LIMNOLOGY AND OCEANOGRAPHY
ASLO e-Lectures

Non-invasive Flux Measurements at the Benthic Interface:

The Aquatic Eddy Covariance Technique

Peter Berg[1], Marie Lise Delgard[1], Ronnie N. Glud[2], Markus Huettel[3], Clare E. Reimers[4], Michael L. Pace[1]

[1]University of Virginia, [2]University of Southern Denmark, [3]Florida State University, [4]Oregon State University

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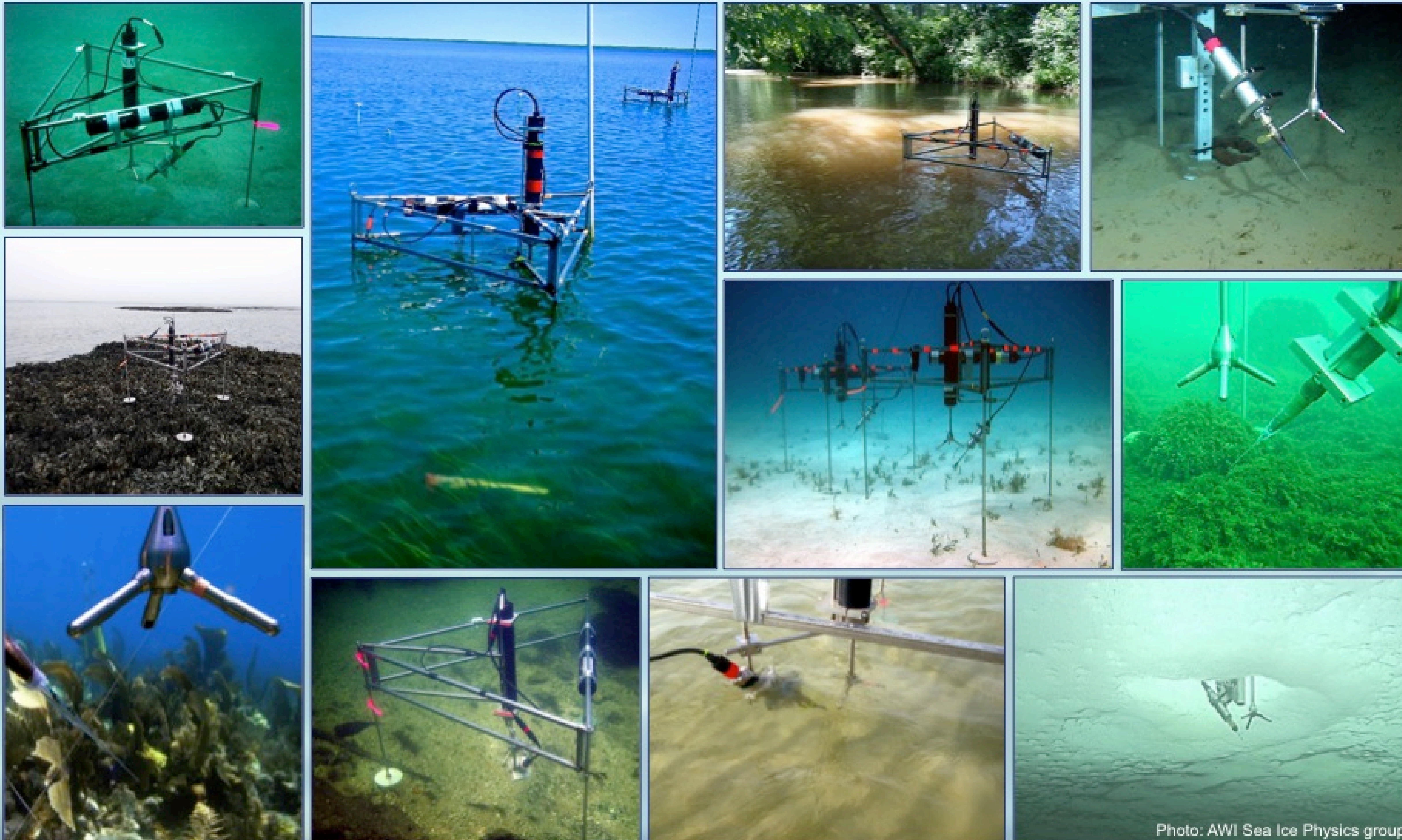
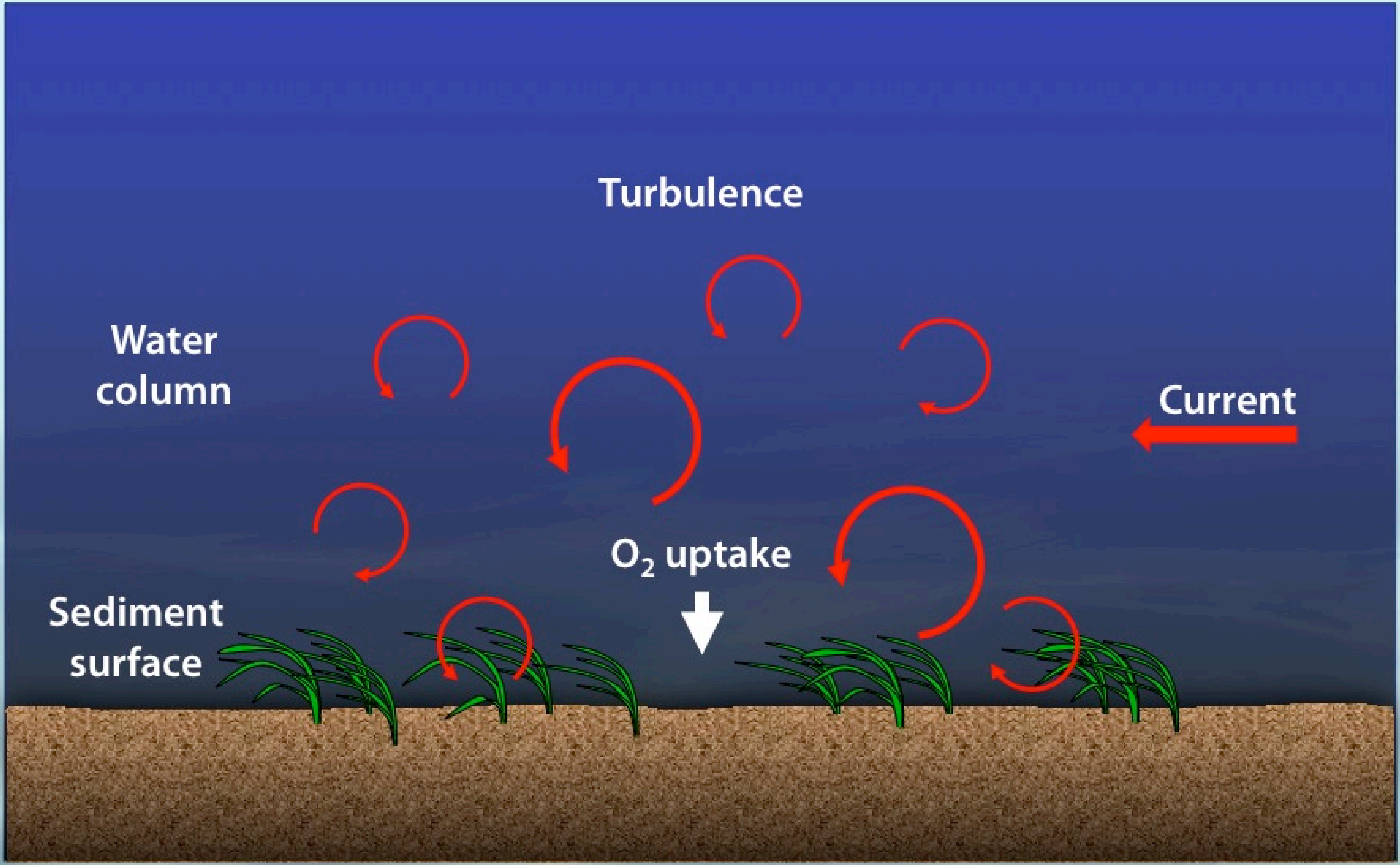
A versatile approach



