Comment on “Measurements of air-sea gas exchange at high wind speeds in the Southern Ocean: Implications for global parameterizations” by D. T. Ho et al.

Xin Zhang

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1. Introduction

[1] Recently, Ho et al. [2006] presented the gas transfer velocity measurements at high wind speeds from the SOLAS New Zealand Air-Sea Exchange (NZ-SAGE) experiment conducted in the western Pacific sector of Southern Ocean. Gas transfer velocities were determined using the $\text{He}/\text{SF}_6$ dual gas tracer technique. The NZ-SAGE experiment alone has more than doubled the number of $\text{He}/\text{SF}_6$-derived gas transfer velocity measurements from the open ocean, and the measurements spread into high wind speed range (above 10 m s$^{-1}$), which is extremely useful in determining empirical parameterizations of gas transfer velocity. One of the conclusions from the paper is that “The results clearly reveal a quadratic relationship between wind speed and gas transfer velocity, rather than a recently proposed cubic relationship.” While we congratulated their significant success in collecting gas transfer velocity measurements at high wind speeds through the NZ-SAGE experiment, we would like to point out that one of the assumptions implied in the data presentation, namely the form of enhancement factor, $\varepsilon$, that was adopted, favors the quadratic relationship between wind speed and gas transfer velocity. Therefore the above conclusion is less convincing, and we also fear that hasty readers could get the wrong impression when comparing gas transfer velocity measured at different timescales. This is of great importance to the outcomes of data-fitting parameterizations that are currently employed in estimating air-sea $\text{CO}_2$ fluxes and in climate models for study of $\text{CO}_2$ cycles.

2. Wind Variability and Gas Transfer Velocity Averaged Over Different Timescales

[2] The gas transfer velocity can be derived from the concentration ratio of injected gases through the following relationship, provided that certain conditions are satisfied [Wanninkhof et al., 1993]:

$$k_{3\text{He}}(t) = \left( 1 - \frac{\text{Sc}_{\text{He}}}{\text{Sc}_{3\text{He}}(t)} \right)^{-1/n} \frac{d}{dt} \left[ h \ln \left( \frac{[\text{He}]}{[\text{SF}_6]} \right) \right],$$

(1)

where $[\text{He}]$ stands for gas concentration, $\text{Sc}$ is Schmidt number, $h$ is the depth of mixed layer, and $n$ is Schmidt number scaling exponential constant [Jähne et al., 1987]. In the NZ-SAGE experiment, samples of $\text{He}$ and $\text{SF}_6$ used to derive gas transfer velocity were taken about every 12 hours or more; that is, the resulting transfer velocity is averaged over a time period of at least $T = 12$ hours since

$$\frac{1}{T} \int_{0}^{T} dk_{3\text{He}}(t) = \frac{1}{T} \left[ h \ln \left( \frac{[\text{He}]}{[\text{SF}_6]} \right) \right]_{0}^{T},$$

(2)

where the ratio of the Schmidt numbers weakly depends on temperature and salinity and can be assumed to be fairly constant throughout the time period. The transfer velocity depends strongly on wind speed and can change rapidly with time. Assuming a simple power law relationship between instantaneous gas transfer velocity and wind speed, $k_{\text{inst}} = a_m U_m$, it follows that

$$\langle k \rangle_T = a_m \langle U_m \rangle_T \simeq \frac{1}{T} \left[ h \ln \left( \frac{[\text{He}]}{[\text{SF}_6]} \right) \right]_{0}^{T} \left( 1 - \frac{\text{Sc}_{\text{He}}}{\text{Sc}_{3\text{He}}} \right)^{-1/n},$$

(3)

where $\langle \cdot \rangle_T$ stands for averaging over a time period $T$ and

$$k_{\text{inst}} = \langle k \rangle_T \frac{U_m}{\langle U_m \rangle_T} = \frac{1}{\varepsilon_{\text{model}}} \langle k \rangle_T,$$

(4)

The chosen enhancement factor, $\varepsilon$, implies a prior condition of parameterization model assumption. On the other hand, the advantage of an enhancement factor is that it eliminates some uncertainties stemming from wind speed variability.

