Response to reviewers comments and questions

Interactive comment on "Technical note: Measurements and data analysis of sediment-water oxygen flux using a new dual-optode eddy covariance instrument" by Markus Huettel et al.

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Review of "Technical note: Measurements and data analysis of sediment-water oxygen flux using a new dual-optode eddy covariance instrument."

The manuscript submitted by Huettel et al. is appropriate as a technical note because it focuses on issues related to the quality of oxygen sensor measurements in the context of aquatic eddy covariance (AEC) measurements of benthic oxygen fluxes. The authors stress biases that can occur when sensors are affected by biofouling, and they illustrate with detailed examples how these artifacts can be recognized and controlled for using a dual-optode system. The examples are from an area of shallow shelf in the Florida Keys, making them unique environmentally. As a practitioner of these methods, I find this manuscript very useful, but I also recommend a number of revisions to improve clarity, especially for readers who may be less familiar with the AEC technique.

Response: We thank Dr. Reimers for the detailed review of our manuscript and the helpful comments and questions.

General recommendations: The manuscript is difficult to follow at times for reasons of organization and language. Most importantly, the introduction does not lead off with a very clear description of how biofouling or other "disturbances" can affect oxygen sensor measurements and corresponding AEC derivations. Instead the authors try to unravel these uncertain effects through the course of detailed reviews of data.

Response: We added a paragraph explaining description how disturbances including biofouling can affect measurements and corresponding AEC derivations.
P2L53: "Irrespective of the technology, the readings of the oxygen sensors can be biased by attachment of particles, bacteria or algal cells, which can affect the sensor signal through shielding of the sensor tip and metabolic processes (Smith et al., 2007;Delauney et al., 2010). Mineral particles may be impenetrable to gases, while organic particles may be sufficiently dense or oxygen consuming such that oxygen diffusion through them is reduced, thereby decreasing and delaying oxygen transport to the sensing surface (Zetsche et al.;Ploug and Passow, 2007). The ensuing increase in the response time of the sensor dampens the oxygen signal and thereby reduces the calculated flux. The most common particles attaching to sensors may be marine snow particles (Fig. 1 a), sticky aggregates of various organic and inorganic particles glued together by extracellular polymeric substances (Alldredge and Silver, 1988). Bacteria and phytoplankton cells commonly contained in these particles can cause oxygen consumption and oxygen production, thereby affecting the signals of the oxygen sensor and the fluxes calculated from these readings."

We also added a sentence and figure explaining how a marine snow particle attached to the oxygen sensor can lead to increased flux estimates when waves are present.

P10L316: "A marine snow particle with photosynthesizing organisms attached to the tip of the oxygen sensor P may have caused the erroneous flux estimates. Oxygen concentration in the centre of such aggregates during light conditions can be increased by 85 % relative to the surrounding water (Ploug and Jorgensen, 1999), or even by 180% within millimetre-size gelatinous colonies of *Phaeocystis spp*., a common global bloom-forming phytoplankton organism (Ploug et al., 1999). The movement of such an attached photosynthesizing particle by wave orbital motion can synchronize vertical current flow oscillations and the effect of the particle on the oxygen reading (e.g. increased oxygen due to photosynthesis) and thereby lead to erroneous flux estimates (Fig. 9.)"

More specific language throughout, as I will suggest below, would be helpful. Core questions are: does the biofouling produce or consume minute amounts of oxygen locally affecting what the sensor detects (sort of a contamination of the ambient condition), and why would this production or consumption be flow sensitive under waves? Zooming in to look at some data under both day and night conditions may help reveal the behavior.

Response: If one of the two parallel measuring sensors showed a temporary increase or drop in oxygen as found in the deployments on 10-11 April 2014 and 14-15 August 2013, we attributed this to the biofouling of that sensor, and in-situ inspections of the sensors revealed biofouling (extreme case now shown in Fig. 1b). We inspected the data and as an example provide the co-spectra shown in Figure 6 that reveal a temporary sensitivity to waves in sensor P, which we explain with the process now depicted in Fig. 10. Measurements have shown that marine snow particles can produce and consume substantial amounts of oxygen (see references listed in the response above) and marine snow was abundant at the study site partly due to the proximity of the coral reefs that release mucus to the water. We added this explanation to the text:
P10L311 "If one of the two parallel measuring sensors showed a temporary increase or drop in oxygen as found in the deployments on 10-11 April 2014 and 14-15 August 2013, we attributed this to the biofouling of that sensor, and in-situ inspections of the sensors revealed biofouling (extreme case now shown in Fig. 1b). Marine snow was abundant at the study site partly due to its proximity to coral reefs that release mucus to the water (Wild et al., 2004).

