egusphere-2024-628 | Honkanen et al. (2024): Interannual and seasonal variability of the air–sea CO_2 exchange at Utö in the coastal region of the Baltic Sea

Dear anonymous referee #2,

Thank you for your comments. They highly improve the quality of the publication. Especially clarifications on the flux theory and methods were useful.

Below, the referee comments (shown in red) are answered point by point.

The manuscript presents an extensive data-series of valuable data of air-sea exchange using EC technique as well as bulk calculated fluxes. The data shows the seasonal cycle and net excheange over one region in the Baltic Sea and is a valuable analysis. Some significant clarifications are needed to enrure full understanding of the use of the different methods and the accuracy.

Comments: The gas transfer velcocity is controlled bu severla factors (line 45 page 2), this is of particular importance for a coastal site and should be further discussed (see eg Garbet et al ., 2014).

The gas transfer velocity indeed plays a very important role in governing the air-sea CO_2 flux, and the processes controlling it should be elaborated. For this reason, a list of processes will be added in L45:

“Several processes affect the efficiency of the gas transfer, such as micro scale wave breaking, turbulence, bubbles, sea spray, rain, waves and surface films (Garbet et al., 2014, p. 56). Typically the gas transfer velocity is parameterized…“

Also, the appropriate reference will be added to the reference list in L549:

“Garbe, C.S, Rutgersson, A., Boutin, J., de Leeuw, G., Delille, B., Fairall, C.W., Gruber, N., Hare, J., Ho, D.T., Johnson, M.T., Nightingale, P.D., Pettersson, H., Piskozub, J., Sahlée, E., Tsai, W., Ward, B., Woolf, D.K., and Zappa, C.J.: Transfer Across the Air-Sea Interface. In: Liss, P.S., Johnson, M.T. (eds), Ocean-Atmosphere Interactions of Gases and Particles, Springer Earth System Sciences, Springer, Berlin, Heidelberg, https://doi.org/10.1007/978-3-642-25643-1_2, 2014“

Page 7, line 160. The choice of accurate data is unclear (26% of the time), is this due to wind directions only, what about fluxes below detection limit and other errors in the data. Is the non-stationarity the only quality control criteria?

The EC flux data was quality controlled by removing data that was (1) during wrong wind directions, (2) non stationary, (3) affected by the ships or (4) measured during maintenance/malfunction of system. The detection limit was not considered in the quality control. In Honkanen et al. (2018), the wind turbulence statistics are discussed. We also briefly looked into the EC fluxes during low flux months, and the EC fluxes seemed mostly to behave nicely as a function of friction velocity (data not shown).

L159-162 will be modified to describe the amount of data removed due to the wrong wind directions:

"The EC method was supported by flux gap-filling for those periods, when **reliable** EC data were not available due to flux footprint originating from the island (outside of the 190–350◦ wind sector), non-stationary flux conditions or CO2 molar fraction disturbance by ships passing the flux footprint area. The EC data were considered appropriate for 26% of the time and the remaining periods were gap-filled as described below. **Approximately 60 % of the time, the wind at Utö blows from appropriate direction suitable for the air-sea exchange measurements (Honkanen et al. 2018). Thus, the reminder of the data removal is caused by the nonstationarity, ship interference or instrument maintenance/malfunctions.** Based on…"

Page 8,line 175: The parameteirsation is stated to be site specific, why is this? What makes the parameterisation site specific. it is enerally thought that the transfer coefficient could be generally described in terms of forcing processes.

Many aspects of the coast, such as fetch and bottom geometry, modify the wave field, and thus likely affect the gas transfer. Fetch is an important factor limiting the wind induced waves. In the case of Utö, the closest shoal is approximately 1.4 km west-southwest, and likely the waves can not grow as freely as in open sea areas. Here, we did not analyse in detail the gas transfer as a function of wind direction but might be interesting in future, especially if connected to other measurements.

L174 will be modified accordingly: "This parametrization is a site specific, due to for instance the wind fetch and the bottom geometry, and slightly differs from the one given for the open ocean…"

Line 180: three sources of data: EC, Bulk and reconstructed, it is unclear how much data of each category and the distribution of situations. Does this in some way bias the analysis?

Combining EC fluxes with parameterized fluxes are common practice. The EC and parameterized flux data likely are distributed uniformly. However, the parameterization using reconstructed/interpolated may have been used mostly during the summer time, when the pipe system was offline. The interpolated or reconstructed data was used for less than 15% of the time. Its accuracy was discussed briefly in L454. Typically, during summer time, the seawater pCO2 is low, the absolute gradient between the sea and the water is large, and the relative inaccuracy effect on the calculated flux should be small.

L462 A text showing the net exchange based on the EC flux will be included:
"The comparison between the annual budgets calculated using the parametrization and the EC method is not straightforward as the EC data set contains frequent gaps. However, the average annual air-sea CO2 exchange using only the EC method was 19.6 gC m^{-2} y^{-1}, which is slightly lower than the estimate received using the parametrization and the EC data together."

section 3.4: How are the large drops in salinity explained?

L244 A brief explanation on the salinity drops will be added:

"Large drops in salinity indicate fresh water intrusion. As they seem to occur during the late winter or early spring, they are possibly a result of melting snow or ice."

section 3.5: How can the variability in Chl-a be explained?

The full picture of the Chl-a development is out of scope this paper, as it is governed by a complex mixture of meteorological, hydrographical and biological processes. Kraft et al. (2022) has studied the algal dynamics at Utö.

