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Note on estimating air-sea flux of CO_2 using mean wind speed statistics

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Abstract

Statistical properties of the air-sea flux of CO_2 are estimated based on mean wind speed statistics. This is achieved by applying the same eight wind speed-dependent transfer velocity parameterizations of CO_2 as used by Woolf et al. (2019) together with mean wind speed statistics from one location in the North Sea and one in the North Atlantic. These results demonstrate solely the contribution of the statistical uncertainties in terms of large standard deviations of the wind speed-dependent gas transfer velocity of the CO_2 flux at both locations.

Keywords
Air-sea flux of CO_2; Transfer velocity of CO_2; Air-sea exchange; Mean wind speed statistics; Stochastic method

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1. Introduction

The atmosphere-ocean exchange of carbon dioxide (CO_2) affects the processes of climate change, and the mechanisms of these exchange processes have been investigated extensively over the last decades. Examples of recent works including literature reviews are provided by Roobaert et al. (2018), Woolf et al. (2019), and Fay et al. (2021). The air-sea exchange of CO_2 is primarily driven by the turbulence in the sea surface boundary layer due to the interaction of wind, waves, and currents. However, most of the CO_2 exchange relationships are parameterized in terms of wind speed (Villas Bôas et al., 2019).

Roobaert et al. (2018) discussed the uncertainty in air-sea CO_2 flux associated with various parameterizations of the gas transfer velocity and wind speed products. Among their findings were that particular attention is required when choosing the parameterization calculating regional and global CO_2 flux. For global flux estimates, they found that the uncertainty attributed to the choice of wind speed products is limited to about 10%. However, uncertainties attributed to the choice of wind speed products were more pronounced in regional flux estimates, e.g. for the North Atlantic.

Fay et al. (2021) provided a data set facilitating a standardized approach for CO_2 flux calculations based on observations of surface ocean partial pressure of CO_2. This was applied to demonstrate that the global scaling of the gas transfer velocity can change the CO_2 flux on average by 5% compared to non-standardized flux calculations. Moreover, the application of the appropriate gas exchange coefficient through proper scaling appears to have a larger impact on the resulting flux than only the choice of wind speed products.

Woolf et al. (2019) addressed the uncertainties in the air-sea CO_2 flux, using eight polynomial parameterizations of the transfer velocity of CO_2 to evaluate the standard uncertainty as a result from several sources of error. However, some uncertainties were not considered explicitly, such as those relating to e.g. different data sets of wind speed. Hence, motivated by this, the purpose of this note is to give examples of results estimating the CO_2 flux by solely using the same eight transfer velocity formulations as in Woolf et al. (2019) together with the mean wind speed statistics at one location in the North Sea and one location in the North Atlantic. These examples of results demonstrate the statistical uncertainties in terms of large standard deviations of the transfer velocity at both locations and thus affecting the uncertainties of the CO_2 flux.

This introduction is followed by giving the background of the CO_2 flux including the transfer velocity parametrizations used. Then, the statistical properties of the transfer velocity of CO_2 are given. Finally, a summary and the main conclusions are provided.

2. Background

Woolf et al. (2019) (hereafter referred to as W19) used a standard equation for the net air-sea flux, F, of a gas:

$$F = -K_w\left(\frac{C_a}{H} - C_w\right) \tag{1}$$

where K_w is the transfer velocity, H is the Henry's law constant, C_a and C_w are the concentrations at the top and at the base, respectively, of the mass boundary layer at the sea surface. Moreover, W19 substituted the waterside transfer velocity k_w for K_w, using a traditional polynomial wind speed-dependent transfer velocity parameterized as

$$k_w = \left(\frac{Sc}{660}\right)^{-\frac{1}{2}}\left(c_0 + c_1V + c_2V^2 + c_3V^3\right) \tag{2}$$

Here $V \equiv U_{10}$ is the instantaneous wind speed 10 m above the sea surface, Sc is the Schmidt number of the dissolved gas, and c_0, c_1, c_2, c_3 are coefficients. W19 calculated V by a computationally efficient method as described in the supporting information of their paper. Eight polynomial relationships of k_w were used, where the coefficients c_0, c_1, c_2, c_3 of the respective studies referred to as models 1–8, are given in Table 1. It should be noted that the $k_w - V$ polynomials for models 1, 3, 5 are quadratic; models 2, 4, 8 are cubic; model 7 is hybrid linear, quadratic; model 6 is hybrid linear, quadratic, cubic. Moreover, models 1–7 are based on the dual traces experiments method, while model 8 is based on the direct micrometeorological method (more details are provided in W19).