doi: 10.1002/loe2.10005

Basic principles of eddy covariance



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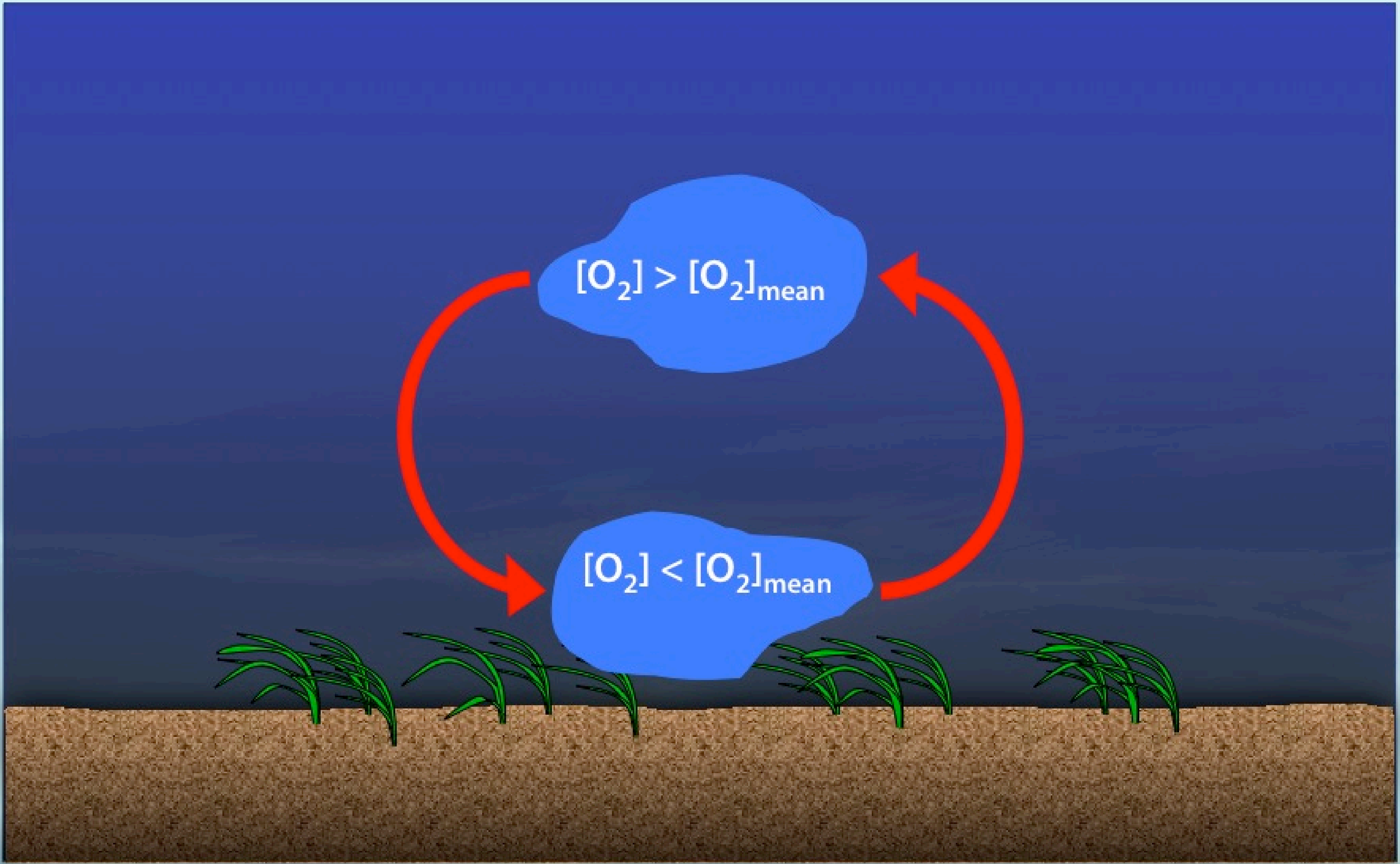

