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Interactive comment

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.

Markus Huettel et al.

mhuettel@fsu.edu

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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. Clare Reimers (Referee) clare.reimers@oregonstate.edu Received and published: 2 June 2020

Review of "Technical note: Measurements and data analysis of sediment-water oxygen

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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

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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.

P9L308: "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. X.)"

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

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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: P10L304 "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

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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 unsupported 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".

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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

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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 a 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. 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 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, unpublished).

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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: P5L155 “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 $\int 0hdC/dth, wassubtractedfromthemeasurededdyfluxtodeterminethebenthicoxygenflux(dC/dt = changeoftheaverageoxygenconcentrationovertime, calculatedthroughlineardetrendingofthemeasuredoxygendataover15$ $heightofthemeasuringvolume)(Rheubanetal., 2014a).$

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.

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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: P5L163 "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, and standard deviations of the fluxes reflect the deviations between three hourly slope determinations.

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 P10L308 "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. 10.)

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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: P11L324 “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

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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.

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