Do Clouds Affect Ocean Carbon Uptake?

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(\textit{yes, they do!})
Preindustrial sea-air CO₂ flux (control)
End-of-century sea-air CO$_2$ flux (control)
Drivers of Sea-Air CO$_2$ Flux, $\phi$

$$\phi = k \left( [CO_2]_{ocn} - [CO_2]_{atm} \right)$$

Causes of surface disequilibrium ($[CO_2]_{oc} \neq [CO_2]_{atm}$):
1) Surface heating or cooling
2) Biology (photosynthesis or respiration)
3) Circulation

Effects on the gas exchange velocity, $k$:
1) Wind stress increases $k$ by increasing turbulent mixing.
2) Temperature can affect $k$ by changing the viscosity of water.
Global Climate Impacts of Fixing the Southern Ocean Shortwave Radiation Bias in the Community Earth System Model (CESM)

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(Manuscript received 19 May 2015, in final form 21 March 2016)

ABSTRACT

A large, long-standing, and pervasive climate model bias is excessive absorbed shortwave radiation (ASR) over the midlatitude oceans, especially the Southern Ocean. This study investigates both the underlying
The Modeling Experiment

Absorbed Solar Radiation at the Surface Relative to Satellite Observations

Frey and Kay 2017
Kay et al. 2016
Difference in solar radiation absorbed at the surface (experiment – control)

Kay et al. 2016
Thermal component of the preindustrial CO$_2$ flux difference
Preindustrial sea-Air $\text{CO}_2$ flux difference due to cloud changes (experiment – control)
Non-thermal component of the preindustrial CO$_2$ flux difference
Preindustrial sea-air CO$_2$ flux (control)

Integrated over this region
Brightening clouds increases the preindustrial Southern Ocean carbon sink

~0.1 Pg = 100 million metric tons
100 million tons C = \sim 370 million tons of CO_2

About the total emissions of California in 2016.
The Southern Ocean CO₂ flux is similarly increased in the 21st century.
Summary

1) Changes to the clouds in CESM1 alter the spatial distribution of the sea-air CO2 flux while maintaining a globally integrated flux of zero.
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2) While the net flux difference resembles the thermal component, non-thermal effects compensate strongly for the thermal effects.
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1) Changes to the clouds in CESM1 alter the spatial distribution of the sea-air CO2 flux while maintaining a globally integrated flux of zero.

2) While the net flux difference resembles the thermal component, non-thermal effects compensate strongly for the thermal effects.

3) Integrated over the Southern Ocean, the cloud changes result in a flux into the ocean that is 0.1 Pg/year larger. This difference is maintained through simulations of the 21st century.
$$\Phi = kS_A(pCO_2^{atm} - pCO_2^{ocn})$$

**Decomposition of carbon fluxes into components**

The thermal component of the flux is given by:

$$\frac{\partial \Phi}{\partial T} \Delta T = \frac{\partial \Phi}{\partial pCO_2} \Delta pCO_2 = \frac{\partial \Phi}{\partial pCO_2} \frac{\partial pCO_2}{\partial T} \Delta T$$  \hspace{1cm} (2.3.1)

The sensitivity of pCO$_2$ to temperature is known (Takahashi et al. 1993):

$$\frac{\partial pCO_2}{\partial T} \approx pCO_2 0.0423^\circ C^{-1}$$  \hspace{1cm} (2.3.2)

And the sensitivity of the flux to pCO$_2$ can be obtained by taking the derivative of equation 1.0.1 with respect to $pCO_2^{ocn}$:

$$\frac{\partial \Phi}{\partial pCO_2} = k(1 - I)S$$  \hspace{1cm} (2.3.3)
where \( k = \frac{\Phi}{(1-I) \Delta CO_2^*} \) such that

\[
\frac{\partial \Phi}{\partial pCO_2} = \frac{\Phi}{\Delta CO_2^*} S
\]  

(2.3.4)

\( \Delta CO_2^* \) is the difference in CO2 concentrations (not partial pressures) between the ocean and the atmosphere. The solubility, \( S \), is a function of temperature and salinity and is obtained empirically:

\[
S = \exp\left[ -162.8301 + (218.2968/T) + 90.9241 \times \log(T) - 1.47696 \times T^2 + SALT \times (0.025695 - 0.025225 \times T + 0.0049867 \times T^2) \right]
\]
Solar Radiation and Liquid Water Path (Experiment – Control)

Kay et al. 2016