and

Figure 9: False flux increase caused by the rhythmical deformation of a marine snow particle attached to an oxygen fibre optode. Erroneous fluxes result when wave orbital motion modulates the distance between photosynthesising organisms contained in the gelatinous marine snow particle and the sensing surface of the optode.

It would also be helpful to simply refer to the three deployments used for illustration as something like "Case A, Case B and Case C". The dates of the deployments were so similar, that a reader has trouble differentiating the examples by date alone.

Response: We followed the suggestion of the reviewer and now use "Case A, Case B and Case C".

Specific suggestions for edits:
Figures 2, 4 and 6 panels (b) units should be micromoles per liter. (Use consistent unit designations in tables and figures).

Response: Done.

There is duplication of references: McGinnis et al. 2008a and b are the same, Reimers et al. 2012a and b are the same.

Response: Thanks for pointing this out, we removed the duplication

Line by line:

Page 1 lines 9-10: First example of a vague reference to the core problem "but a main weakness of the commonly used instrumentation is the susceptibility of the delicate oxygen microsensors required for the high frequency measurements to disturbances." This needs to be rewritten. Might be best to say something like "but a critical requirement is that EC sensors are able to resolve high frequency variations in dissolved oxygen concentration and vertical velocity without artifacts."

Response: We followed the suggestion of the reviewer and changed the sentence. It now reads:
P1L8 In-situ fluxes can be measured non-invasively with the aquatic eddy covariance technique, but a critical requirement is that the sensors of the instrument are able to correctly capture the high frequency variations in dissolved oxygen concentration and vertical velocity".

Page 1 lines 15-17. Revise. For example as: "Short-term changes in flux were confirmed or rejected with the 2OEC, giving more certain insights into the temporal dynamics of benthic oxygen flux in permeable carbonate sands."

Response: We revised the sentence that now reads:
P1L15 "Short-term changes in flux that are dubious in measurements with single oxygen sensor instruments can be confirmed or rejected with the 2OEC and in our deployments provided new insights into the temporal dynamics of benthic oxygen flux in permeable carbonate sands."

Page 1 line 18. Why do you say "within a couple of hours"? Do you mean that this is how much time is needed to capture a representative flux under steady conditions?

Response: We clarified our statement following the suggestion of the reviewer. It now reads:
P1L17 "Under steady conditions, representative benthic flux data can be generated with the 2OEC within a couple of hours, making this technique suitable for mapping sediment-water, intra-water column, or atmosphere-water fluxes.

Page 2 line 36. Add: Reimers et al., 2016. Microelectrode velocity effects and aquatic eddy covariance measurements under waves. J. Atm. Ocean. Tech. 33, 263-282.

Response: Done.

Page 2. lines 40-42. I question the statements: "Optodes consume no oxygen and have very low or no stirring sensitivity (Holtappels et al., 2015). Compared to micro- electrodes, they are less susceptible to signal drift and keep their calibration over longer time." It appears they may develop a stirring sensitivity once biofouled, and my experience is they may drift quite a bit due to their loss of sensitivity. Perhaps you could qualify these statements as: "Optodes consume no oxygen and may have very low or no stirring sensitivity (Holtappels et al., 2015). Compared to microelectrodes, we have observed they are less susceptible to signal drift and keep their calibration over longer time."

Response: We followed the recommendation of the reviewer, and the sentence now reads:
P2L41 "Optodes consume no oxygen and may have very low or no stirring sensitivity (Holtappels et al., 2015). Compared to microelectrodes, we have observed they are less susceptible to signal drift and keep their calibration over longer time."

Page 2. lines 51-54. Here is where the authors need to give a clearer initial description of how biofouling will alter signals from an optical sensor. The statement “through shielding of the sensor tip from the water current and metabolic processes (i.e. respiration, photosynthesis)” is unclear. What kind of changes in signal magnitide and dynamics occur and why? These things are rarely “obvious”, especially to new users.

