Are anthropogenic changes in the tropical ocean carbon cycle masked by Pacific Decadal Variability?

Pedro N. DiNezio[1], Leticia Barbero[2], Matthew C. Long[3], Nikki Lovenduski[4], Clara Deser[3]

[1]University of Hawaii, Manoa
[2]NOAA Atlantic Oceanographic and Meteorological Laboratory
[3]National Center for Atmospheric Research
[4]University of Colorado, Boulder

Observed changes in the tropical Pacific carbon cycle

The tropical Pacific is the ocean's largest natural source of CO_2 to the atmosphere, thus playing a key role in the global carbon cycle (Takahashi et al. 2009; Gruber et al. 2009). Strong equatorial upwelling of carbon-rich thermocline waters causes partial pressure of CO2 (pCO_2) in the surface ocean to exceed that in the atmosphere. This $pCO2$ difference, surface ocean pCO_2 minus the atmospheric $pCO2$ (ΔpCO_2), drives outgassing of CO_2 into the atmosphere. Additional factors such as wind speed, and to a lesser degree salinity and temperature, modulate the CO_2 flux at the sea-air interface. Anthropogenic emissions continue to drive increasing atmospheric CO_2 concentrations. Understanding and predicting how sea-air CO_2 fluxes respond to this change is a major challenge in carbon cycle research. Observational evidence on the mechanisms driving changes in outgassing over the equatorial Pacific is inconclusive. Studies using the near-continuous observational record of ocean pCO_2 in the central equatorial Pacific show that since 1980, ocean pCO_2 has risen at about the same rate as atmospheric pCO_2 (Feely et al. 2006; Fay and McKinley 2013). This near-zero trend in ΔpCO_2 implies a near-zero trend in sea-air CO_2 flux. The sea-air CO_2 flux, however, has increased in this region, mainly driven by increases in wind speed (Feely et al. 2006).

Anthropogenic response

The Earth System Models (ESMs) participating in the 5th phase of the Coupled Model Intercomparison Project (CMIP5) and a 28-member ensemble of simulations conducted with the Community Earth System Model (CESM) show a robust decrease in ΔpCO_2 and sea-air CO_2 flux in the equatorial Pacific over the 50-year period of 2030 to 2079 as atmospheric CO_2 concentration rises (Figure 1). The following two mechanisms could explain this response: (1) Water in the equatorial thermocline is mostly isolated from the anthropogenic CO_2 perturbation in the atmosphere. When this water upwells to the surface, it is exposed to an atmosphere with ever-increasing CO_2 concentration, resulting in a negative trend in
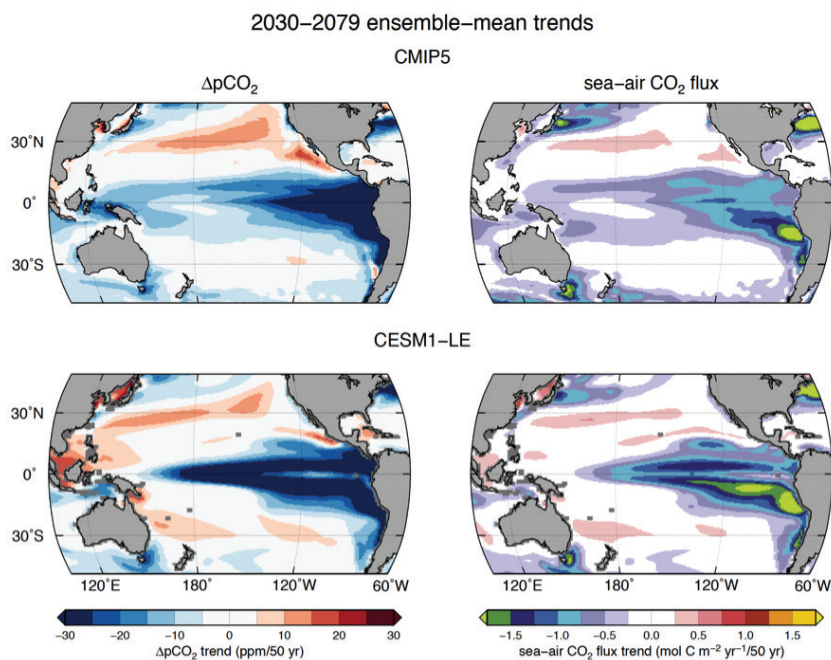

Figure 1: Ensemble-mean trends (2030-2079) in ΔpCO_2 (left; ppm/50 yr) and sea-air CO_2 flux (right; mol C m^{-2} yr^{-1}/50 yr) simulated by CMIP5 models (top) and the CESM1-LE (bottom). Positive sea-air CO_2 flux indicates increased outgassing.