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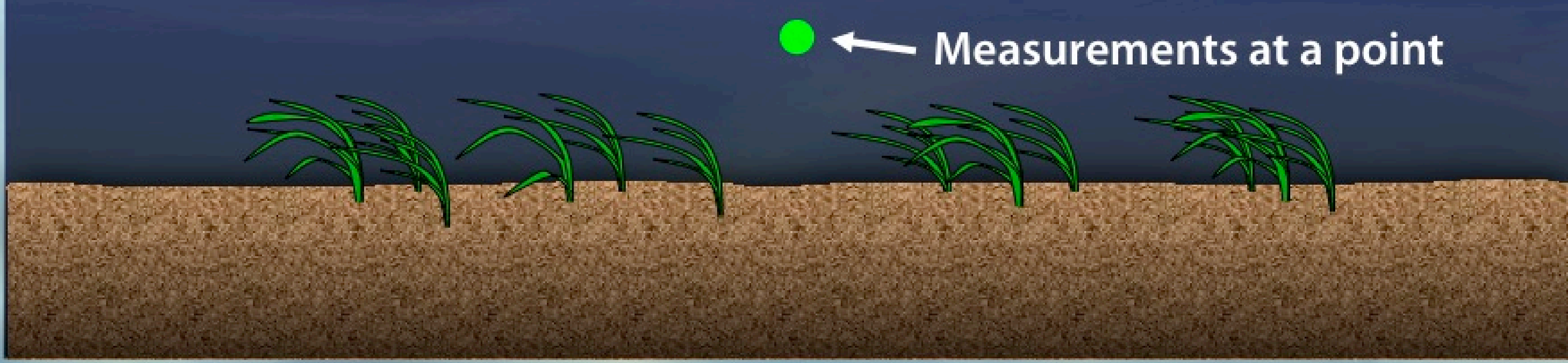
Basic principles of eddy covariance

- Key variables: vertical velocity (w) and oxygen concentration (C)
- Instantaneous vertical advective flux = $w\,C$

Unit: [cm s^{-1}] [nmol cm^{-3}] = [nmol s^{-1} cm^{-2}]



