Technical Report

Comparison of the global air-sea CO$_2$ gas flux on the difference of transfer velocity model

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Abstract
The air-sea CO$_2$ gas transfer velocity is generally expressed as a function only of the wind speed $U_{10}$. However, there exists considerable disagreement among the observed values. The disagreement is especially large in the context of the different sea surface conditions (wind wave growth and swell etc.). Consequently, many models of the air-sea CO$_2$ gas transfer velocity are proposed by field and laboratory experiments. In this study, we evaluate the estimated global air-sea CO$_2$ gas flux using the different some air-sea CO$_2$ gas transfer velocity models (field experiment model, laboratory experiment model and hybrid model considering wave breaking). The 6-hourly wind speed and mean period of wind and wave data sets by ECMWF were used. The maximum difference of annual global air-sea CO$_2$ gas flux was 0.76 PgC/year. The annual global air-sea CO$_2$ gas flux of each laboratory experiment models were the smallest value, and each hybrid models were near value to each field experiment models. The difference of each model in low latitude is large, same as the difference in middle latitude. This shows that the difference of the result of each model in low latitude is significant for the estimation of air-sea CO$_2$ gas flux.

Keywords: air-sea CO$_2$ gas transfer velocity, air-sea CO$_2$ gas flux, air-sea interaction, wave breaking, whitecap coverage

1. Introduction
As the increase of CO$_2$ gas in atmosphere is less than the rate of carbon release, some released CO$_2$ must have been absorbed by either the terrestrial biosphere or the oceans. The exchange of CO$_2$ between the atmosphere and ocean is therefore of great importance and growing attention due to the increase of CO$_2$ concerns over environmental pollution and climate changes.

The air-sea CO$_2$ gas flux is estimated by

$$F = k_L S \Delta pCO_2,$$  \hspace{1cm} (1.1)

where $k_L$ (m/s) is the CO$_2$ transfer velocity, $\Delta pCO_2$ (μatm) is the partial pressure difference between ocean and atmosphere and $S$ (mol l$^{-1}$ atm$^{-1}$) is the solubility in sea water. The CO$_2$ transfer velocity is generally expressed as a function of the wind speed at 10 m above the sea surface, $U_{10}$ (m/s). Historically many models (Wanninkhof (1992), Wanninkhof and McGillis (1999), etc.) are proposed to determine the CO$_2$ transfer velocity by field observation. Also, many models (Liss and Merlivat (1986), Jahne et al. (1987), Iwano et al. (2013), etc.) are proposed by laboratory experiment using wave tank. However, there exists considerable disagreement among the observed values. The disagreement is especially large in the context of the wind wave growth and wave breaking. Therefore, hybrid models considered wave breaking together with wind speed using the ratio of whitecap coverage are proposed by Monahan and Spillane (1984), Woolf (2005) and Suzuki et al. (2015) etc. However agreement has not reached yet. By knowing the difference of the air-sea CO$_2$ gas flux using the different air-sea CO$_2$ gas transfer velocity’s models, we can explore the effect of the different models by difference between field and laboratory and wave breaking on the annual global air-sea CO$_2$ gas flux. Consequently, in order to clarify the effects of different models of observation type on the annual global air-sea CO$_2$ gas flux estimation, global air-sea CO$_2$ gas flux was compared using the different models.

2. Estimation of the air-sea CO$_2$ gas flux
The following air-sea CO$_2$ gas transfer velocity models (field and laboratory experiment and hybrid model considering wave breaking) on the global air-sea CO$_2$ gas flux estimation were used. For the air-sea CO$_2$ gas transfer velocity by field experiment, we used both models Wanninkhof (1992) and Wanninkhof and McGillis (1999) and McGillis (1999). For the air-sea CO$_2$ gas transfer velocity by laboratory experiment, Liss and Merlivat (1986) and Iwano et al. (2013) were used. We used both models Woolf (2005) and Suzuki et al. (2015) for the air-sea CO$_2$ gas
The air-sea CO$_2$ gas flux $F$ was estimated by eq. (1.1). Above models was used to calculate the CO$_2$ transfer velocity using the Schmidt number, $S_c$. Weiss (1974, 1980) provided an empirical formula to estimate the CO$_2$ gas solubility $S$ on the basis of data fitting among the solubility, temperature and salinity. The monthly sea surface salinity of WOA2013/ NODC/NOAA (World Ocean Atlas 2013 version 2/National Oceanographic Data Center/National Oceanic and Atmospheric Administration) climatological data was used. $\Delta p$CO$_2$ is taken from the global monthly climatology by Takahashi et al. (2009). In order to estimate the CO$_2$ transfer velocity, the 6 hourly (1.5 $\times$ 1.5 grid) wind speed and sea surface temperature data sets of ECMWF (European Centre for Medium-Range Weather Forecasts) 40 year reanalysis and 6 hourly (1.5 $\times$ 1.5 grid) wave period of the wind wave data set of ECMWF wave model were used. The data period is one year for 2001. This year does not include El Niño or La Niña events.