A brief description of the algal dynamics will be added in L253:

"The algal dynamics is controlled by multiple factors, such as solar irradiation, wind and temperature, e.g. calm and warm weather favors cyanobacterial growth (Kraft et al. 2021)."

section 3.7: Also the variability in the wind is relevant, this should be discussed.

Wind is an important factor contributing to the gas transfer and requires more attention. The importance of the wind will be added in L272:

"As the gas transfer velocity has typically been parameterized using a quadratic relation of wind speed (Wanninkhof, 2014), small changes from the 5-year average may prove to be important for enhancing or suppressing the air-sea CO_2 flux. For instance, calm weather in late 2019 likely restricted the release of CO_2 to the atmosphere."

Page 13, line 340: Here upwelling is discussed as one explanation, it would require some further discussion on the relevance and frequency of upwelling at this site.

In L341 a discussion on the relevance and the frequency of mixing processes will be added:

"The annual overturning of the water column plays an important factor bringing the carbon in the surface, to be released to the atmosphere. Similar effect can be generated by the wind-induced upwelling events, which can occasionally occur in the outer Archipelago (Lehmann et al, 2012)."

In L592 the reference will be added:

" Lehmann, A., Myrberg, K. and Höflich, K.: A statistical approach to coastal upwelling in the Baltic Sea based on the analysis of satellite data for 1990-2009, OCEANOLOGIA, 54, 369-393, https://doi.org /10.5697/oc.54-3.369/, 2012.

line 344: What is here meant by atmospheric deposition (of what)?

L344 will be clarified:

"… atmospheric deposition of carbon which constitutes carbon entering the system by precipitation (wet deposition) and from the atmospheric particles (dry deposition)."

Line 352: Uncertainty estimates on these numbers should be discussed. In addition there are several other estimates to compare with, based on observations and/or modelling.

A discussion on the uncertainty will be added in L355:

"The inaccuracies for the annual air-sea CO_2 exchanges were within 7.9-17.9 g C m^{-2} y^{-1}, indicating an inaccuracy range of approximately 40 % of the total exchange, and thus the positive net exchanges for all years are certain. The inaccuracy arises mostly from the gas transfer velocity parametrization (Appendix A), and attempts to improve the parametrization are needed."

Appendix A: The EC method, Again, it is unclear if the non-stationalrity is enough as quality criteria (what about detection limit).

The EC flux data was quality controlled by removing data that was (1) during wrong wind directions, (2) non stationary, (3) affected by the ships or (4) measured during maintenance/malfunction of system. The detection limit was not considered in the quality control. In Honkanen et al. (2018), the wind turbulence statistics are discussed. We also briefly looked into the EC fluxes during low flux months, and the EC fluxes seemed mostly to behave nicely as a function of friction velocity.

Two different criteria seems to be used for EC data (for budgets and estimates of transfer velocity). This should be further described and discussed.

A clarification will be added in L458:

"For the analysis of the gas transfer velocity, more strict quality control, compared to the general EC flux data, were used in order to robustly analyze the gas transfer velocity as a function of wind speed."

The choice to not include small pCO2 gradients helps to avoid problems of small values in the denominator, when solving the k from the flux equation. In the case of small values in the denominator, small relative inaccuracies can become problematic.

Description of error estimate is unclear.

L472-477 will be rewritten to be clearer:

"The error estimates for the air–sea CO2 fluxes were calculated assuming that the parametrization of the gas transfer velocity is the dominant source of uncertainty. The error estimate for the annual net exchange of air–sea CO2 was obtained by multiplying the annual balance with the median absolute percentage error (between the EC and parameterized flux), weighted by the proportion of parametrized fluxes. The uncertainty for the average net exchange of CO2 was 11.3 gC m^{-2} y^{-1}.

The error estimates for each year are given in Table 1. The error estimates for the monthly flux averages (shown in Fig. 9) are calculated as a monthly median absolute difference between the EC flux and parameterized flux, weighted by the proportion of parametrized fluxes."

Garbe C S et al 2014 Ocean-Atmosphere Interactions of Gases and Particles eds P Liss and M

Johnson (Springer-Verlag) 55-112

Suggested upwelling literature:

Lehmann, A., Myrberg, K., 2008. Upwelling in the Baltic Sea - A review. J. Mar. Syst. 74, S3–S12. https://doi.org/10.1016/j.jmarsys.2008.02.010.

Lehmann, A., Myrberg, K., Hoflich, K., 2012. A statistical approach to coastal upwelling in the Baltic Sea based on the analysis of satellite data for 1990–2009. Oceanologia 54, 369–393. https://doi.org/10.5697/oc.54-3.369. Norman, M., Parampil, S.R., Rutgersson, A., Sahl´ee, E., Norman, M.,

Parampil, S.R., Rutgersson, A., Sahl´ee, E., 2013. Influence of coastal upwelling on the air–sea gas exchange of CO 2 in a Baltic Sea Basin. Tellus B Chem. Phys. Meteorol. 65, 1–16. https://doi.org/10.3402/tellusb.v65i0.21831.

Zhang, S., L. Wu, J. Arnqvist, C. Hallgrenand A. Rutgersson. Mapping coastal upwelling in the Baltic Sea from 2002 to 2020 using remote sensing data. Int. J. of Appl. Earth Observation and Geoinformatics, Volume 114, November 2022, 103061, https://doi.org/10.1016/j.jag.2022.103061

Thank you for the suggestion of literature.

Best regards,

Martti Honkanen