Study on air-sea CO_2 exchange with wave breaking

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Overview

Parameterization from laboratory experiment

The CO_2 gas transfer velocity K_{CO_2} at air-water interface in a wind-wave flume is estimated at the circumstance of wave breaking. Three types of dynamic processes in the flume are created:

1. monochromatic waves generated by wavemaker
2. mechanically-generated monochromatic waves with superimposed wind forcing
3. pure wind waves with 10-meter wind speed ranging from 4.5 m/s to 15.5 m/s

The role of breaking waves in facilitating CO_2 gas exchange is highlighted in monochromatic wave experiments.

With full wave spectrum in the coupled wind/mechanical wave experiments and pure wind wave experiments, statistical parameters based on all waves are chosen to describe K_{CO_2}.

Test with campaign observational data

The parameterization is further tested by utilizing field observational data from ship cruises.

The results from lab can be reconciled with field data based on our parameterization.

A second parameterization is developed by emphasizing the importance of wave breaking and breaking induced bubbles in the CO_2 gas exchange.

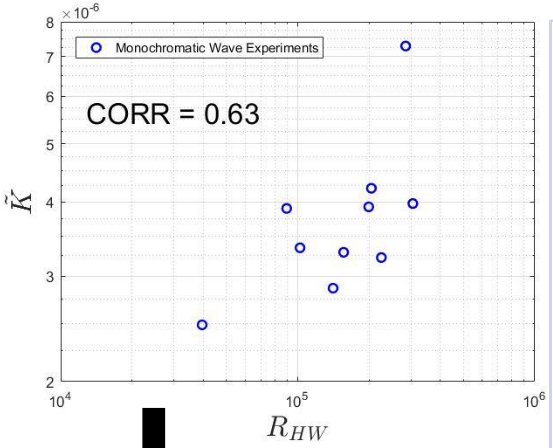
Application in estimating global ocean CO_2 flux

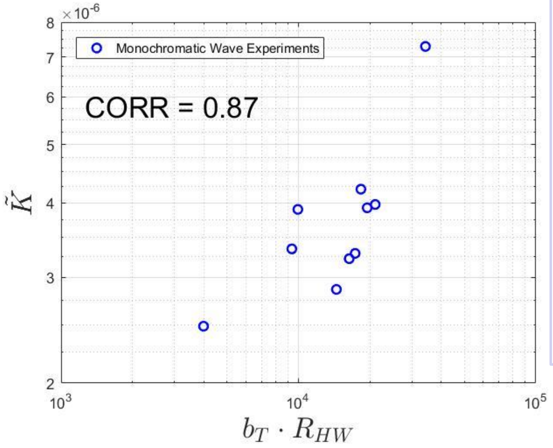
CO_2 budget of global ocean in year 2011 is estimated by using our formula and complied well with reported values.

A 33-year (1985-2017) trend of CO_2 uptake by ocean including the contribution from wave breaking area is analysed.

Parameterization from laboratory experiment

$$\widetilde{K} = \frac{K_{CO_2}}{U_{wm}} \sim b_T \cdot R_{HW} = b_T \cdot \frac{H_b \cdot U_{wb}}{\upsilon}$$





$\widetilde{K}$, non-dimensional CO_2 gas transfer velocity

K_{CO_2}, corrected CO_2 gas transfer velocity

b_T , wave breaking probability

U_{wm}, mean wave orbital velocity

U_{wb}, mean wave orbital velocity of breakers

U_{ws}, wave orbital velocity using $\pi H_s / T_{02}$

H_b, mean wave height of breakers.