In the present article the mean wind speed statistics of V is used, which often is available for the considered ocean area, e.g. as parametric models of the cumulative distribution function (cdf) (or the probability density function (pdf)) of the in situ mean wind speed of V (Bitner-Gregersen, 2015). The present note provides examples of results adopting two $cdfs$ of V based on mean wind speed statistics from the North Sea (NS) (Johannessen et al., 2001), and the North Atlantic (NA) (Mao and Rychlik, 2017). Johannessen et al. (2001) based their cdf on 1 hourly values of V from wind measurements covering the years 1973–1999 from the northern North Sea (see the reference for more details). Mao and Rychlik (2017) based their four $cdfs$ on the wind speed along different ship routes in the North Atlantic (NA) fitted to 10 years of mean wind speed data; the cdf adopted here are from the location 20°W 60°N (South of Iceland) (see the reference for more details). Both these $cdfs$ are given by the two-parameter Weibull model

$$P(V) = 1 - \exp\left[-\left(\frac{V}{\theta}\right)^{\beta}\right]; \qquad V \geq 0 \tag{3}$$

with the Weibull parameters θ and β as

$$\text{NS}: \ \theta = 8.426 \ \text{m/s} \qquad \beta = 1.708 \tag{4}$$

$$\text{NA}: \ \theta = 10.99 \ \text{m/s} \qquad \beta = 2.46 \tag{5}$$

Figure 1 depicts the $pdfs$ of V for NS and NA (i.e. $p(V) = \mathrm{d}P(V)/\mathrm{d}V$):

$$p(V) = \frac{\beta}{\theta}\left(\frac{V}{\theta}\right)^{\beta-1}\exp\left[-\left(\frac{V}{\theta}\right)^{\beta}\right]; \qquad V \geq 0 \tag{6}$$

It is observed that the peak value of the NA pdf is located at a larger value of V than for the NS pdf, and that the peak value of the NA pdf is slightly lower than for the NS pdf. These observed features reflect that the expected (mean) value of V is larger for NA than for NS (see Section 3).

Table 1. CO_2 flux formulae and coefficients according to Eq. (7) for models 1–8. Authors: H06 (Ho et al., 2006); H07 (Ho et al., 2007); S11 (Smith et al., 2011); W09 (Wanninkhof et al., 2009); N00 (Nightingale et al., 2000); M01 (McGillis et al., 2001).

Model number	Authors	c_0	c_1	c_2	c_3	NS $E[k]$ [m/s]	NS $R[k]$	NS $\frac{k(E[V])}{E[k]}$	NA $E[k]$ [m/s]	NA $R[k]$	NA $\frac{k(E[V])}{E[k]}$
1	H06	0	0	0.254	0	19.6	1.18	0.73	28.7	0.82	0.84
2	H07	0	0	0	0.0162	15.7	1.88	0.44	24.0	1.23	0.63
3	H07	3.6	0	0.231	0	21.4	0.98	0.78	29.7	0.72	0.86
4	H07	9.2	0	0	0.0124	21.2	1.06	0.68	27.5	0.82	0.75
5	S11	0	0	0.299	0	23.0	1.18	0.73	33.8	0.82	0.84
6	W09	3	0.1	0.064	0.011	19.3	0.66	0.62	27.5	0.95	0.74
7	N00	0	0.318	0.212	0	18.7	1.10	0.77	27.0	0.77	0.86
8	M01	3.3	0	0	0.026	28.5	1.66	0.50	41.7	1.13	0.66