### 3. Results

Fig. 1 shows the relation between the CO$_2$ transfer velocity and wind speed $U_{10}$ for each CO$_2$ transfer velocity models. Although wind speed range is from 0 to 15 m/s for the CO$_2$ transfer velocity models without Iwano et al. (2013), wind speed range is just extend it in the high wind speed region (over about 15 m/s). Wind speed range for Iwano et al. (2013) proposed from 0 to 60 m/s by wave tunnel experiment. Although the ratio of extreme wind speed more than 15 m/s

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![Fig. 1](image-url)

**Fig. 1** Relationship between the CO$_2$ transfer velocity $k_L$ and wind speed $U_{10}$ (black dotted and dashed line Wanninkhof (1992), black dotted line Wanninkhof and McGillis (1999), black dashed line Liss and Merlivat (1986), black solid line Iwano et al. (2013), blue solid line Woolf (2005) with significant wave height $H_s = 3$ m, blue dotted line Woolf (2005) with significant wave height $H_s = 5$ m, red solid line Suzuki et al. (2015) with wave age $C/U = 1$, red dotted line Suzuki et al. (2015) with wave age $C/U = 1/2$, $C$ is the theoretical phase speed) All data have been normalized to $S_c = 660$. 

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transfer velocity by hybrid model considering wave breaking.

The air-sea transfer velocity for each model is expressed as following,

- **Wanninkhof (1992):**
  $$ k_L = 0.31U_{10}^2 $$ (2.1)

- **Wanninkhof and McGillis (1999):**
  $$ k_L = 0.0283U_{10}^3 $$ (2.2)

- **Liss and Merlivat (1986):**
  $$ k_L = 2.85U_{10} - 9.65 $$
  $$ 3.6 m/s < U_{10} < 13m/s $$ (2.3a)

- **Iwano et al. (2013):**
  $$ k_L = 1.6U_{10}^{25} $$
  $$ U_{10} < 33.6 m/s $$ (2.4a)

- **Woolf (2005):**
  $$ k_L = 5.9U_{10} - 49.3 $$
  $$ U_{10} > 13m/s $$ (2.3c)

- **Iwano et al. (2013):**
  $$ k_L = 8.43 \times 10^{-4}U_{10}^{4.4} $$
  $$ U_{10} \geq 33.6 m/s $$ (2.4b)

- **Suzuki et al., (2015):**
  $$ k_L = 2.06U_{10}(1-W)+1035W $$ (2.6)

$W$ is the fractional area of whitecap coverage, $W = 3.88 \times 10^{-7} R_d^{0.9}$
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for the used wind speed data of ECMWF was about 3%, the time and spatial resolution of used data is 6 hourly and 1.5 deg. × 1.5 deg. grid, respectively. Ratio of extreme wind speed region may be increase, because of the time and spatial resolutions for the global data set improve steadily. Consequently, the comparison of the different model include extreme wind speed region is necessary. In this figure, it shows large variation of the CO₂ transfer velocity by difference of each model. Laboratory experiment’s model and Woolf’s (2005) hybrid model shows smaller values compared with other models. Wanninkhof and MacGillis’s (1999) model shows larger values compared with other models. Wanninkhof’s (1992) model and Suzuki’s et al. (2015) model shows nearly values. Woolf’s (2005) hybrid model includes a wave parameter on whitecap coverage, but in the whitecap-free region the relationship between the air-sea CO₂ transfer velocity and friction velocity from the result of laboratory experiments (Jahne et al. 1987). Therefore, Woolf’s (2005) hybrid model shows nearly values to laboratory experiment models.