ν, water kinematic viscosity

U_*, wind friction velocity

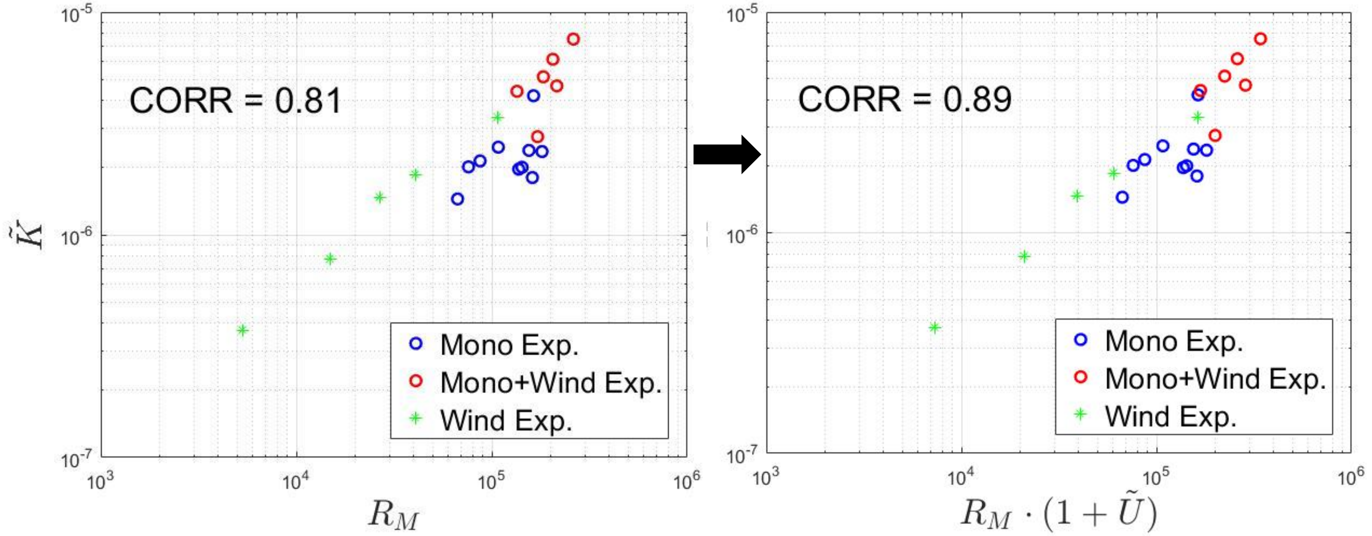
H_s, significant wave height

g, gravitational acceleration

T_{02}, wave period based on second moment

Formula 1.

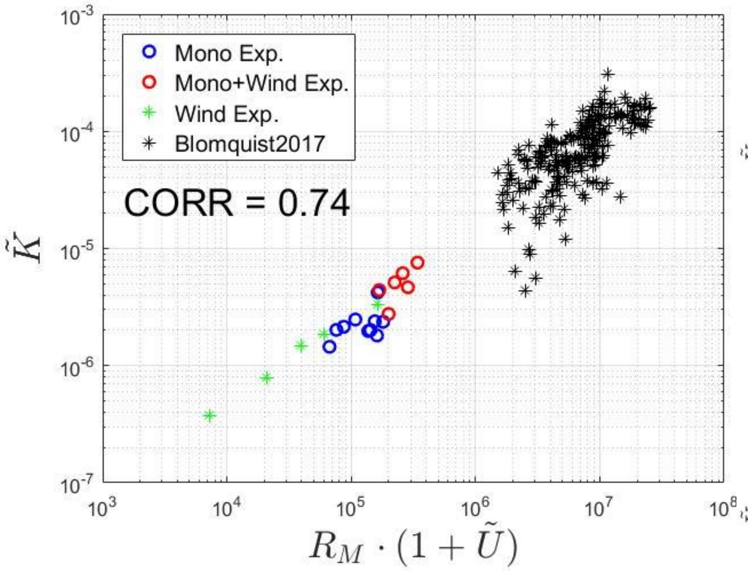
$$\widetilde{K} = \frac{K_{CO_2}}{U_{ws}} \sim R_M \cdot (1 + \widetilde{U}) = \frac{H_s \cdot U_{ws}}{\upsilon} \cdot \left(1 + \frac{U_*}{\sqrt{g \cdot h_s}}\right)$$

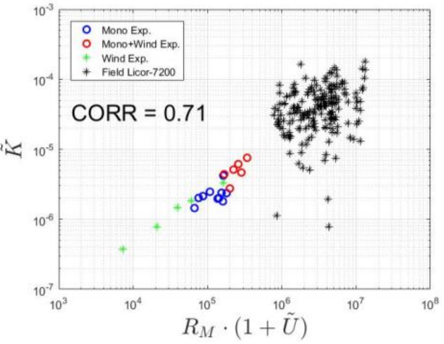


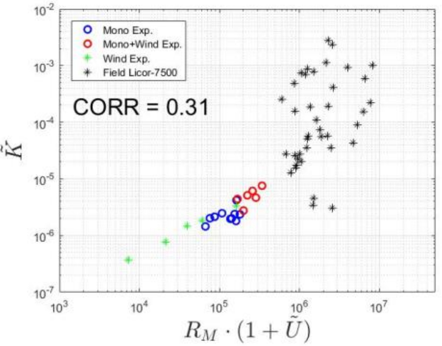
Test with campaign observational data

Formula 1.