Response: Thank you for pointing this out. We added the following information:
P2L53 “Irrespective of the technology, the readings of the oxygen sensors can be biased by attachment of particles, bacteria or algal cells, which can affect the sensor signal through shielding of the sensor tip and metabolic processes (Smith et al., 2007;Delauney et al., 2010). Mineral particles may be impenetrable to gases, while organic particles may be sufficiently dense or oxygen consuming such that oxygen diffusion through them is reduced, (Zetsche et al.;Ploug and Passow, 2007) thereby decreasing and delaying oxygen transport to the sensing surface. The ensuing increase in the response time of the sensor dampens the oxygen signal and thereby reduces the calculated flux. Berg et al. (2015) explained how the resulting time offset between the oxygen and the velocity data can cause significant over- or underestimation of the flux. The most common particles attaching to sensors may be marine snow particles (Fig. 1a), sticky aggregates of various organic and inorganic particles glued together by extracellular polymeric substances (EPS) (Alldredge and Silver, 1988). Bacteria and phytoplankton cells commonly contained in these particles can cause both, oxygen consumption and oxygen production, thereby affecting the signals of the oxygen sensor and the fluxes calculated from these readings. As an example, we observed oxygen flux increases up to 4.4 mmol m^{-2} h^{-1} caused by photosynthesis and decreases up to -5.2 mmol m^{-2} h^{-1} caused by respiration of microbes contained in marine snow attached to the oxygen sensor.”
”

Page 2. line 78. Revise as “is relatively robust compared to microelectrodes”. . .

Response: We followed the suggestion of the reviewer, and the sentence now reads:
P3L73 “With the advantages of being relatively robust compared to microelectrodes and less expensive, optodes are predisposed to become the preferable sensor-type for aquatic eddy covariance measurements”

Page 2. line 80. If the discussion of sensor drift and lifetime is based generally on previous measurements, make this clear. If it is based on the experiments in this paper, move this reporting to the results section.

Response: Sensor lifetime and drift were observed in previous field deployments. We added this information to the text:
P3L93 “Our previous field measurements indicated that when operated continuously at a measuring frequency of ~ 8 Hz, the useful lifetime of the OXR430-UHS typically was 3 to 7 days before the signal decreased to a level precluding reliable data interpretation. The signal drift over this period was negligible (< 0.03%) (Huettel, unpubl.).

Page 5. lines 136-137. Revise as: “the product of instantaneous oxygen fluctuation and instantaneous vertical velocity change” or something clearer.

Response: Done

Page 5. lines 140-146. The use of a storage term here is not well justified and later on is not clearly discussed. Is this the correction referred to in Figure 3C? Holtappels et al. (2013) illustrate transient contributions to eddy fluxes linked to changes in C, but their model predictions of these effects are different from the storage term (although both are dependent on dC/dt). At the heart of the matter is: does oxygen change due to advection or due to localized cumulative production of consumption in the bottom boundary layer? You appear to assume a changing diurnal “storage” balance in dissolved oxygen, but the oxygen time series show other drivers of change. The statement given at lines 202-204 also indicates you recognize advection.

Response: We agree with the reviewer that this was not explained sufficiently. We added the following text: P5L150 “At our measuring height of 35 cm above the seafloor, the diurnal fluctuation in mean water column oxygen concentration can result in substantial changes in the oxygen inventory of the water column below the measuring volume, which can bias the local eddy flux measurements. To correct for this effect, an oxygen storage term, calculated as $\int_0^h dC/dt\, h$, was subtracted from the measured eddy flux to determine the benthic oxygen flux (dC/dt = change of the average oxygen concentration over time, calculated through linear detrending of the measured oxygen data over 15 minute intervals, h = height of the measuring volume)(Rheuban et al., 2014b).

Page 6. line 168. Here you start referring to data processing steps as “corrections”. It would help the reader if section 2.3 separated these different corrections more clearly and let the reader know their effects on flux records would be evaluated as part of the results.

Response: We agree with the reviewer and moved the effects of the flux corrections we applied to the results section.

