Response to Anonymous Referee #2

We thank you very much for your constructive comments and suggestions.
Below the reviews are reproduced in black font, our replies are interspersed in **blue** while preliminary updates of the text are in ***green***.

The authors analyze the enhancement of gas exchange velocities by surface waves in large lakes and explore the performance of a broad range of empirical and mechanistic models to predict this dependence based on wind speed and fetch length. As the authors point out correctly, the effect of surface waves on gas exchange is neglected in most studies, and observations are largely lacking – particularly in lakes. By analyzing CO2 flux measurements obtained during different seasons in Lake Geneva, the authors demonstrate, that waves have a potentially significant influence on gas exchange velocity and gas fluxes in large lakes, although sufficiently large waves occur during rare events only.

The manuscript addresses an important research gap and makes an original contribution to advancing the prediction of gas exchange in numerical models. It is well written and organized.

Reply: We appreciate this overall positive assessment and believe we can address the Reviewer's concerns as detailed below.

The largest shortcoming of the study is certainly the lack of wave observations (wave height was derived from wind speed using a model adopted from marine systems). Apparently there are only very few wave measurements from lakes available. I suggest that the authors emphasize this issue in their discussion and mention the need for direct wave observations in lakes in future studies. As listed below, I have a few additional comments, which can be addressed in minor revisions of the manuscript.

Reply: This is indeed an important point that was also raised by Reviewer 1. The lack of direct wave observations is a major shortcoming of our study. We put more attention on this in the discussion where we also developed a small part on spatial integration as proposed by referee 1 (see below reply to comment L. 173). We detailed the different methods to quantify these wave fields (see below reply to comment L. 173). As a matter of fact, direct wave measurements are one of the upcoming challenges to be undertaken at the Lexplore platform.

We stressed the need for more observations of surface waves in lakes. However, our study is still solid as based on one of the few studies of surface waves in lakes conducted in a similar lake (Lake Neuchatel, another deep lake located a few kilometers away from Lake Geneva). More details on the changes made are detailed below (L. 135 and L. 173).

Detailed comments:

1. L. 31: "...these approaches suffer from limited time and space integration..." I don't think that this applies to EC measurements.

Reply: We will rephrase this sentence like this and add a new reference:

"… CO_2 fluxes can be directly measured with floating chamber or eddy covariance systems (Vachon et al., 2010; Vesala et al., 2006). However, both approaches have their own constraints. The former suffers from limited time and space integration (from minutes to hours, and centimetres to metres; Klaus and Vachon, 2020), while the latter remains technically difficult and can be influenced by non-local processes (entrainment from the shore or advection; Vachon et al., 2010; Ester et al., 2020)."

2. L. 52: "with order larger than unity" consider rewording

Reply: We rephrased this sentence like this:

"… with an exponent larger than 1…"

3. L. 135: I suggest being more clear here: the wind observations of Simon showed that the JONSWAP parameterization did not hold for wind speed > 5 m/s

Reply: We have rewritten the passage of the methodology containing the explanations of the formula for significant wave heights (line 132-136) to clarify for the reader.

"This variable H_s is defined as the average height of the highest one-third of the waves (crest to trough) corresponding to the thickness over which the wind can push laterally (Wüest and Lorke, 2003). This equation is equivalent to the formulation by Carter (1982) that is more widely used in the oceanic literature. Simon (1997) tested the model for significant wave heights in Lake Neuchâtel (a lake close to Lake Geneva) with a fetch distance of 9 km. These results showed that the significant wave height in this lake was consistent with this oceanic formulation. However, Simon (1997) highlighted that the Joint North Sea Wave Project (JONSWAP) wave breaking parametrization did not hold for winds greater than 5 m s^{-1} producing faster wave breaking and with a higher probability in the case of not fully developed surface waves. Such lake waves are characterized by steeper slopes that favour their wave breaking and wave action (Wüest and Lorke, 2003)."

