What controls the variability of CO_2 fluxes in eastern boundary upwelling systems?

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Abstract. TEXT

1 Introduction

2 Methods

2.1 Model Configuration and Upwelling Regions

We utilize monthly output from 34 members of the Community Earth System Model Large Ensemble Project (CESM-LENS), which is derived from a fully coupled Atmosphere-Ocean General Circulation Model (AOGCM) with ocean biogeochemistry (Kay et al., 2015). Round-off level perturbations are made to the atmospheric temperature in 1920, leading to an ensemble of simulations that diverge solely due to the influence of internally generated variability. This provides us with a set of 34 independent representations of climate variability, with which we can robustly assess the controls on air-sea CO_2 flux variability in EBUS. The ensemble is forced with historical radiative forcing from 1920–2005 and RCP8.5 radiative forcing from 2006–2100. Output is made available at approximately 1^ox1^o global resolution.

2.2 Statistical Analysis

Air-sea CO_2 fluxes in CESM are computed following the parameterization of Wanninkhof (2014):

$$\mathrm{F} = \mathrm{k} \cdot \mathrm{K}_0 \cdot (p\mathrm{CO}_2^{\mathrm{o}} - p\mathrm{CO}_2^{\mathrm{a}}) \tag{1}$$

where k represents the gas transfer velocity (dependent on the wind speed squared), K_0 the solubility of CO_2 in seawater, and pCO_2^o and pCO_2^a the partial pressures of CO_2 in the surface ocean and atmosphere, respectively. Surface ocean pCO_2 tends to be the largest term in this equation, since the variability of ocean pCO_2 is much larger than that of the atmosphere (Takahashi et al., 2002; Gruber et al., 2002). However, the influence of wind variability on k cannot be ignored in EBUS, since these systems are aligned with the eastern flank of subtropical gyres that exhibit interannual to decadal variability (Hasanean, 2004; Schroeder et al., 2013). Further, both upwelling and biological productivity in EBUS are highly sensitive to the structure, intensity, and persistence of alongshore winds (Enriquez and Friehe, 1995; Capet et al., 2004; Botsford et al., 2006). This sensitivity feeds back onto the CO_2 fluxes, since these processes in turn influence DIC, Alk, and SST.

We use a linear Taylor expansion to quantify the relative contribution of each parameter to internally generated variability in air-sea CO_2 flux following Lovenduski et al. (2007) and Turi et al. (2014).

$$\Delta F = \frac{\partial F}{\partial U}\Delta U + \frac{\partial F}{\partial pCO_2^{oc}}\Delta pCO_2^{oc} \tag{2}$$

where $\frac{\partial F}{\partial U}$ and $\frac{\partial F}{\partial pCO_2^{oc}}$ are determined from the model equations and mean values in each EBUS, and the influence of sea ice was assumed to be negligible. Δ's represent the linear regression of the given variable onto a climate index. The contributions from ΔpCO_2^{oc} is further decomposed into DIC, Alk, SST, and salinity terms.

$$\Delta pCO_2^{oc} = \frac{\partial pCO_2^{oc}}{\partial DIC}\Delta DIC + \frac{\partial pCO_2^{oc}}{\partial Alk}\Delta Alk + \frac{\partial pCO_2^{oc}}{\partial T}\Delta T + \frac{\partial pCO_2^{oc}}{\partial S}\Delta S \tag{3}$$

Because DIC and Alk can be diluted by freshwater fluxes, as well as altered by physical circulation and biology, we further partitioned the linear expansion. We introduce salinity-normalized DIC (sDIC) and Alk (sAlk), in addition to a separate freshwater term.

$$\Delta F = \frac{\partial F}{\partial U}\Delta U + \frac{S}{S_0}\frac{\partial F}{\partial DIC}\Delta sDIC + \frac{S}{S_0}\frac{\partial F}{\partial Alk}\Delta sAlk + \frac{\partial F}{\partial fw}\Delta fw + \frac{\partial F}{\partial T}\Delta T + \frac{\partial F}{\partial S}\Delta S \tag{4}$$

To compensate for autocorrelation that is characteristic of climate indices and also introduced from smoothing, we replace the *t* statistic sample size *N* with an effective sample size, N_{eff}:

$$N_{eff} = N\left(\frac{1 - r_1 r_2}{1 + r_1 r_2}\right) \tag{5}$$

where r_1 and r_2 are the lag-1 autocorrelation coefficients of the two time series being correlated (Bretherton et al., 1999; Lovenduski and Gruber, 2005). N_{eff} represents the number of statistically independent measurements, thus requiring a higher r-value for a significant correlation with high autocorrelation in one or both time series.

2.3 Model Evaluation

CESM-LENS air-sea CO_2 fluxes were compared to the SOM-FFN (Self-Organizing Map-Feed Forward Network) neural network product (Landschützer et al., 2017) along the four major EBUS outlined by Chavez and Messié (2009). The SOM-FFN was generated by a two step process. First, the global oceans were grouped in 16 biogeochemical provinces, based on common relationships between sea surface temperature, sea surface salinity, mixed layer depth, and pCO$_2$ climatology from Takahashi et al. (2009). Secondly, nonlinear relationships were determined between an expanded set of predictor variables and the Surface Ocean Carbon Atlas version 4 (Bakker et al., 2016) database of surface ocean CO_2 measurements to interpolate pCO$_2$ to monthly resolution spanning 1982-2015 at 1^ox1^o global resolution. Extensive details on and validation of the procedure can be found in Landschützer et al. (2013) and Landschützer et al. (2016).

3 Results

3.1 Internal Variability in Upwelling Systems

3.2 California Current

We find that natural CO_2 flux anomalies in the CalCS are most strongly correlated with the North Pacific Gyre Oscillation (NPGO). On the other hand, correlations between the CalCS and El Nino Southern Oscillation (ENSO) are modest. However, recent literature shows that the CalCS responds uniquely to any given ENSO event (Fiedler and Mantua, 2017; Turi et al., 2017; Frischknecht et al., 2017).

3.3 Humboldt Current

3.4 Canary Current

3.5 Benguela Current

4 Conclusions

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Code availability. TEXT

Data availability. TEXT

Code and data availability. TEXT

Appendix A

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Author contributions. TEXT

Competing interests. TEXT

Disclaimer. TEXT

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