Page 6. line 172. It is not clear what the authors mean by “over the time course of the deployment”. Can they indicate over what time intervals the cumulative slope was evaluated? Did they assess the slope burst by burst, or over longer intervals? How is the standard deviation derived for these calculations?

Response: We added the following text to clarify this point:
P5L157 “For the comparison of the temporal evolution of the fluxes that were determined using the recordings of the two optodes, we calculated the cumulative fluxes over the duration of the deployments. The slopes of the increasing cumulative fluxes during daylight and decreasing cumulative fluxes during nighttime were assessed for hourly time intervals. Standard deviations of the fluxes reflect the deviations between three hourly slope determinations. All error estimates are reported as ±1 standard deviation.”

Page 7. lines 216-218. A better explanation of the signal produced by biofouling under waves needs to be given. I have seen this effect in my data too. An oscillation develops at the wave frequency that appears to be greater than what would occur if the water column gradient was moving up and down or back and forth with wave motions. Looking at segments of the oxygen, velocity and pressure time series may help sort this out. It appears to be a “velocity effect”.

Response: We added an explanation and figure 9
P10L316 “A marine snow particle with photosynthesizing organisms attached to the tip of the oxygen sensor P may have caused the erroneous flux estimates. Oxygen concentration in the centre of such aggregates during light conditions can be increased by 85 % relative to the surrounding water (Ploug and Jorgensen, 1999), or even by 180% within the sticky millimetre-size gelatinous colonies of *Phaeocystis spp*., a common global bloom-forming phytoplankton organism (Ploug et al., 1999). The movement of such an attached photosynthesizing particle by wave orbital motion can synchronize vertical current flow oscillations and the effect of the particle on the oxygen reading (e.g. increased oxygen due to photosynthesis) and thereby lead to erroneous flux estimates (Fig. 9).”

Page 8. line 236. Here you discuss another reason for poor sensor performance (particle impact). This should also be mentioned in the introduction under optode weaknesses.

Response: We added the following sentence in the introduction
P2L46 "Although most optodes are more robust than microelectrodes, they can break due to particle collision."

Page 9. line 286-287. State more specifically how current measurements can be affected and why. Differentiate between real changes in the flow reaching the ADV sampling volume (flow obstruction) and measurement artifacts due to acoustic returns off the sensor tip.

Response: We added the following explanation:
P11L332"A cylindrical sensor placed in the path of the flow upstream the ADV measuring volume can shed a vortex street thereby compromising the flow in the measuring volume and the flux estimates based on the flow measurements. Depending on the flow Reynolds number, such vortices may extend between 5 to 20 times the diameter of the cylinder downstream the sensor (Green, 2012). By using the Pyroscience fiber optode for the 2OEC, one of the smallest and fastest oxygen sensors presently available, potential errors caused by the disturbance of the flow and interference with the acoustic pulses of the Doppler velocimeter can be avoided. At the turbulent Reynolds numbers typical for our study site ($4000 < Re < 110000$), the vortices shed by the 430 µm fiber exposed to the water currents extend between 2 to 10 mm downstream of the fiber (Green, 2012). Since the tips were placed at 30 mm horizontal distance from the lower edge of the ADV measuring volume, turbulence caused by fiber-flow interaction could not reach the ADV measuring volume. Similarly, the sensor tips at that distance did not interfere with the acoustic pulses of the ADV, and when initially positioning the optode tips, we confirmed that the optode fibers did not cause any disturbances in the ADV signal."

Page 10. The paper conclusions are relatively weak. The authors could easily expand a bit on how the fluxes measured in this study compare to other inner shelf and coastal environments with permeable sediments, e.g. those of Berg et al. 2013.