We instead stress that such measurements are needed in large lakes to better constrain the air-water exchanges under various surface roughness in the new section (4.2. see below)

4. L. 144-47: I cannot really follow the argumentation using the standard deviation. Maybe this needs to be explained in a better way. Besides leakage of the chamber in a wavy environment, there can also be flux enhancement by artificial (chamber-generated) turbulence.

Reply: Following your comment and that of the first referee, we added a few lines (after line 142) to the flux measurement methodology and created a new figure for the appendix to show the different designs.

"One typical problem with floating chambers arises from the possible atmospheric leakage under rough surface (Fig. A2a). To work around this problem, Vachon et al. (2010) advise to create 10 cm long-edges entering the water (Fig. A2b) and this design also reduces artificial turbulence generated by the chamber's walls at surface. A second typical issue with this method is potential flux enhancement by artificial (chamber-generated) turbulence. This was also studied in Vachon et al. (2010), who demonstrated that the overestimations by this effect can be as high as 1000 % at low wind but less than 50 % when the wind speed exceeds 4 m s^{-1} in large lakes. At even higher wind speed, this overestimation should further decrease because the surface water turbulence becomes much greater than that produced by the floating chamber. Thereby, our flux chamber was specifically conceived to increase stability under calm and windy conditions and limiting artificial turbulence, but we do not exclude a bias at low and moderate wind (Fig. A1, Fig. A2c).

Regarding the operation of the eosFD, it has two independent cavities: one for the chamber and one for the atmosphere (Fig. A1). These are connected to the same CO_2 sensor by a pump which sends at regular intervals (about 20 s) either the chamber gas or the air gas to the sensor and then completely flushes the chamber cavity according to the programmed measurement timestep (15-minutes or 30-minutes). The advantage of this new instrument is therefore to have a constant monitoring of the chamber's variation, but also of the atmosphere. In addition, the use of the same CO_2 sensor for the two measurements limits the need for intercalibration between CO_2 sensors. We tested the performance of the floating chamber by comparing the standard deviation of the CO_2 concentrations of the atmosphere and in the chamber estimated from two separated cavities (Fig. A1; Risk et al., 2011). We did not observe any difference in the standard deviation between high and low wind conditions (Fig A3), suggesting that the measured fluxes remained reliable at high wind speed without leakage of the chamber."

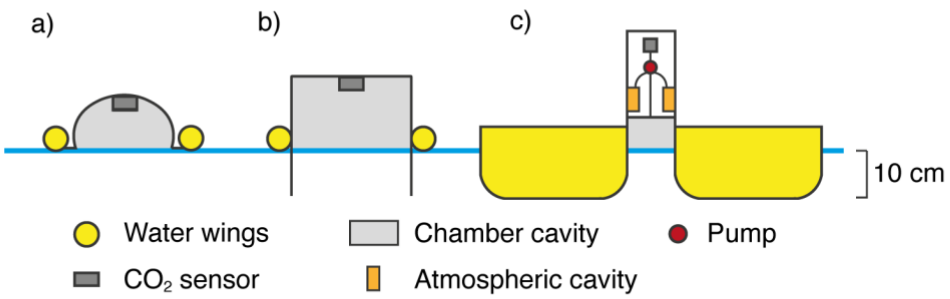

Figure A2new: a) Classic floating chamber; b) Floating chamber with 10 cm long-edges; c) Platform design used in this study: 10 cm long-edges, rounded-edges, and flat and long water wings.

5. L. 173: there is a square missing in the equation for surface shear stress

Reply: We corrected this typo and added the square missing in this equation.

6. L. 334 (and elsewhere): I'm not sure if the cumulative k is a very illustrative quantity (as the numbers are kind of meaningless). Did you consider analyzing the cumulative mean values of k instead? (cumulative sum normalized by number of observations)

Reply: We understand your concern about the significance of the "cumulative k" but we prefer to keep it for the following reason. The cumulative k was used to highlight temporally the contribution of the wind on k. With this, we see that strong wind (> 5 m s-1) accounted for ~40% of the cumulative k while representing less than 15% of the time.