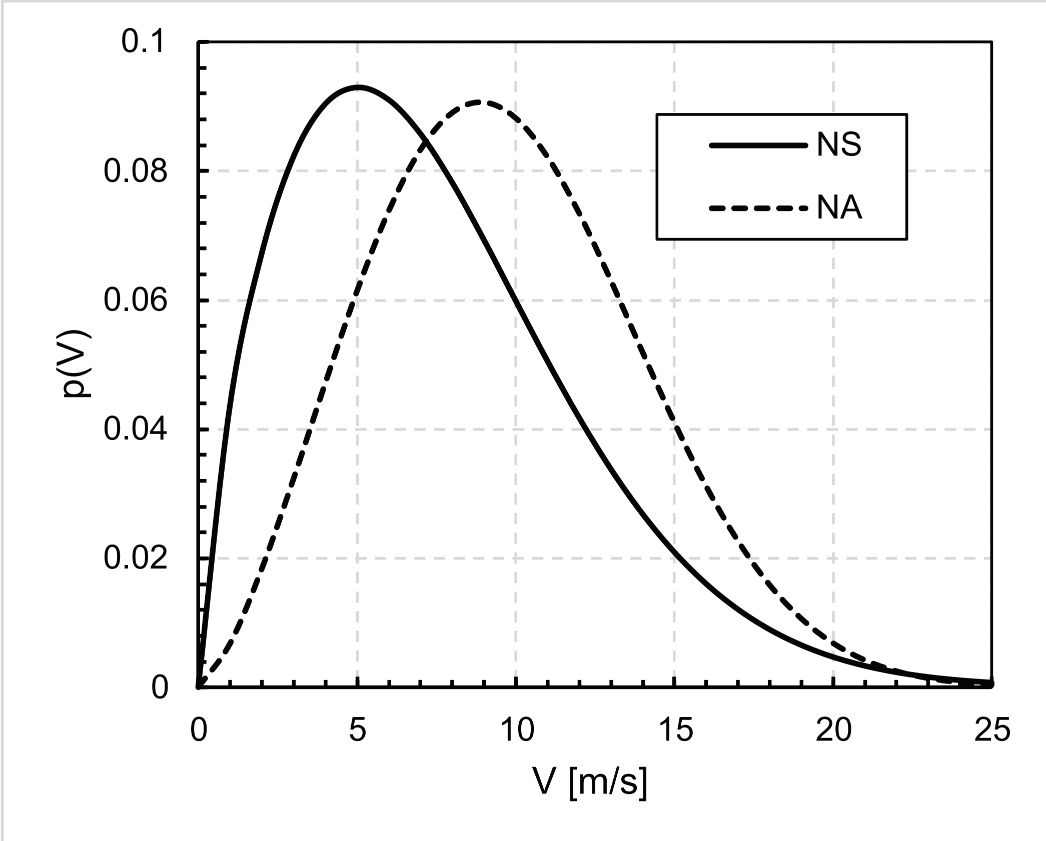

Figure 1. $p(V)$ versus V for the North Sea (NS) and the North Atlantic (NA) (see Eqs. (4) to (6)).

3. Estimation of wind speed-dependent transfer velocity of CO_2

First, the combination of Eqs. (1) and (2), and defining k yields

$$k \equiv \frac{F}{\left(\frac{Sc}{660}\right)^{-1/2}\left(\frac{C_a}{H} - C_w\right)} \tag{7}$$

$$= c_0 + c_1 V + c_2 V^2 + c_3 V^3$$

Now the statistical values of F (for given values of Sc, H, C_a, C_w, c_0, c_1, c_2, c_3) are given in terms of the statistical quantities of V, which are calculated from the $cdfs$ of V. Here results are exemplified by the expected (mean) value of F, $E[F]$, and the variance of F, $Var[F]$, which requires calculation of $E[k]$ and

$$Var[k] = E[k^2] - (E[k])^2 \tag{8}$$

Then, calculation of $E[V^n]$ is required, which for the Weibull-distributed V is given by (Bury, 1975)

$$E[V^n] = \theta^n \Gamma\left(1 + \frac{n}{\beta}\right) \tag{9}$$

where Γ is the gamma function. Now, from Eq. (7):

$$k^2 = {c_0}^2 + 2c_0c_1V + (2c_0c_2 + {c_1}^2)V^2 \tag{10}$$
$$+2(c_0c_3 + c_1c_2)V^3 + (2c_1c_3 + {c_2}^2)V^4$$
$$+2c_2c_3V^5 + c_3^2V^6$$

Then, $Var[k]$ is obtained from Eq. (8) by substituting $E[k]$ (using Eqs. (7) and (9)) and $E[k^2]$ (using Eqs. (10) and (9)).