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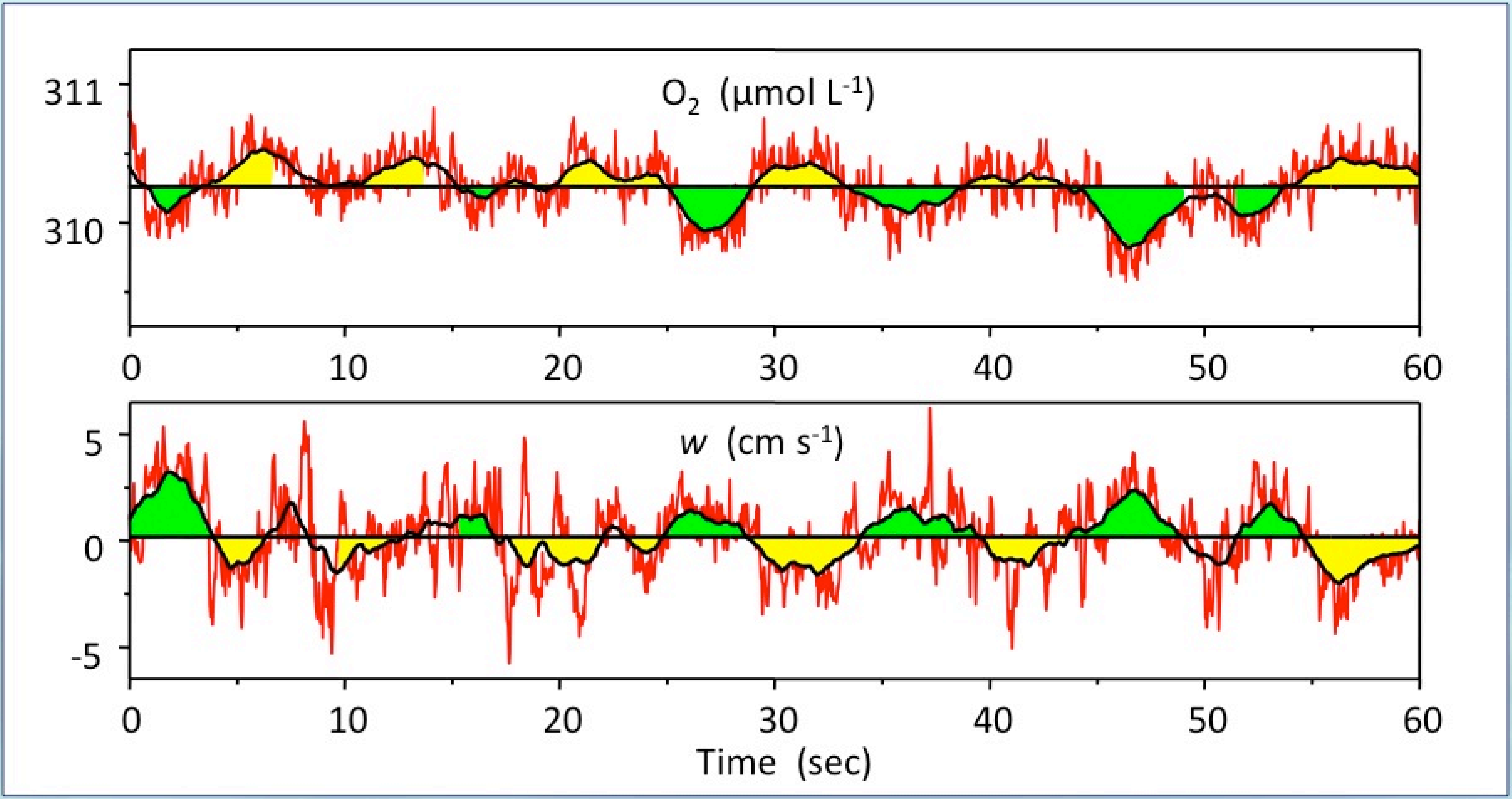
Basic principles of eddy covariance

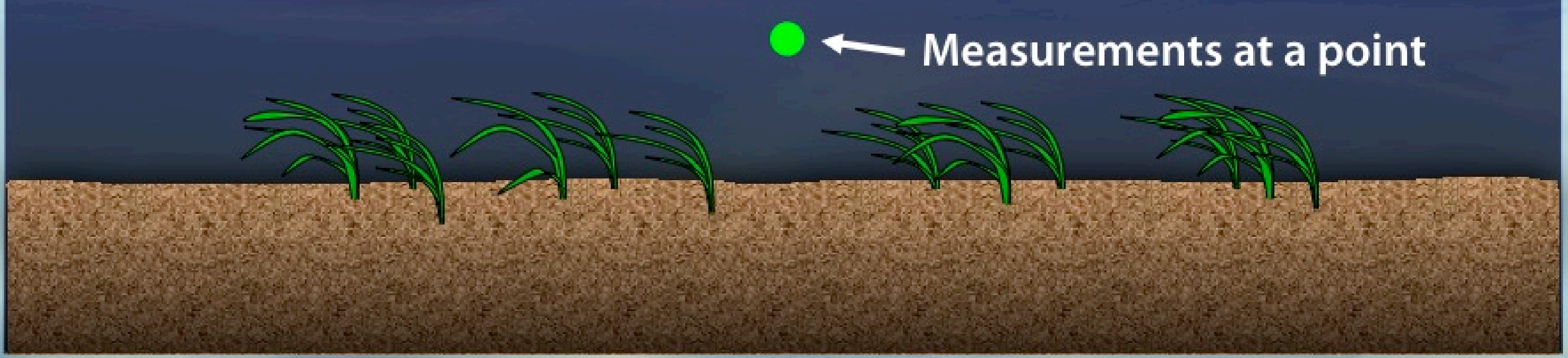


- One min of real data measured over an oxygen-consuming substrate

Berg, Delgard, Glud, Huettel, Reimers, Pace
doi: 10.1002/loe2.10005

Basic principles of eddy covariance

- Reynolds decomposition: $w = \overline{w} + w'$ and $C = \overline{C} + C'$
- Averaged flux $= \overline{w\,C}$