7. L. 171: missing word

Reply: We are not sure what you think about the missing word. Do you mean this?

"… 2.4.1. Wind shear stress…"

8. L. 173 (and elsewhere): when discussing the frequency of occurrence of waves exceeding a certain height and corresponding enhancement of k and fluxes, it is important to keep in mind that these estimated are site-specific (within the lake). I suggest that the authors briefly discuss to what extent the observations made at the platform are representative for the entire lake. Given the distribution of wind directions and lake geometry – are there sites where wave can be expected to make large/smaller contributions?

Reply: Following your comment and those of the first reviewer, we suggest implementing in the discussion a section on the spatial variability of wind-waves after the section 4.2.2.

"4.3 Wind and wave field on Lake Geneva and their impact on the spatial integration of k_{600}

SD21 and *SD21-fit* were built on the basis of a single measurement point on the lake, just as for most of the existing *k* models. Therefore, the question of the extrapolation of the model to the whole lake remains essential. Herein, we showcase two snapshot situations of high-wind to (i) illustrate how process-based models could enable spatially resolved estimates of *k*-values, and (ii) exemplify how much *k* can vary as a result of the spatially variable wave and wind-fields during a single episode. Two events of high and similar wind speed (11 m s^{-1}) but different directions (NE: 2020.03.30 08:00 and WS: 2020.02.10 06:00; Fig. 8a-b) were extracted from the 0.01° hourly resolved numerical weather model of the Swiss Federal Office of Meteorology and Climatology (COSMO-1, MeteoSwiss) The two fetch distances from both prevailing wind directions (NE, SW) were then measured at each pixel of the grid (n = 583), from which the wave height field was mapped (Fig. 8c-d) considering Equation (3) and the two wind grids. The maps were qualitatively consistent with previous studies on wind waves for Lake Geneva using the spectral wave model (SWAN) for wave height (Amini et al. 2016). Spatially resolved *k*-values were computed from the fetch and wind grids, using the wind-based model *CC98*, the process-based model without lake wave implementation *R12* and the *SD21-fit* model containing the lake wave parametrization.

Taking H_s > 0.4 m as a threshold for the significant effect of wave on k, the two prevailing winds show opposite waves response, with long fetch and higher wave heights affecting either the North or the South shores for respectively the WS and NE winds. In both conditions, more than 60 % of the full lake surface area experience H_s values > 0.4 m, leading to k-values as computed by *SD21-fit* as high as 68 cm h^{-1} (Fig. 8g). The Eastern part of lake experiences the lowest wind speeds and wave heights in both situations, as a consequence of the orographic effect of the Alps surrounding the Grand Lac.

Both the range and the mean of estimated k-values increase with the increasing model's complexity. Accounting only for wind speed, through the wind-based model *CC98*, leads to a spatially integrated k value for 15.7 cm h^{-1} (range 1-22 cm h^{-1}). k-values computed from *R12*, accounting for both the windshear and buoyancy flux, are on average 55 % greater (24.3 cm h^{-1}) with a moderate effect on the range of spatial variability. Finally including surface waves results in a spatially averaged k-value more than doubled as compared to the k-value computed from wind speed only (35.5 cm h^{-1}), with a variability that is almost three times greater (range 0-68). Noteworthily, the spatial average of k-values computed by the wind grids (Fig. 8g Diamonds) is equivalent to the average of k-values computed from the spatial mean fetch (NE: 9.5 and SW: 9.3 km; Fig. 8g cross) in these specific weather conditions. The application of an average fetch would thus be relevant to estimate a spatially averaged k-value.

For all models, the integration of spatially resolved wind-fields may improve the accuracy of k at the lake scale but accounting for wind only would underestimate both the average gas piston velocity and its spatial variability. A better understanding of wave behaviour in large lakes, using different approaches such as field and laboratory measurements, new physical models, and technical development, would therefore improve the accuracy of gas exchange estimates at the lake-water interface, at both the temporal and spatial scales. Further estimates of lake-scale CO_2 fluxes would require to also account for the spatial variability of CO_2. The question of the spatial variability of the ΔCO_2 is still open and remain difficult to analyse at high frequency in large lakes.

