Coupled air-sea interaction and variability in ocean biogeochemistry

(Case studies in carbon and oxygen cycles of the tropical Pacific)

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CO₂ and O₂ cycles

Pattern of surface $\Delta pCO_2$ due to heating (+), cooling (-), photosynthesis (-) and upwelling of respired DIC (+).

Thermocline O₂ is high where water is descending from surface where atmospheric equilibrium, low where water is upwelling and has undergone respiration.

Annual mean $\Delta pCO_2$ (μatm)  
*Takahashi [2002]*

Annual mean O₂ at 400m [μM]  
*World Ocean Atlas [2005]*
Climate-driven trends

Climate warming is predicted to cause a slowdown of CO₂ uptake and a “deoxygenation” of the ocean.

Common mechanisms (decreased thermal solubility and increased stratification) but magnitudes vary widely.

See also: Sarmiento et al. [1998], Plattner et al. [2001], Matear and Hirst [2003]
The strength of long-term trends can be constrained by observing the same process at shorter time scales (if dynamics are similar).

Climate example: snow albedo feedback.

Can this approach be used for climate/carbon cycle interactions?
CO$_2$ and O$_2$ Variability

RMS of pCO$_2$ (surface)

RMS of O$_2$ (0-500m)

Doney et al. [2009]

The tropical Pacific is a place of exceptional variability in biogeochemical cycles.  
→ A good natural laboratory for quantifying sensitivity to climate?

see also McKinley et al. [2004], LeQuere et al. [2000], Obata and Kitamura [2003]
CO$_2$ flux – “Observations”

Based on empirical relationships between pCO$_2$ and SST.

Suggests the equatorial Pacific (EPO) accounts for the largest fraction of global ocean CO$_2$ flux variability.

(see also Feely et al. [2006])
El Nino and CO$_2$ flux drivers

El Nino effect: “piston velocity” solubility Upwelling of respired carbon CO$_2$ fixation

Strutton et al. [2008]
Contributions to CO$_2$ variability

Rate of CO$_2$ exchange depends on

1) Partial pressure gradient ($\Delta p$CO$_2$)
   Largest role in Central Pacific

2) Surface turbulence $\rightarrow$ wind speed
   Largest role in East Pacific

Doney et al. [2009]
Weakening Walker Cell

Vecchi et al. [2006]

Weakened equatorial winds (observed and simulated) lead to:
1) Less upwelling
2) Shallower thermocline in west
Flavors of ENSO

Analysis of tropical SST variability reveals two distinct anomaly patterns:

1) conventional El Nino in the east Pacific (EP)
2) El Nino “Modoki” centered in central Pacific (CP)

Ashok et al. [2005]
Shifting frequencies?

Some indications that the frequency of CP El Niño is increasing relative to EP El Niño.

On average, models show this tendency getting stronger under warmer climate.

Associated with overall shoaling of thermocline.

Yeh et al. [2009]
ENSO and NPGO?

Di Lorenzo et al. [2008]

Di Lorenzo et al. [2009]
Future climate and CO$_2$ outgassing/uptake

• Does a weakening Walker Cell reduce the mean rate of CO$_2$ release from the tropical Pacific?

• Will the changing character of ENSO alter the dominant interannual variability of oceanic CO$_2$ sources?

• Can we use the observed interannual changes to better constrain the long-term trends?
Hypoxic Variability

Volume of low $O_2$ zones is highly variable (model hindcast simulation).

Amplitude grows as $O_2$ threshold decreases.

Suboxic zone expands/contracts by 2-fold over decades.

Consistent in phase/sign/amplitude with CalCOFI data.

*Deutsch et al. [2011]*
Mechanisms of $O_2$ variability

Clear relationship between anomalies in depth of thermocline ($13^\circ$ isotherm) and suboxic zone.

Variations in suboxic zone depth are much greater (5x) than for thermocline depth.

Thermocline heaving/shoaling drives multiplicative effects on export and respiration.
Climate Forcing

The dominant synchronous mode of low-latitude thermocline depth variations (13% of variance) occurs throughout the Eastern Pacific.

It is highly correlated to the Pacific Decadal Oscillation (PDO).

The PDO explains 25% of the variance in suboxic volume (P<0.01).

Simple Ocean Data Assimilation (SODA), Carton and Geise [2008]
The Role of Winds

Wind stress curl

Thermocline depth

Correlation between Curl(τ) and Z_{13} anomalies, (where P<0.05).

Output from Simple Ocean Data Assimilation (SODA), Carton and Geise [2008]
Thermocline trends

Model thermocline in eastern tropical Pacific (off equator) deepens. Amount depends on metric → export versus water mass view.
Can the tropical OMZ really shrink in the face of ocean deoxygenation?
Future climate and ocean hypoxia/anoxia

• How will the thermocline of the eastern tropical Pacific change in a warmer climate?

• At what time scales are thermocline depth fluctuations the most important? (What about basinwide $O_2$ adjustment? $\rightarrow$ Deglacial anoxic expansion)
Discussion Questions

– For which processes, and at which time scales, is natural variability in carbon cycle a useful analogue of long-term trends? (Where are amplitudes likely correlated across time scales?)

– What are the observational requirements to narrow the intermodel range at the shorter time scales (e.g. seasonal cycle to interannual variability)?

– Do we need a coordinated effort to analyze the upcoming IPCC archive in these ways?