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Basic principles of eddy covariance

- Reynolds decomposition: $w = \overline{w} + w'$ and $C = \overline{C} + C'$
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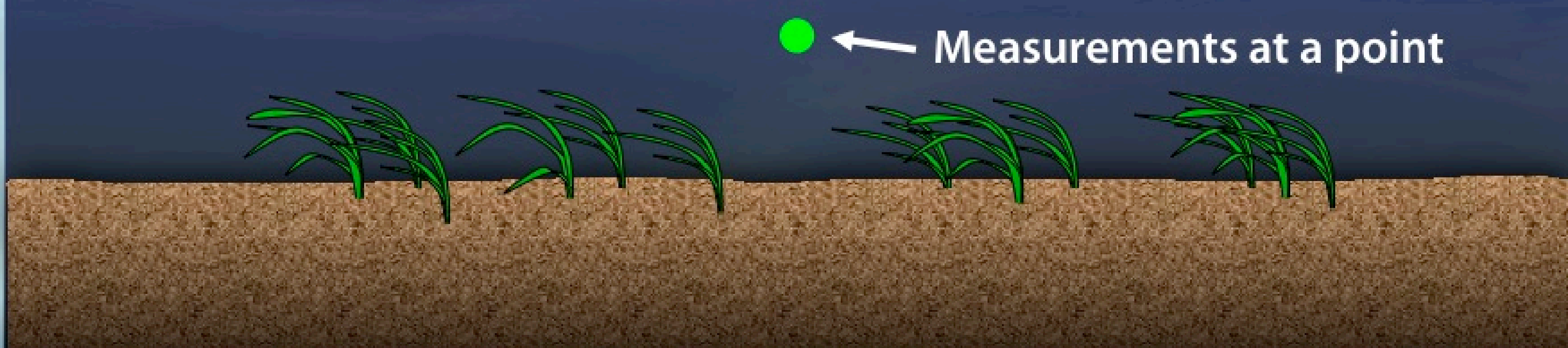

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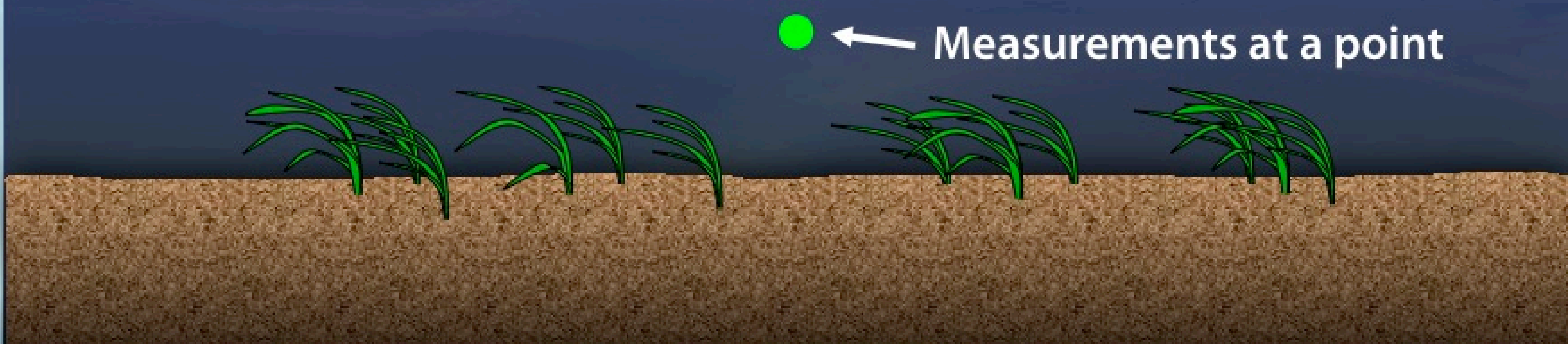

