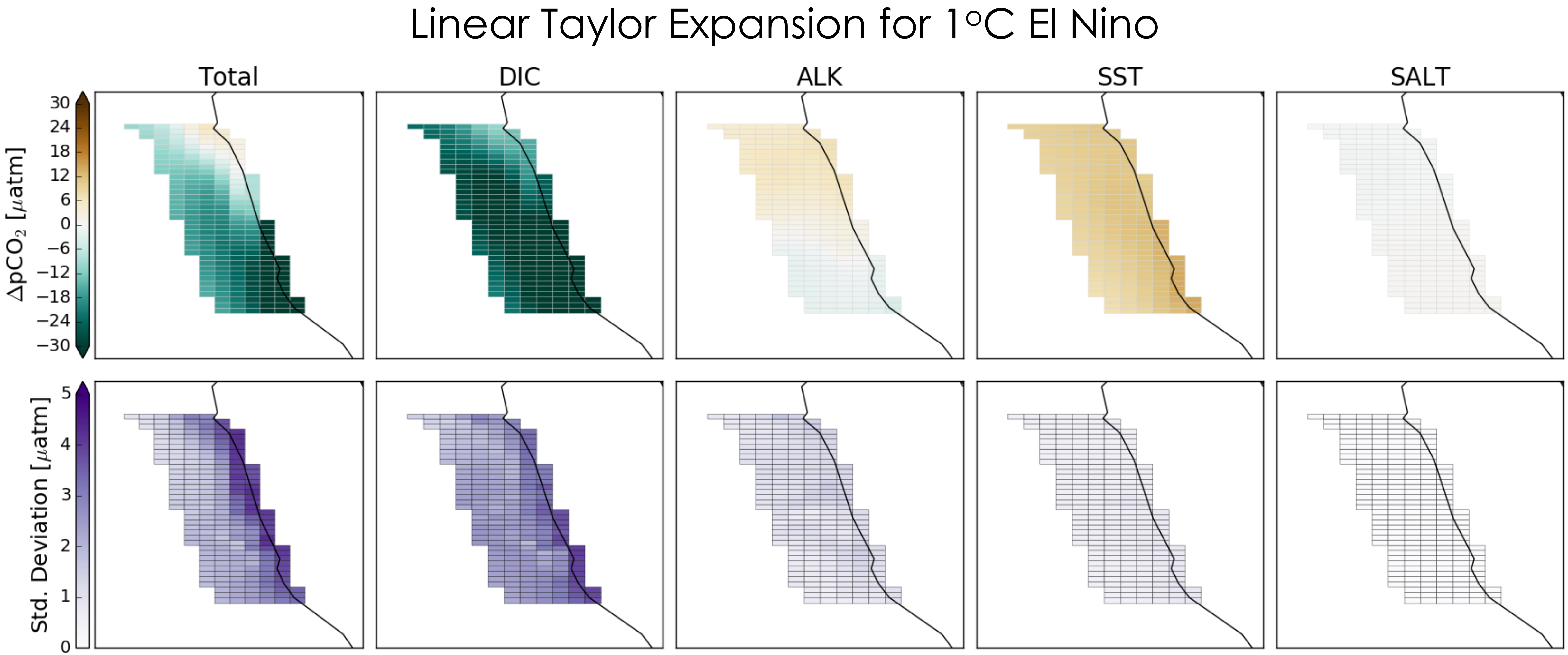
Uptake occurs during a positive AMO event due to upwelling suppression.

Ensemble spread vastly outweighs the signal in the Benguela Current.

A spatial decomposition of pCO_2 changes reveals the same dipole in the California Current as seen earlier.



The Humboldt Current does not exhibit any strong dipole like in the California Current.



pCO_2 Analysis Summary

A careful analysis of contributing factors to pCO_2 variability allows us to point directly to temperature-based solubility as the driving force for California Current flux anomalies.

We find that the Humboldt Current and Canary Current behave similarly during positive climate anomalies. Suppression of DIC-rich circulation greatly outweighs the influence of temperature.

The Benguela Current continues to raise questions about what is controlling its CO_2 flux variability.

The California Current stands alone as a system exhibiting an intriguing spatial dipole in variability.

Next Steps

Perform a Taylor Expansion for CO_2 flux directly:

$$\Delta F = \frac{\partial F}{\partial U}\Delta U + \frac{\partial F}{\partial Ice}\Delta Ice + \frac{\partial F}{\partial pCO_2}\Delta pCO_2$$

Develop an index for variability in the position and intensity of the South Atlantic High. Perhaps this is what is controlling Benguela Current anomalies.

Characterize variability in remaining components of the carbonate system: pH, $[CO_3^{2-}]$, and aragonite/calcite saturation depths.