[2] The mixed plots of mean transfer velocities of different timescales against mean wind speed can be quantitatively deceiving since the coefficients of nonlinear power relationship depend on the variability of wind during the averaging periods. For example, let

$$k_{\text{inst}} = a_0 + a_1 U_1 + a_2 U_2^2 + a_3 U_3^3,$$

(5)
then, fitting mean transfer velocity, \( \langle k \rangle_T \), with mean wind speed, \( \langle U \rangle_T \), according to the same form of polynomial, it can be found that

\[
\langle k \rangle_T = a_0 + a_1 \langle U \rangle_T + a_2 \langle U \rangle_T^2 + a_3 \gamma_T \langle U \rangle_T^3
\]

where

\[
a_2 = a_2 \frac{\langle U \rangle_T^3}{\langle U \rangle_T^2} = \varepsilon_2 a_2, \quad \text{and} \quad a_3 = a_3 \frac{\langle U \rangle_T^3}{\langle U \rangle_T} = \varepsilon_3 a_3.
\]

[4] For the purposes of seeking intrinsic empirical fitting coefficients, it makes better sense to compare the mixed data in the vector space of \{1, \langle U \rangle, \langle U^2 \rangle, \langle U^3 \rangle\} since, as far as wind speed variability is concerned, the corresponding nonlinear coefficients should be independent of the averaging duration.

3. Discussions

[5] The wind variability enhancement factors can be expanded as

\[
\varepsilon_2 = 1 + \sigma_T^2
\]

\[
\varepsilon_3 = 1 + 3 \sigma_T^2 + \frac{\sigma_T^3}{\langle U \rangle_T} \gamma_T
\]

[6] The wind enhancement factor, \( \varepsilon_2 \), of the NZ-SAGE data is given by Ho et al. [2006] (Table 1 and Figure 2) (As noted by Ho et al. [2007], the transfer velocities of Ho et al. [2006, Table 1] are misprinted. The transfer velocities of Ho et al. [2006, Figure 2] are used in the final revision here.); therefore, \( \gamma_T \) can be calculated. It should be noted here that \( \gamma_T \) is small over the long sampling periods (24–59 hours) of high wind events. The pseudo skewness cannot be precisely calculated from the data given in the paper. However, since \( \gamma_T \) is small over the long sampling periods (24–59 hours)

\[
\text{pseudo deviation: } \sigma_T^2 = \frac{\langle U - \langle U \rangle_T \rangle^2}{\langle U \rangle_T^2}
\]

\[
\text{pseudo skewness: } \gamma_T = \frac{\langle U - \langle U \rangle_T \rangle^3}{\sigma_T^3}
\]
coefficient, $r^2$, equaled 0.79 and 0.80 for $\langle k \rangle_T$ correlating $\langle U^2 \rangle_T$ and $\langle U^3 \rangle_T$ respectively. This test cannot indiscriminately reject either one of the simple power law hypotheses. There is no significant difference in fitting errors between quadratic and cubic relationships between wind speed and transfer velocity, provided that our approximation of $\varepsilon_3$ holds. While there are other rigorous statistical methods to determine the goodness of fit, we are limited by the amount and quality of the data here. The linear regression suggests a significant nonzero intercept, $b_0 > 0$. The requirement of zero transfer velocity at zero wind speed is nonphysical, therefore not necessary [Zhang and Cai, 2007]. It should be pointed out here that the two measurement points at the highest wind speed have a heavy weight in deciding the slope of the linear fitting, $a_0$, while the rest of data points, which contain most of the discrepancies of wind speeds between the ship-based measurements and satellite observations, affect zero intercepts of the linear regression. [7] The calculations here are basically similar to those of the SOFeX by Wanninkhof et al. [2004]; however, the analysis is made more rigorous by interpreting the results in a frame of statistical hypothesis testing. They found that the cubic relationship is somewhat better than the quadratic relationship. Since the transfer velocities measured in the SOFeX experiment are systematically larger than those derived from the NZ-SAGE experiment, it is not surprising that $a_2$ and $a_3$ derived from the SOFeX are larger than those of NZ-SAGE. Wanninkhof et al. [2004] have pointed out that only samples with continues decaying of $[^3H]/[SP_3]$ were selected, which is a necessary condition for equation (1).

4. Conclusions

[8] Because of the nature of nonlinear relationship between transfer velocity and wind speed, readers need to take particular caution when considering plots of transfer velocity against mean wind speed, especially with mixed average data over different timescales. As we have demonstrated here, statistical hypothesis testing theories, that are well established, can be used in making a better decision with respect to an uncertain hypothesis. While the simple power law relationships of wind speed [Wanninkhof, 1992; Wanninkhof and McGillis, 1999] are discussed here, the arguments may also be applied to test other nonlinear models, such as a hybrid surface and bubble transfer model [Woolf, 2005] and surface roughness model [Glover et al., 2002]. It is essential to continue accumulating open sea measurements of gas transfer velocity both in short and long timescales with respect to the timescale of wind variability.

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References


[8] X. Zhang, Scripps Institution of Oceanography, University California, San Diego, La Jolla, CA 92093–0213, USA. (xzhang@ucsd.edu)