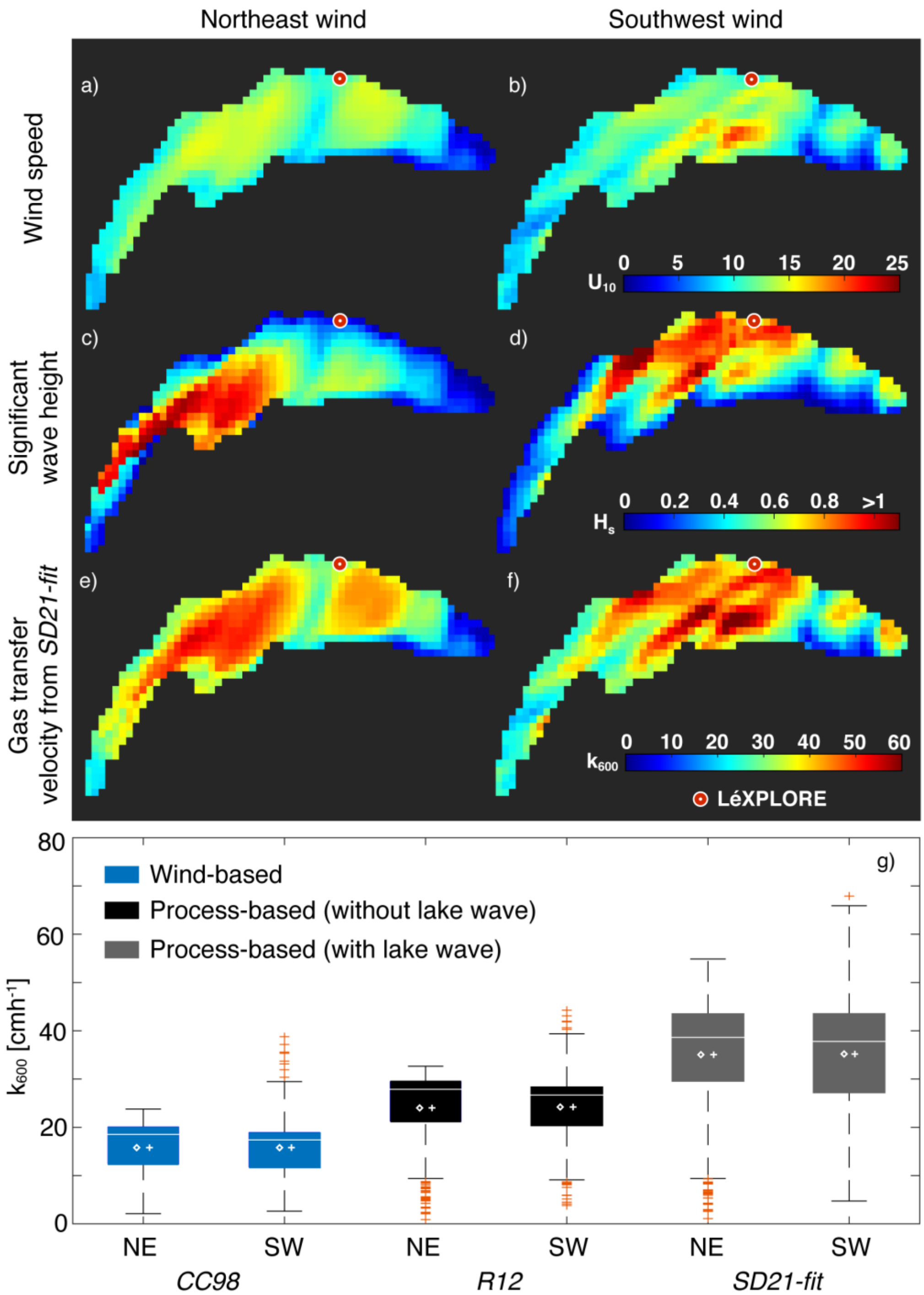

Figure 8: a-b) Wind fields from COSMO-1 in situations of Northeast and Southwest wind directions; c-d) Wave fields on Lake Geneva considering the two prevailing winds (Northeast and Southwest); e-f) Gas transfer velocity from *SD21-fit*; g) Boxplots of the spatial variability, at the lake scale, of *k*-values computed from *CC98*, *R12* and *SD21-fit* under both meteorological conditions. Diamonds represents the spatial mean and the cross (+) the *k*-value through computed from a fixed average fetch distance (NE: 9.5 km and SW: 9.3 km).

Finally, we will clarify in section 4.2.2 that our estimate of CO2 fluxes remains a coarse estimate which main goal is to scale the effects of wave integration on annual CO2 fluxes. More data would be needed to provide an accurate estimate of CO2 emissions at the lake scale.

9. L. 407 ff.: how well do the monthly mean pCO2 values represent the conditions during high wind speed (high waves)? As pointed out later, pCO2 could be expected to be much higher

(entrainment) or much lower (depletion of CO2 in the surface layer due to strong outgassing) during these events. Do the authors have observations from such events?

Reply: We agree that annual flux estimates will gain in accuracy using high frequency data for surface CO2. However, the purpose of this paper (section 4.2.2) is to compare the fluxes estimated through different k models, in order to scale the importance of integrating/omitting surface waves at an annual scale. For this aim, monthly data for surface CO2 are sufficient to quantify the effects of waves on gas exchange velocities. Using high-frequency surface CO2, we would need to tease apart wind-wave effect on CO2 fluxes due to changes in k only from those due changes in surface CO2 following wind-driven mixing or internal waves, and we fear this would finally dilute the focus of the paper. We will make the purpose of the exercise clearer for the reader in this part and highlight the need to obtain high frequency data of CO2 in water to study these two possibilities (entrainment - depletion) when it comes to accurate estimates of CO2 fluxes at the lake-water interface.