$\Delta p\mathrm{CO_2}$ and sea-air $\mathrm{CO_2}$ flux (Maier-Reimer and Hasselmann 1987). (2) Models also project reduced upwelling due to weaker equatorial easterly winds associated with a reduced Walker circulation in response to global warming (Vecchi and Soden 2007; DiNezio et al. 2009), which could drive decreases in $\Delta p\mathrm{CO_2}$ and sea-air $\mathrm{CO_2}$ flux.

Impact of decadal climate variability

The fact that $\Delta p\mathrm{CO_2}$ has remained steady over the observation-rich historical period (1980-present) is inconsistent with the consensus among ESMs. Can these differences be reconciled? It is well known that climate variability associated with El Niño/Southern Oscillation (ENSO) can complicate the detection of anthropogenic changes (McKinley et al. 2004; Feely et al. 2006; Sutton et al. 2014). However, the effect of decadal variability has not been explored because the observational record is too short to span more than one realization of Pacific Decadal Variability (PDV) for a robust assessment.

The post-1980 period was characterized by a multi-decadal strengthening of the Pacific trade winds and an acceleration of the shallow overturning circulation and equatorial upwelling (McPhaden and Zhang 2004; Merrifield and Maltrud 2011). We hypothesize that during this period, stronger upwelling driven by strengthened trade winds led to increases in $\Delta p\mathrm{CO_2}$ and sea-air $\mathrm{CO_2}$ flux that counteracted the decreases expected from the anthropogenic perturbation of atmospheric $\mathrm{CO_2}$ concentration. Here, we test this hypothesis using an ensemble of simulations performed with CESM1, an ESM that simulates a realistic mean tropical carbon cycle as well as its seasonal and interannual variability (Long et al. 2013). The large number of realizations (28; hereafter referred to as the CESM1-LE; Kay et al. 2015) allows separation of internal decadal variability and externally forced changes.

For each realization of the CESM1-LE, we estimate the changes in both climate and biogeochemistry by computing linear trends over the period 1980-2014 when continuous observations of $p\mathrm{CO_2}$ in the equatorial Pacific are available. We also focus on the central tropical Pacific defined by a modified

Niño-3.4m box (170°E-130°W, 5°S-5°N). The 28 simulations of the CESM1-LE show $\Delta p\mathrm{CO_2}$ changes ranging from -12.6 ppm to +5.6 ppm, suggesting that multi-decadal climate variability has a sizable impact during this 35-year period. The ensemble-mean (forced) change is -6.2 ppm, consistent in sign with the response of $\Delta p\mathrm{CO_2}$ to anthropogenic increases in atmospheric $\mathrm{CO_2}$ discussed above. We extract two 9-member sub-ensembles, grouped according to the lower and upper terciles of the $\Delta p\mathrm{CO2}$ trends over the Nino-3.4m box. The lower-tercile sub-ensemble shows a pronounced decrease in $\Delta p\mathrm{CO_2}$ over the tropical Pacific and associated
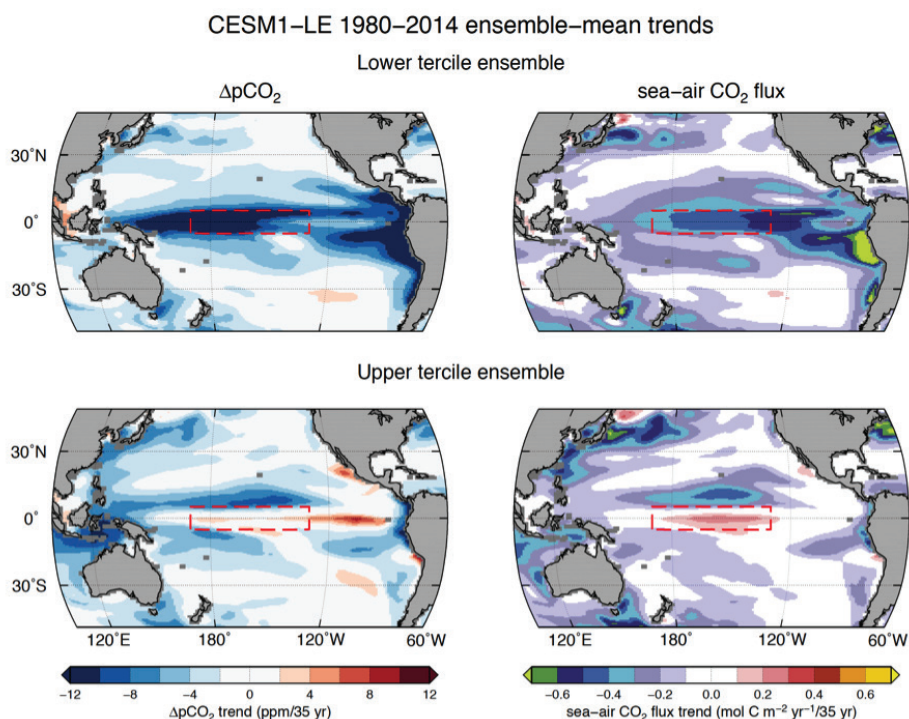