$$\widetilde{K} = \frac{K_{CO_2}}{U_{ws}} \sim R_M \cdot \left(1+\widetilde{U}\right) = \frac{H_s \cdot U_{ws}}{\upsilon} \cdot \left(1 + \frac{U_*}{\sqrt{g \cdot h_s}}\right)$$





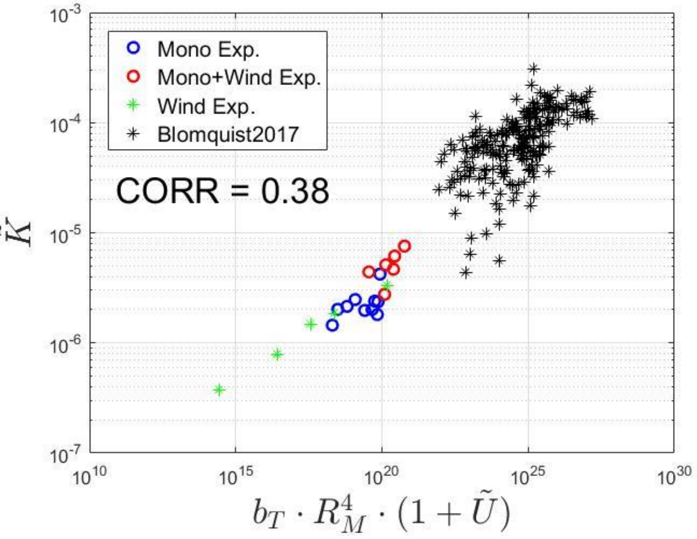


$\widetilde{K} = a[R_M \cdot (1+\widetilde{U})]^b$,
$a = 7.50 \cdot 10^{-10}$,
$b = 0.69$,

Formula 2.

$$\widetilde{K} = \frac{K_{CO_2}}{U_{ws}} \sim b_T \cdot R_M^4 \cdot \left(1+\widetilde{U}\right) = b_T \cdot \left(\frac{H_s \cdot U_{ws}}{\upsilon}\right)^4 \cdot \left(1 + \frac{U_*}{\sqrt{g \cdot h_s}}\right)$$

To highlight the contribution of wave breaking and breaking induced bubbles, formula 2 was developed based on result of lab monochromatic wave experiments, $\widetilde{K} \sim b_T \cdot R_{HW}$. From field data, the non-dimensional bubble entrainment rate $\left(\frac{V_b}{U_{ws}}\right)$ was related with R_M^3. Thus, the combination is $b_T \cdot R_M^4$.



$\widetilde{K} = a[b_T \cdot R_M^4 \cdot (1+\widetilde{U})]^b$,
$a = 8.18 \cdot 10^{-10}$,
$b = 0.18$,

* Blomquist, B. W., et al. "Wind speed and sea state dependencies of air-sea gas transfer: Results from the high wind speed gas exchange study (HiWinGS)." *Journal of Geophysical Research: Oceans* 122.10 (2017): 8034-8062.

