What controls the variability of CO$_2$ fluxes in Eastern Boundary Upwelling Systems?

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Eastern Boundary Upwelling Systems (EBUS) are highly productive regions characterized by coastally driven and curl-driven upwelling. This supplies the surface with nutrient- and carbon-enriched waters.
$\text{CO}_2$ fluxes in upwelling systems are characterized by significant internal variability that tends to be larger than the seasonal cycle.
What controls this CO$_2$ flux variability?
The CESM Large Ensemble provides 34 independent simulations with a unique representation of the natural climate system.
CESM-LENS captures the general characteristics of CO$_2$ fluxes in EBUS.
The North Pacific Gyre Oscillation (NPGO) is the primary driver of California Current variability.
El Niño modulates CO$_2$ fluxes in the Humboldt Current.
AMOC and the NAO control the variability of the Canary Current.
The Benguela Current remains a mystery.
What are the mechanisms that control the CO$_2$ flux anomalies?
CO₂ flux is complex and is driven by a myriad of factors, including ocean state, circulation, biology, and chemistry.

\[ F_{\text{CO}_2} = k \cdot (p\text{CO}_2^{oc} - p\text{CO}_2^{atm}) \]
Anomalous outgassing occurs in the California Current during a positive NPGO. SST and smaller positive factors outweigh the reduction in DIC.
The Humboldt Current experiences anomalous uptake during El Niño. The large reduction in DIC is the dominating term.
Anomalous outgassing in the Canary Current occurs during a positive NAO. Increased winds and the supply of DIC drive this change.
Conclusions

EBUS have significant internal variability in $F_{\text{CO}_2}$ relative to the coastal oceans and much of the global oceans. This internal variability tends to be larger than the seasonal cycle.
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California Current $F_{\text{CO}_2}$ anomalies are most prominently driven by the NPGO ($R = -0.5$). Colder SSTs and smaller negative terms outweigh DIC enhancement to promote anomalous uptake during positive events.
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Humboldt Current anomalies are modulated by ENSO ($R = -0.42$). Large reductions in DIC cause anomalous uptake during El Niño.
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Humboldt Current anomalies are modulated by ENSO (R = -0.42). Large reductions in DIC cause anomalous uptake during El Niño.

Canary Current anomalies are produced by the NAO (R = 0.28) and AMOC (R = 0.31). A strong Azores High supplies more DIC to the system, causing anomalous outgassing.
Supplemental
Regional variability in surface ocean $p$CO$_2$ drives carbon fluxes between the ocean and atmosphere.
The CESM Large Ensemble is generated from round-off perturbations to the initial conditions, leading to an ensemble that approximates internal variability.
\[ \Delta F = \frac{\partial F}{\partial U} \Delta U + \frac{\partial F}{\partial T} \Delta T + \frac{\partial F}{\partial S} \Delta S + \frac{\partial F}{\partial DIC} \frac{S}{S_0} \Delta sDIC + \frac{\partial F}{\partial ALK} \frac{S}{S_0} \Delta sALK + \frac{\partial F}{\partial FW} \Delta FW \]

Regression of CO₂ flux onto climate predictor.

Empirical or model-derived sensitivity.

Regression of variable onto climate predictor.
CalCS $1^\circ$ NPGO Response (N = 24)

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Contribution to $F_{CO_2}$ Change [mol/m²/yr]
HumCS 1° Nino3 Response (N = 34)

Sensitivity | \( \Delta \) | Term
---|---|---
U | + | + | +
SST | + | + | +
SALT | + | - | -
sDIC | + | - | -
sALK | - | - | +

Contribution to \( F_{CO_2} \) Change [mol/m²/yr]

Total  U  SST  SALT  sDIC  sALK  FW

R = -0.4
CanCS 1σ NAO Response (N = 11)

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Contribution to $\Delta F CO_2$ [mol/m$^2$/yr]

R = 0.28