Figure 2: Trends (1980-2014) in $\Delta p\mathrm{CO_2}$ (left; ppm/35 yr) and sea-air $\mathrm{CO_2}$ flux (right; mol C m^{-2} yr^{-1}/35 yr) simulated by the CESM1-LE, over grouped according to the lower and upper terciles of the $p\mathrm{CO_2}$ trends over the Nino-3.4m region. The lower tercile ensemble (top) contains 9 simulations with the most negative Nino-3.4m $\Delta p\mathrm{CO_2}$ trends. The upper tercile ensemble (bottom) contains 9 simulations with negligible trends. The red box over the central equatorial Pacific indicates the Nino-3.4m region. Positive sea-air $\mathrm{CO_2}$ flux indicates increased outgassing.

reduction in outgassing (Figure 2 top), while the upper-tercile sub-ensemble shows negligible changes in $\Delta p\mathrm{CO_2}$ over the equatorial Pacific, and a slight increase in $\mathrm{CO_2}$ sea-air flux (Figure 2 bottom). Moreover, the former shows climate anomalies consistent with the positive phase of PDV (Figure 3 top), while the latter shows climate anomalies consistent with its negative phase (Figure 3 bottom). This suggests that wind-driven changes in equatorial upwelling
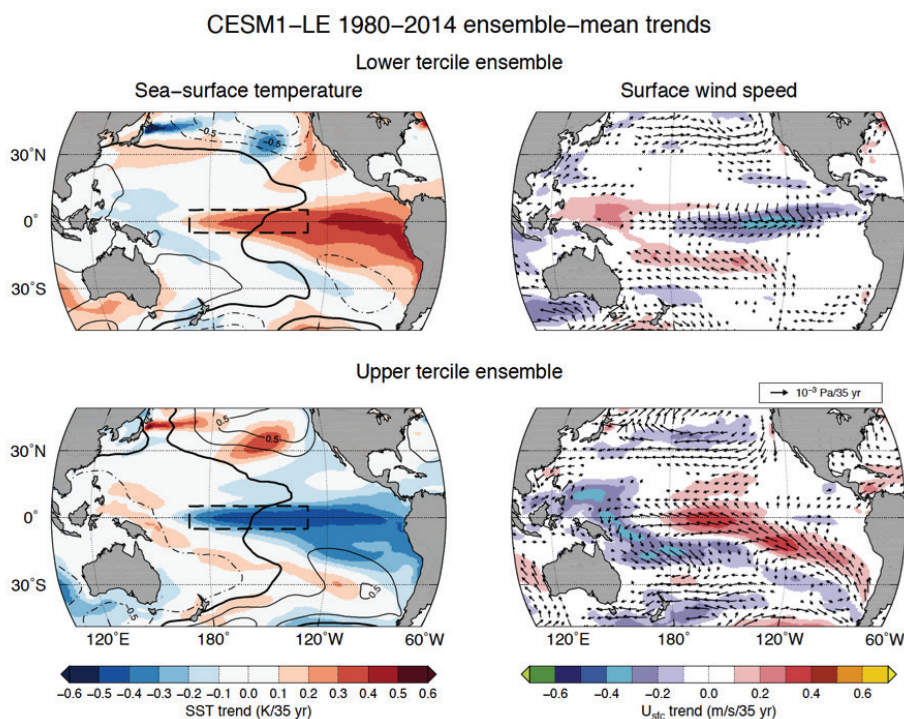
Figure 3: As in Figure 2, but for (left) sea-surface temperature (colors; K/35 yr) and sea-level pressure (contours) and (right) surface wind stress (vectors; 10-3 Pa/35 yr) and wind speed (colors; m s^{-1}/35 yr).