The annual global air-sea CO₂ gas flux using models (Wanninkhof (1992), Wanninkhof and McGillis (1999), Liss and Merlivat (1986), Iwano et al. (2013), Woolf (2005) and Suzuki et al. (2015)) are shown in Table 1. The result of Wanninkhof and McGillis’s (1999) model has the biggest value and the result of Liss and Merlivat’s (1986) model has smallest value. The difference between the result of Wanninkhof and McGillis’s (1999) model and Liss and Merlivat’s (1986) model was 0.76 PgC/year.

Fig. 2 shows the monthly global air-sea CO₂ gas flux from each model. It shows the difference between the results of each model is small in August and September, and large in the other months. It is corresponding to global mean ΔpCO₂ values near zero. Laboratory experiment’s models (Liss and Merlivat (1986) and Iwano et al., (2013)) and Woolf’s (2005) hybrid model also shows smaller values compared with other models, because of small model values (see Fig. 1). Fig. 3 shows the air-sea CO₂ gas flux in 7.5 degree latitude bands. In low latitude region, the result of Iwano et al.’s (2013) model of labo-

Table 1 Annual global net air-sea CO₂ gas flux for 2001

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<tr>
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<th>Annual global net air-sea CO₂ gas flux (PgC/year)</th>
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<tr>
<td><strong>Field experiment:</strong></td>
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<tr>
<td>Wanninkhof (1992)</td>
<td>–1.18</td>
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<tr>
<td>Wanninkhof and McGillis</td>
<td>–1.43</td>
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<td>(1999)</td>
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<td>Laboratory experiment:</td>
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<td>Liss and Merlivat (1984)</td>
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<td>Iwano et al. (2013)</td>
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<td>Hybrid (wind speed and</td>
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<td>whitecap coverage):</td>
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<tr>
<td>Woolf (2005)</td>
<td>–1.04</td>
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<tr>
<td>Suzuki et al. (2015)</td>
<td>–1.22</td>
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Fig. 2 Monthly series of global air-sea CO₂ gas flux estimated by each CO₂ transfer velocity models (filled circle and solid line Wanninkhof (1992), filled circle and dashed line Wanninkhof and McGillis (1999), open circle and dashed line Woolf (2005), open circle and solid line Suzuki et al. (2015), triangle and dashed line Liss and Merlivat (1986), triangle and solid line Iwano et al. (2013))
ratory experiment shows largest value. In Fig. 4, we have extracted, from Fig. 1, the CO₂ transfer velocity in wind speed range from 0 to 15 m/s. Iwano et al.’s (2013) model shows largest the CO₂ transfer velocity’s value in wind speed about 5 m/s without Woolf’s (2005) model with significant wave height 5 m. The difference of each model in low latitude is large, same as the difference in middle latitude. Importance of the influence of the wave and wave breaking had been sug-
gested in a high wind speed region of middle and high lati-
tude, however the results shows the importance of the difference of each model in low wind speed region, low latitude. The result of Suzuki et al.’s (2015) model shows largest value in middle latitude. The results of Wanninkhof’s (1992) model and Wanninkhof and McGillis’s (1999) model have almost same value without low latitude region.

Fig. 4 Relationship between the CO₂ transfer velocity $k_L$ and wind speed $U_{10}$ in wind speed range from 0 to 15 m/s in Fig. 1.
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4. Summary

In this study, in order to clarify the effects of different models of observation type on the annual global air-sea CO$_2$ gas flux estimation, global air-sea CO$_2$ gas flux was compared using the different models: Wanninkhof (1992) and Wanninkhof and McGillis (1999) for field measurement, Liss and Merlivat (1986) and Iwano et al., (2013) for laboratory measurement and Woolf (2005) and Suzuki et al., (2015) for hybrid of the composition of wind speed and ratio of whitecap coverage. The maximum difference of annual global air-sea CO$_2$ gas flux was 0.76 PgC/year for difference between Wanninkhof and McGillis’s (1999) model and Liss and merlivat (1986). As a result of monthly change, the difference between the results of each model is small in August and September, and large in the other months. In middle latitude, the air-sea CO$_2$ gas flux of each model without Liss and Merlivat’s (1986) model is large. In low latitude, the air-sea CO$_2$ gas flux of Iwano et al.’s (2013) model is large. The difference of each model in low latitude is large, same as the difference in middle latitude. It was shown that there is a significant difference of each model for different observation type and especially the difference of the result of each model in low latitude is significant for the estimation of air-sea CO$_2$ gas flux.

References


