New parameterizations of air-sea CO$_2$ gas transfer velocity on wave breaking

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Ocean surface waves and wave breaking play a pivotal role in air-sea Carbon Dioxide (CO$_2$) gas exchange by producing abundant turbulence and bubbles. Contemporary gas transfer models are generally implemented with wind speed, rather than wave parameters, to quantify CO$_2$ transfer velocity ($K_{CO2}$). In our work, the direct relationship of $K_{CO2}$ and waves is explored through the combination of laboratory experiment, field observational data and estimation of global ocean uptake of CO$_2$.

In laboratory, the waves and CO$_2$ transfer at water surface are forced for simultaneous measurements in a wind-wave flume. Three types of waves are exercised: mechanically generated monochromatic waves, pure wind waves with 10-meter wind speed ranging from 4.5 m/s to 15.5 m/s, and the coupling of monochromatic waves with superimposed wind force. The results show that $K_{CO2}$ is well correlated with wave height and orbital velocity. In the connection of $K_{CO2}$ with breakers, wave breaking probability ($b_T$) should also be considered. The wind speed is competent too in describing $K_{CO2}$ but may be inadequate for varied wave ages. A non-dimensional formula (hereafter the RHM model) is proposed in which gas transfer velocity is expressed as a main function of wave Reynolds number ($R_{HM} = U_w H_s / \nu_w$, where $U_w$ is wave orbital velocity, $H_s$ is significant wave height, $\nu_w$ is viscosity of water) while wind is accounted as an enhancement factor ($1+U$, where $U$ is non-dimensional wind speed denoting the reverse of wave age). For wave breaking dominated gas exchange, second formula (hereafter the BT model) is developed by replacing components of $R_{HM}$ with breaker's statistics and integrates an additional factor of $b_T$.

Utilizing campaign observations from open ocean, the RHM model can effectively reconcile the laboratory and field data sets. The BT model related with wave breaking, on the other hand, is adapted by including a complementary term of bubble-mediated gas transfer in which the bubble injection rate is parameterized with $R_{HM}$. The updated BT model also performs well for the data. The conventional wind-based models show similar features as in laboratory experiments: the wind speed successfully captures the variation of gas transfer for respective observation yet is insufficient to neutralize the gaps among data sets.

Our wave-based gas transfer models are applied for the estimation of net annual CO$_2$ fluxes of global ocean in the period of year 1985-2017. The results are in high agreement with previous studies. The wind-based gas transfer models might underestimate the CO$_2$ fluxes although the estimations still distribute within the range of uncertainty. Moreover, the models using wave
parameters are found advantageous over the wind-based models in reducing the uncertainties of gas fluxes.