Response: We agree with the reviewer that the discussion of the flux results could be expanded, however, this paper was designed to introduce the instrument and the data interpretation, and, with all due respect, decided not to expand the discussion of the flux results in this paper. We are presently working on a manuscript that uses the results from these deployments together with other flux data measured at this study site to demonstrate the high metabolic activity of the coarse carbonate sands and to discuss their role in the coral reef ecosystem. This paper will also include a comparison of the fluxes presented here with fluxes measured in other inner shelf environments. We expanded the Conclusion sections with material directly related to the method development presented in this paper:

P12L359"We propose using the agreement/disagreement between the fluxes calculated from the signals of two independently measuring optodes as a tool to assess the quality of the measured fluxes. The nearly identical cumulative fluxes calculated from the two optodes in our August (Case A) and April (Case B) deployments strongly imply that the dynamics of the fluxes were measured accurately by the system. Likewise, the near linearity of the cumulative flux increase during daytime and decrease during nighttime (Figs. 3e, 5e) and the very similar slopes of these cumulative flux curves support that the measurements recorded representative fluxes. The good agreement of the fluxes measured with the eddy covariance instrument and the fluxes measured independently with a very different method (advection chambers, Fig. 8a, b, d) indicate that the magnitudes of the fluxes recorded by the 2OEC were correct. The deployments of the 2OEC in the Florida Keys sandflat revealed that biofouling frequently affects the aquatic eddy covariance measurements even in such an oligotrophic environment with very clear water containing low amounts of phytoplankton, bacteria and particles. Further developments of the aquatic eddy covariance technique therefore may benefit from installations of devices that monitor (e.g. with a camera) and reduce or prevent biofouling (e.g. through a cleaning mechanism). This project intended improving the reliability of the aquatic eddy covariance technique and the procedures of data analysis in order to promote this powerful technique."

Interactive comment on Biogeosciences Discuss., https://doi.org/10.5194/bg-2020-172, 2020.
Interactive comment on "Technical note: Measurements and data analysis of sediment-water oxygen flux using a new dual-optode eddy covariance instrument" by Markus Huettel et al.

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General comments
Huettel et al. present a technical study describing a new dual-optode eddy covariance system. The authors integrate two independent O2 sensors within a standard eddy covariance setup to cross-check fluxes extracted using two independent O2 sensor output streams, and to identify any biases in the measurements which are most likely caused by sensor fouling. Dual O2 sensor eddy systems are not new per se (e.g. McGinnis et al. 2011, Attard et al. 2014), but it is the first time that the two sensor signals have been compared in the level of detail provided in this study. The authors also perform chamber incubator measurements in parallel with eddy covariance to resolve O2 fluxes using two different state-of-the-art methods. Finally, the authors also provide a comparison between the three most popular O2 sensor systems for eddy covariance measurements.
The paper by Huettel et al will find broad interest among the growing community of aquatic eddy covariance users. The length of the paper and the angle of the study make it appropriate to be published as a Technical Note in Biogeosciences. The scientific methods are clearly outlined, language is fluent and precise, referencing is appropriate and up-to-date, and the overall presentation is well-structured and clear. I have one main comment and several smaller comments that the authors may wish to address.

Response: We thank Dr. Attard for the detailed review of our manuscript and the helpful comments and questions.

My main comment concerns how flux quality is evaluated. Currently, the authors determine quality based on (a) diel dynamics of O2 fluxes in relation to PAR, and (b) by comparison to chamber incubator measurements. If the quality-checking aspects could be expanded to include other metrics, then I foresee that the dual sensor approach would be useful in a broader range of settings.

Response: We agree with the reviewer that assessing the quality, validity and accuracy of the fluxes is central when conducting non-invasive eddy covariance measurements. In addition to the two methods mentioned by the reviewer (i.e. diel flux dynamics in relation to PAR, and comparison to chamber measurements), we use here the agreement/disagreement between the fluxes calculated from the signals of two independently measuring optodes as a tool to assess the quality of the measured fluxes. To make that point more clear, we added the following text to the conclusions:
P12L359 "We propose using the agreement/disagreement between the fluxes calculated from the signals of two independently measuring optodes as a tool to assess the quality of the measured fluxes. The nearly identical cumulative fluxes calculated from the two optodes in our August (Case A) and April (Case B) deployments strongly imply that the dynamics of the fluxes were measured accurately by the system. Likewise, the linearity of the cumulative flux increase during daytime and decrease during nighttime (Figs. 3e, 5e) and the very similar slopes of these cumulative flux curves support that the measurements recorded representative fluxes. The good agreement of the fluxes measured with the eddy covariance instrument and the fluxes measured with independently with a very

different method (advection chambers, Fig. 8a, b, d) indicate that the magnitudes of the fluxes recorded by the 2OEC are correct."