associated with the positive and negative phases of PDV could have a considerable influence on trends in the tropical Pacific carbon cycle.

Towards detection of anthropogenic changes

The CESM1-LE shows a strong reduction in $\Delta p\text{CO}_2$ and outgassing when the PDV is trending positive (constructive effects of PDV and anthropogenic forcing). Conversely, it shows negligible changes in $\Delta p\text{CO}_2$ and a slight increase in outgassing when the PDV is trending negative (cancelling effects of PDV and anthropogenic forcing). The latter case is analogous to the changes observed during 1980-2014, when the Pacific Ocean has trended toward a negative PDV phase, characterized by stronger trade winds and stronger upwelling.

Within the context of the CESM1-LE, internally driven and forced trends can have similar magnitudes, suggesting that PDV can overwhelm the forced response in particular ensemble members. Translating this result to nature implies that equatorial outgassing could be already diminishing in response to increasing atmospheric CO_2. However, this signal has not emerged from the background of internal variability, particularly due to the ongoing multi-

decadal changes in Pacific climate. Therefore, the steady $\Delta p\text{CO}_2$ trend seen in observations (Feely et al. 2006; Fay and McKinley 2013) could be indicative of an anthropogenic response; otherwise, $\Delta p\text{CO}_2$ should be increasing following the observed multi-decadal acceleration of the tropical circulation (McPhaden and Zhang 2004; Merrifield and Maltrud 2011). Furthermore, we cannot reject the model projections of decreasing tropical Pacific outgassing in response to increasing atmospheric CO_2. The anthropogenic response could be masked by decadal variability in Pacific climate.

We expect that these ideas will stimulate further efforts to reconcile observations and model projections. A next step is a full attribution of the effects of natural and anthropogenic influences on the tropical Pacific carbon cycle. How much of the observed $\Delta p\text{CO}_2$ change is anthropogenic, and how much is driven by the strengthening of the Pacific Ocean circulation? Could observations be used to determine whether the carbon content of upwelled waters is increasing more slowly than atmospheric CO_2, as proposed by Maier-Reimer and Hasselmann (1987)? Will the reduction in outgassing vanish once the tropical thermocline fully equilibrates with the atmospheric CO_2? Answering these questions requires process-based understanding of the observed and simulated changes and would ultimately lead to reduced uncertainty in model projections (Friedlingstein et al. 2014).

Changes in the CO_2 sources and sinks are highly uncertain, and they could have a significant influence on future atmospheric CO_2 levels (Le Quéré et al. 2009). It is therefore crucial to reduce these uncertainties. For instance, a recent trend in the airborne fraction of the total emissions suggests that the growth in uptake rate of CO_2 sinks is not keeping up with the increase in CO_2 emissions (Canadell et al. 2007; Le Quéré et al. 2009). For how long will the ocean continue to increase its CO_2 uptake? A more complete understanding of the role played by the tropical Pacific in the global carbon cycle is critical to answering these important questions.