The results for NS and NA for models 1–8 are given in Table 1 in terms of $E[k]$, and the coefficient of variation, $R[k] = (Var[k])^{1/2}/E[k]$. One should note that $R[k] = R[F] = (Var[F])^{1/2}/E[F]$ for given values of Sc, H, C_a, C_w. From Table 1 it appears that the values of $E[k]$ are larger at the NA location than at the NS location for all models, with the largest value for model 8 and the smallest value for model 2 at both locations. Thus, this is also the case for $E[F]$ for given values of Sc, H, C_a, C_w. Furthermore, for all models the uncertainties in terms of the coefficient of variation $R[k] = R[F]$ is fairly large; in the ranges of 0.66–1.88 and 0.72–1.23 for NS and NA, respectively, i.e. reflecting large standard deviations $(Var[k])^{1/2}$ and $(Var[F])^{1/2}$ at both locations. More specifically, for NS within quadratic/cubic models, it appears that the quadratic models give better results with lower uncertainty than the cubic models, where the quadratic model 3 gives the lowest uncertainty with $R[k] = 0.98$, while the cubic model 2 gives the highest uncertainty with $R[k] = 1.88$. However, for NA within quadratic/cubic models it appears that the cubic model 8 gives the lowest uncertainty with $R[k] = 1.13$, while the quadratic model 3 gives the highest uncertainty with $R[k] = 0.72$. It is also noted that the hybrid linear, quadratic, cubic model 6 gives lower uncertainty for NA ($R[k] = 0.95$) than for NS ($R[k] = 0.66$), while the hybrid linear, quadratic model 7 gives lower uncertainty for NS ($R[k] = 1.10$) than for NA ($R[k] = 0.77$). Thus, these results suggest that it cannot be concluded which of the models gives the lowest uncertainty at a given location. However, it is demonstrated that the uncertainty for a specific model depends on the mean wind speed statistics at the location considered.

As an exercise, the global value of the coefficient c in the transfer velocity, $c = c^* = 0.251$ (as suggested by Roobaert et al. (2018) using the quadratic model by Wanninkhof (2014)), which is very close to $c = c_2 = 0.254$ for model 1 (Table 1). Thus, if this c^* value is used together with the NS and NA wind speed statistics, the results are very close to the present results for $R[k]$ in Table 1, i.e. the uncertainty is 18% for both NS and NA.

An alternative to the presented stochastic method is to use a deterministic method by substituting $E[V]$ for V in Eq. (7) for models 1–8, i.e. to calculate $k(E[V])$. From Eqs. (4), (5) and (9) it follows that the values of $E[V]$ are 7.52 m/s and 9.75 m/s for NS and NA, respectively, i.e. reflecting the features of the $pdfs$ of V depicted in Figure 1. The results of substituting this in Eq. (7) using the results for $E[k]$, yield the deterministic to stochastic method ratios $k(E[V])/(E[k])$ given in Table 1. Here it is noted that these ratios equals $F(E[V])/(E[F])$ for given values of Sc, H, C_a and C_w. At both locations these ratios are smaller than one; with a mean value of 0.66 for NS and 0.77 for NA. Thus, it is recommended to use the stochastic method as the stochastic features of the CO_2 flux are taken into account consistently, which is not the case using the deterministic method.

The present discussion of the uncertainties is solely based on the $k - V$ relationships without considering the other constituents in the CO_2 calculations. This implies that if the regional or global values of Sc, H, C_a, C_w and the associated uncertainties are taken into account, the present results may be altered. However, a complete uncertainty analysis on a regional or global scale should include mean wind speed statistical data using the stochastic analysis method, as well as including the uncertainties in the other constituents used in the CO_2 calculations.

4. Conclusions

Statistical properties of the air-sea flux of CO_2 are estimated based on mean wind speed statistics. This is achieved by applying the same eight wind speed-dependent transfer velocity parameterizations of CO_2 as Woolf et al. (2019) and with mean wind speed statistics from one location in the North Sea and one in the North Atlantic. Thus, these examples of results demonstrate solely the contribution of the statistical uncertainties of the wind speed-dependent gas transfer velocity of the CO_2 flux.

The flux of CO_2 is largest in the North Atlantic for the cubic model 8 (McGillis et al., 2001) and smallest in the North Sea for the cubic model 2 (Ho et al., 2007). For all models, the coefficient of variation is fairly large, i.e. in the range of 0.66 (in the North Sea for the hybrid linear, quadratic, cubic model 6) to 1.88 (in the North Sea for the cubic model 2), and it cannot be concluded which of the models that give the lowest uncertainty at a given location. However, the results may be altered if the uncertainties associated with the other constituents in the CO_2 calculations are included.

The present stochastic method should be used rather than the deterministic method since the statistical features of the CO_2 flux are consistently taken into account.

A complete uncertainty analysis should include mean wind speed statistical data using the stochastic analysis method, as well as including the uncertainties in the other constituents used in the CO_2 calculations.

Conflict of interest

The author is an Editorial Board Member for this journal and was not involved in the editorial review or the decision to publish this article.

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