Specific comments Introduction

L20-67: It would be fair to mention that dual O2 sensor eddy systems have been in use for years (e.g. McGinnis et al. 2011 L&O Methods, Attard et al. 2014 L&O) but that so far, no detailed comparison between sensor signal output has been presented.

Response: We thank the reviewer for pointing out the missing references to other dual sensor instruments. In a earlier version of the manuscript, we had an extended discussion of microlectrode-equipped eddy instruments, which included the dual electrode systems deployed by Attard et al (2014) and McGinnis et al. (2011). This matter was removed when shortening the paper and we now re-inserted these references. To the best of our knowledge, eddy instruments based on dual optode measurements have not been introduced, and we are not aware of publications that use the date evaluation approach explained here. The following section was inserted into the text:
P2L35 "To improve the reliability of the flux measurements, eddy covariance with dual microelectrodes were developed, e.g. (Attard et al., 2014;McGinnis et al., 2011;Rodil et al., 2019;de Froe et al., 2019;Rovelli et al., 2015)"

Methods

L70: It is worth mentioning that these meters only use half the potential voltage range of the Vector analog channels (0-2.5V), but developments are in place to increase this to the full range (0-5V).

Response: We thank the reviewer for this suggestion and added the following sentence to Table A1 in Appendix A: "the meter presently uses half the potential voltage range of the Vector analog input, but developments are in place to increase this to the full range (0-5V)"

L71: I cannot find this model on the Pyroscience website. Do you mean the FSO2- SUBPORT? https://www.pyroscience.com/en/products/all-meters/fso2-subport

Response: We thank the reviewer for pointing this out. The Pyroscience™ FireStingO2-Mini oxygen meter recently has been replaced by the Pyroscience™ PICO-O2, which is similar to the meter we used but more compact. The FireStingO2-Mini oxygen meter is still available in combination with the Pyroscience™ FSO2-SUBPORT. We added this information to the text:
P3L84The eddy covariance instrument we developed uses two Pyroscience™ FireSting O_2-Mini oxygen meters (specifications listed in Table A1 in Appendix A, now sold in combination with the Pyroscience™ subport (FSO2-SUBPORT)) that read two ultra-high speed Pyroscience™ OXR430-UHS retractable oxygen minisensors (Table A2).
We also added the following text to the legend of Table A1 in Appendix A:
"This oxygen meter recently has been replaced by the Pyroscience™ PICO-O2, which is similar to the FireStingO2-Mini but more compact. The FireStingO2-Mini oxygen meter is still available in combination with the Pyroscience™ subport (FSO2-SUBPORT)."

L86-87: It would be useful to specify whether you powered the analog channels through the Vector

Response: Thank you for this suggestion. We added
P3L86 "The FireSting O2-Mini oxygen meters were supplied with the output power of the ADV (see below)."

L95: Firesting O2Mini: Again here, please check that this is the right model, or specify whether this was an older model that has since been replaced by the FSO2-SUBPORT.

Response: To avoid confusion we added the following text:
P3L84 "(specifications listed in Table A1 in Appendix A, now sold in combination with the Pyroscience™ subport (FSO2-SUBPORT)"

L97: 30 mm is quite a large distance. Any reason for not moving closer to the measurement volume (e.g. 1 cm)?

Response: We chose this distance to prevent any potential interference with the flow and acoustic pulses of the Vector ADV. We added the following sentence to make this clear
P4L114 "This distance prevents any disturbance of the flow in the measuring volume of the ADV and any interference with the acoustic pulses of the Vector."

L143-145: This reads like Results.

Response: We agree and moved this sentence to the results section.

L148-161: It would be useful to describe the chamber measurements in more detail. How were the chamber O2 fluxes calculated? Did you have an optode inside the chamber measuring O2 concentration continuously? How long did the deployments last? Ultimately, what are we comparing in Fig. 7?