Methods

Earth System Models (ESMs) simulate coupled interactions among the atmosphere, ocean, land, as well as ocean ecosystems and chemistry, and the ocean and terrestrial carbon cycle. We use output from two different types of ESM ensembles, each of which addresses a key source of uncertainty. The first is a multi-model ensemble of simulations of 21st Century climate and biogeochemistry (BGC) change coordinated by CMIP5 and performed with 11 ESMs ran under the same external forcings defined by the RCP8.5 scenario. The models are: CESM1-BGC, MPI-ESM-LR, MPI-ESM-MR, HadGEM2-CC, HadGEM2-ES, IPSL-CM5A-MR, IPSL-CM5B-LR, IPSL-CM5A-LR, MIROC-ESM, GFDL-ES-M2G, GFDL-ESM2M. This ensemble was specifically designed to explore the effect of model (structural) uncertainty, although they also contain uncertainty due to internal variability. We use this ensemble to explore the robustness of the anthropogenic response. We focused on the period 2030-2079 because this is when the forced response of the global ocean carbon cycle is more pronounced.

The second ensemble consists of 28 simulations performed with one single model, in this case the Community Earth System Model Version 1 (CESM1). All the simulations in this large ensemble (CESM1-LE) were started at year 1920 and run under historical forcings until year 2005 and under RCP8.5 scenario from year 2006 to year 2100. A small random perturbation was applied to each simulation in the initial air temperature at year 1920, which causes them to simulate independent weather and internal climate variability. All 28 simulations, however, have the same anthropogenic response because of the common forcing. Thus this large initial-condition ensemble is ideally suited to study the interplay between anthropogenic changes and natural climate variability (Kay et al. 2015). The 28-member ensemble analyzed here is made of 24 simulations with BGC from the 30-member CESM1-LE presented in Kay et al (2015) plus 4 additional simulations following the same experimental protocol.

For each simulation of the CESM1-LE we estimate the changes in climate and BGC by computing linear trends over the period 1980-2014. We focus on this period because it corresponds to when there are continuous observations of pCO$_2$ over the equatorial Pacific. We average the trends over a modified Nino-3.4 region (hereafter "Nino-3.4m": 170°E-130°W 5°S-5°N) for two reasons: 1) this is where the observational network is densest and 2) this is where CESM1 exhibits the strongest forced ΔpCO$_2$ change (Figure 1 bottom). This box is zonally wider than the conventional definition in order to capture the full spatial pattern of the forced response. During 1980-2014 the magnitude of the simulated Nino-3.4m ΔpCO$_2$ changes range from -12.6 to 5.6 ppm, suggesting a large influence of natural variability. The ensemble-mean change is -6.2 ppm and the median change is -7.5 ppm consistent in sign with the anthropogenic reduction discussed for the 2030-2079 period.

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Present and projected climate variability at high latitudes and its impact on the ocean carbon cycle

Irina Marinov[1], Raffaele Bernardello[2], and Jaime B. Palter[3]

[1]University of Pennsylvania
[2]National Oceanography Centre, United Kingdom
[3]McGill University, Canada

Given that the ocean carbon reservoir is about fifty times greater than that of the atmosphere, a small perturbation to the ocean could theoretically produce a spectacular change in atmospheric concentrations. So it might at first seem surprising that atmospheric carbon dioxide (CO_2) concentrations have been so stable over the last millennium. High-resolution ice cores suggest that multidecadal- to century-scale variability of atmospheric CO_2 was less than 10 ppm (~3.5% of background concentrations, Ciais et al. 2013), despite climate and ocean circulation variability. Although climate and ocean circulation variability yield regional fluctuations in the ocean carbon cycle that can confound the detection of trends, these ice cores suggest that the preindustrial (or "natural") ocean carbon cycle, when integrated globally, was largely in steady state. This might reflect compensations between underlying climate-driven changes in the solubility and biological components of air-sea carbon fluxes (Marinov et al. 2011). At the start of industrialization, anthropogenic emissions of CO_2 fundamentally altered this global steady state, as atmospheric concentrations began their rapid climb from about 270 ppm in the 18th century to their current concentration above 400 ppm. Throughout this time, the ocean has provided a major sink for anthropogenic CO_2, mitigating its radiative impact (Sabine et al. 2004). Yet the radiative impact of anthropogenic CO_2 remaining in the atmosphere has raised ocean temperatures, changed freshwater and alkalinity fluxes to the ocean, and altered large-scale ocean circulation patterns. Collectively, these changes are projected to influence both the natural carbon cycle and the uptake and storage of anthropogenic carbon as they continue into the future (Figure 1).