10. I suggest to add the observed fluxes to Table 3 to allow others to use or to reproduce the results presented here.

Reply: It is difficult to integrate the observed fluxes in Table 3, because they are not in adequacy with the time steps of the table and were recorded only during 5 different months. Moreover, as explained above, this table allows to compare the results of the k models in terms of flux and do not have to make an overall estimate of the lake knowing the temporal and spatial variability of the CO2 concentration at the surface. However, measured flux data (chamber), as well as the corresponding CO2 concentrations (sensors) will be made available on Zenodo upon acceptance so others could use and reproduce the results (see data availability statement).

11. L. 442: "estimate an average fetch value depending on the wind direction and the geometry of the lake" But the dependence of k on fetch is non-linear (fetch^1/3?). Should the spatial averaging take this into account?

Reply: You are right. The dependence between k and fetch is non-linear. This approach is the simplest to integrate a fetch in the calculations. However, it could propagate errors spatially. We will therefore apply a spatial average fetch in the new part of the discussion on spatial integration as showed above (Figure 8g, diamonds and cross).

Added reference

Ester, L., Rutgersson, A., Nilsson, E. and Sahlée, E.: Non-local impacts on eddy-covariance air-lake CO_2 fluxes, Boundary-Layer Meteorol., 178, 283–300, https://doi.org/10.1007/s10546-020-00565-2, 2021.

Other changes

We add in table 1 (CC98 for Calibrated range) Area (0.15-490 km^2) because CC98 had taken other lakes in the literature to perform his model.

We found a typo in the caption of the figure 6 with a sign error between 5b and 5c (greater and smaller). Here is the correction:

Figure 6: a) Cumulative k_{600} modelled over an annual cycle; b) Cumulative k_{600} for wind > 5 m s^{-1}; c) Cumulative k_{600} for wind ≤ 5 m s^{-1}.

We also found small errors in the labels of y axes of figure 5 which will be corrected.