Response: We added the following paragraph providing more detail about the chamber measurements:
P6L169 "For the deployments at our study site, the pressure gradient in the chambers was set to 0.2 Pa cm^{-1}, corresponding to the gradient produced by a 10 cm s^{-1} bottom flow deflected by a ripple of 7 cm height (Huettel and Gust, 1992a). In highly permeable sediments, the pressure gradient in the chamber causes pore water flow through the surface layer of the enclosed sediment, thereby mimicking the pore water exchange occurring in the surrounding rippled seabed. The transparent chamber and stirring disk allow penetration of light to the enclosed sediment (~10% loss in PAR through light attenuation caused by the acrylic), permitting benthic photosynthesis in the chamber. The acrylic cylinder of the chambers was pushed 12 cm into the sand sediment, resulting in a chamber water volume of 5 L. A Hach Rigid O2 Optode mounted in the chamber lid collected oxygen concentrations at 15 minute time intervals. The fluxes were calculated from the changes of the oxygen concentration in the water column of the chamber over time. Chamber incubations ran for 24 h, then the lid was opened to allow re-equilibration with the ambient water before starting the next measurement cycle."
We added to the legend of figure 8 (former figure 7) "Comparison of cumulative flux measured with the chambers (black line showing the average of the 3 chamber replicates and the standard deviation of the individual measuring points) and the 2OEC (red line: optode P, blue line: optode Q) during the 14-15 August deployments (Case C). The chamber fluxes confirmed that optode P was temporarily compromised during this deployment. Error bars depict standard deviation."

L156: Do the chambers attenuate PAR? Results

Response: Thank you for asking this question. We measured a 10% loss in PAR caused by the acrylic chamber lids and added this information to the text
P6L174 "(~10% loss in PAR through light attenuation caused by the acrylic)"

L164: The first sentence seems out of place here.

Response: We structured the Results sections by these subtitles, and the purpose of these subtitles becomes more clear when reading the related paragraphs.

L171-172: What deployment hours did you use for this analysis? Was it all of daylight hours i.e. until approx. 20:00? If so, does linear regression adequately represent these dynamics?

Response: We used all daylight hours and the flux increase during daylight could be represented well by linear regression ($R^2 > 0.9$). The same applied to the nighttime fluxes. When calculating the fluxes, we avoided sections with disturbances in the cumulative flux curves. We added the following explanation to the text:
P7L194 "The flux increase during daylight and decrease during nighttime could be represented well by linear regression ($R^2 > 0.9$)."

L179-183: I would expect that both optodes located at 35 cm above the seafloor and 1 cm apart would capture these variations, though?

Response: They do capture these variations, however, the higher heterogeneity of the oxygen distribution in the water still causes larger differences between the simultaneous readings of the two optodes during daylight hours (Fig. 4a)

L231: Fig 6E: I suppose that the jump at hour 22 in the cumulative flux for sensor P is not real, but it was offset in post processing to indicate that the two sensors match one another very well beyond this point. I understand the wish to illustrate this, but I think it is confusing, because it suggests that despite the fluxes from both sensors being very different prior to hour 22, the daily integrated flux is very similar, which cannot be the case.

Response: With all due respect, we disagree with the reviewer here. As pointed out in the legend of the figure, P cumulative flux at 18:00 was intentionally reduced by 5 mmol m^{-2} to allow comparison of the two cumulative fluxes based on P and Q data (Panel E). After excluding the time period during which sensor P was compromised by biofouling, the daily integrated fluxes based on the two sensor signals were very similar (P8L335) (daytime: 3.4 ± 0.6 mmol m^{-2} h^{-1}(P), 3.3 ± 0.3 mmol m^{-2} h^{-1} (Q), nighttime -0.9 ± 0.1 mmol m^{-2} h^{-1} (P), -0.9 ± 0. 7 mmol m^{-2} h^{-1} (Q); daytime average 3.3 ± 0.7 mmol m^{-2} h^{-1} (P, Q), nighttime average -0.9 ± 0. 7 mmol m^{-2} h^{-1} (P, Q)).