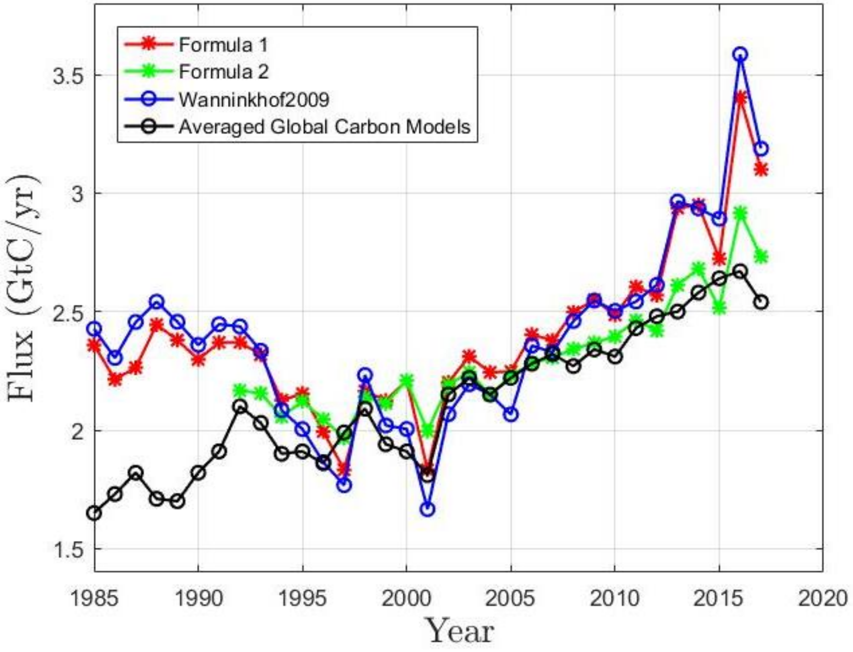
Application in estimating global ocean CO_2 flux

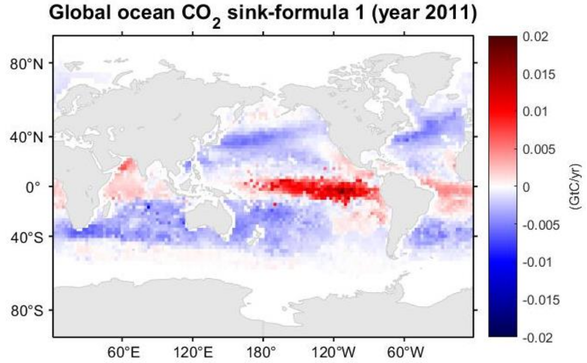
Formula from Wanninkhof (2009):

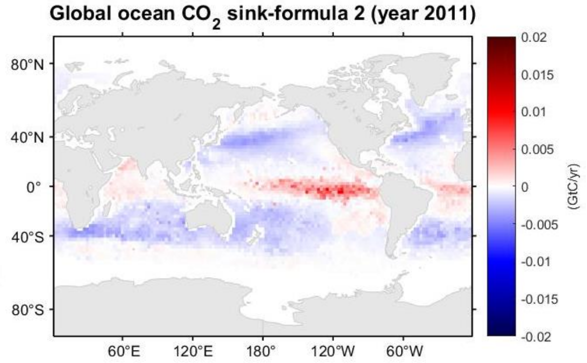
$$k_{CO_2} = 3 + 0.1 \cdot U_{10} + 0.064 \cdot U_{10}^2 + 0.011 \cdot U_{10}^3$$

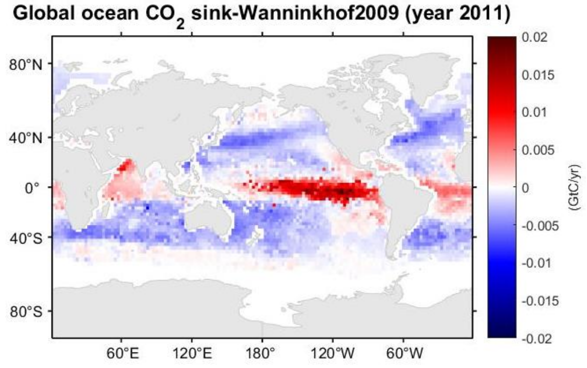
Three equations are used to estimate the global ocean CO_2 sink from 1985 to 2017. Positive values at y axis represent the flux from atmosphere to ocean. The average of several global ocean biogeochemistry models that reproduce the observed mean ocean sink is reported in Friedlingstein (2019) with uncertainty of $\pm$0.5 GtC/yr.

The results of equations are close to model averages from year 1990 onwards, while opposite trend can be found in 1985-1990. The results of formula 1 (red) and Wanninkhof (2009) (blue) are similar to each other. Formula 2 gives a closer estimation to model results with b_T data available from 1992-2017 for now.









Wanninkhof, Rik, et al. "Advances in quantifying air-sea gas exchange and environmental forcing." (2009).
Friedlingstein, Pierre, et al. "Global carbon budget 2019." Earth System Science Data 11.4 (2019): 1783-1838.