L233-234: I generally agree with this interpretation, it makes intuitive sense. One concern I have is that identifying what sensor works best at what time seems somewhat subjective. For instance, in Fig 6D hour 15, PAR drops from 150 to below 50 umol m- 2 s-1, and sensor P registers a concurrent decrease in flux, but sensor Q does not. After hour 16 the fluxes from sensor P are clearly 'compromised', but then again, this assessment is based upon what we'd typically expect to see. I would otherwise be tempted to interpret the drop in fluxes at hour 15 in sensor P as 'real', unless there is some other metric we could use to establish flux quality. Overall, I fear that if we do not adopt some quantitative metrics for establishing flux quality beyond what we expect to see (e.g. diel dynamics in relation to PAR), then we might miss out on something new and interesting. This is especially true during the nighttime or in non-photic habitats. In the absence of light, would we be able to say with the same certainty what flux dynamics is 'true' and what isn't?
We've been using a two-sensor setup since we started using eddy covariance in 2010, and I fully agree that this setup drastically increases the chances of obtaining good data. I typically evaluate the two sensor signals for their performance throughout the deployment by (a) comparing the mean O2 microsensor concentration to the O2 optode, (b) point-to-point noise in the 8 Hz data streams, and (c) linearity of the instantaneous cumulative fluxes for each 15 min flux period (Attard et al MEPS in press https://doi.org/10.3354/meps13372). Yamamoto et

al (2015) L&O (https://doi.org/10.1002/lno.10018, Fig. 3) adopt a similar approach. Would fitting linear regressions to the cumulative instantaneous fluxes for each 15 min flux for sensors P and Q, and evaluating the coefficient of determination (R^2 value), help to shed light on this? An additional analysis could be to fit P-I relationships to the data and see which sensor produces the best R^2 value, like the approach described in Attard & Glud (2020) Biogeosciences Discussions (https://doi.org/10.5194/bg-2020-140, Fig. 2).

Response: We agree with the reviewer that it would be good to develop more quantitative metrics for assessing the quality of the fluxes we measure with the EC systems. We do similar quality checks as described by the reviewer (comparison with reference sensors, noise monitoring, acoustic beam correlation checks), and we here use comparison with benthic chamber incubations and the agreement of independently measuring oxygen sensors to support the flux estimates. Although the chamber fluxes are biased due to the isolation of the incubated sediment, the magnitude of the fluxes can be considered near the true flux. A very close agreement of eddy fluxes based on two independent sensor readings further supports the fluxes we measured. Our experience is that using the linearity of the instantaneous cumulative fluxes for each 15 min flux period can be tricky and time consuming as these cumulative fluxes often change direction midway without producing artifacts and the linearity is dependent on the environment (e.g. homogeneity of the oxygen distribution in the water column) meaning that some of the observed variability is real and not a reflection of low-quality data.

L243-244: Also here, it would be good to mention what part of the integrated curve was used for this analysis.

Response: We added the information as requested by the reviewer:
P9L269 "After exclusion of flux intervals compromised by biofouling (Case A: no exclusion, Case B: 14:00-18:00, Case C: 12:00-22:00, 5:00-9:00), the differences between P and Q optode fluxes derived from the slopes of the cumulative flux curves (Figs. 2E, 4E, 6E)"

Discussion

L222-271: A two sensor setup provides redundancy and cross comparison, no question about that. However, it is also twice the cost in hardware, and twice the amount of work in postprocessing. If fouling seems to be such an issue, wouldn't the right approach be to try to eliminate fouling, rather than to add more sensors? I believe there is scope in the Discussion and in the Conclusion to comment on what future modifications might be valuable. For instance, should we install a pump and back-flush the sensors before each measurement burst? Can we monitor buildup of sensor fouling in some other way?

Response: We appreciate the comment of the reviewer and added the following sentence to the conclusions:
P12L366 "The deployments of the 2OEC in the Florida Keys sandflat revealed that biofouling frequently affects the aquatic eddy covariance measurements even in such an oligotrophic environment with very clear water. Further developments of the aquatic eddy covariance technique therefore may benefit from installations of devices that monitor (e.g. with a camera) and reduce or prevent biofouling (e.g. through a cleaning mechanism)."

Technical corrections
L78: Remove extra 'relative'

Response: Thanks! Done.

L81: . . .established using the jet-nozzle method. . .

Response: Done.

L86: Analogue should read ‘analog’

Response: Biogeosciences uses British English spelling

L127: Apostrophes should be replaced with primes

Response: Done.

L137: should read ‘products of instantaneous. . .’

Response: Done.

L156: ‘permitting’ rather than ‘facilitating’

Response: Done.

L174: Should read ‘The close agreement. . .’

Response: Done.