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Basic principles of eddy covariance

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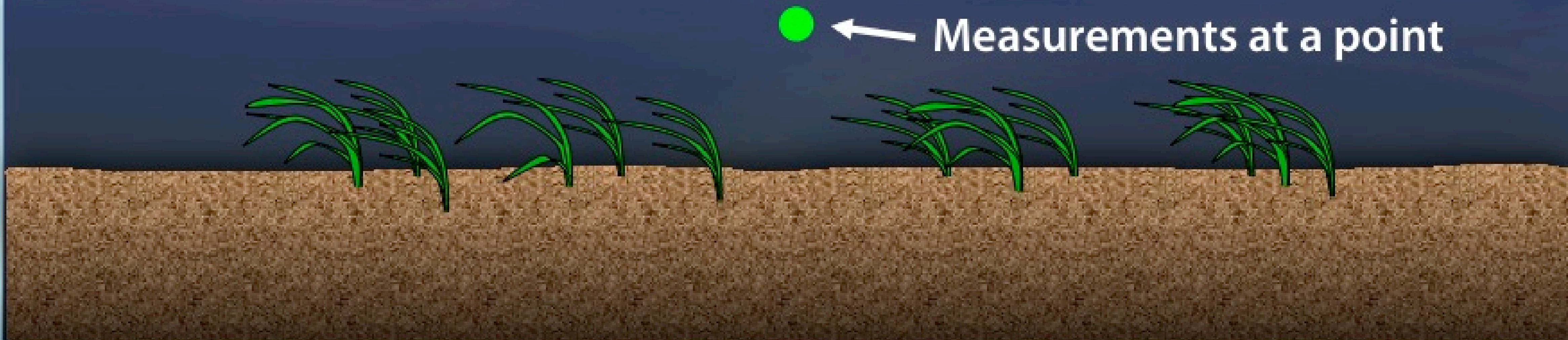
- Assumption: $\overline{w} = 0 \longrightarrow$ $\boxed{\text{Averaged flux} = \overline{w'C'}}$



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Basic principles of eddy covariance

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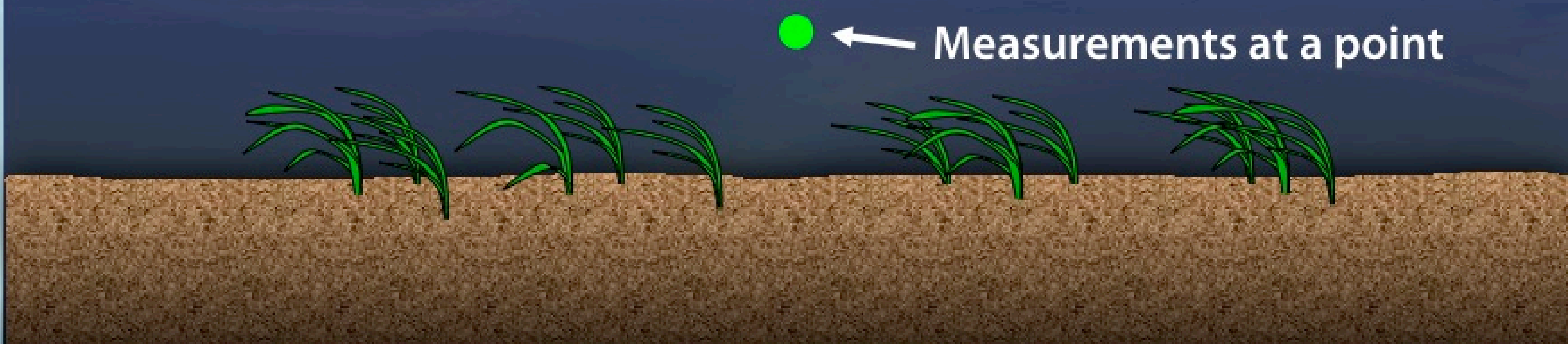

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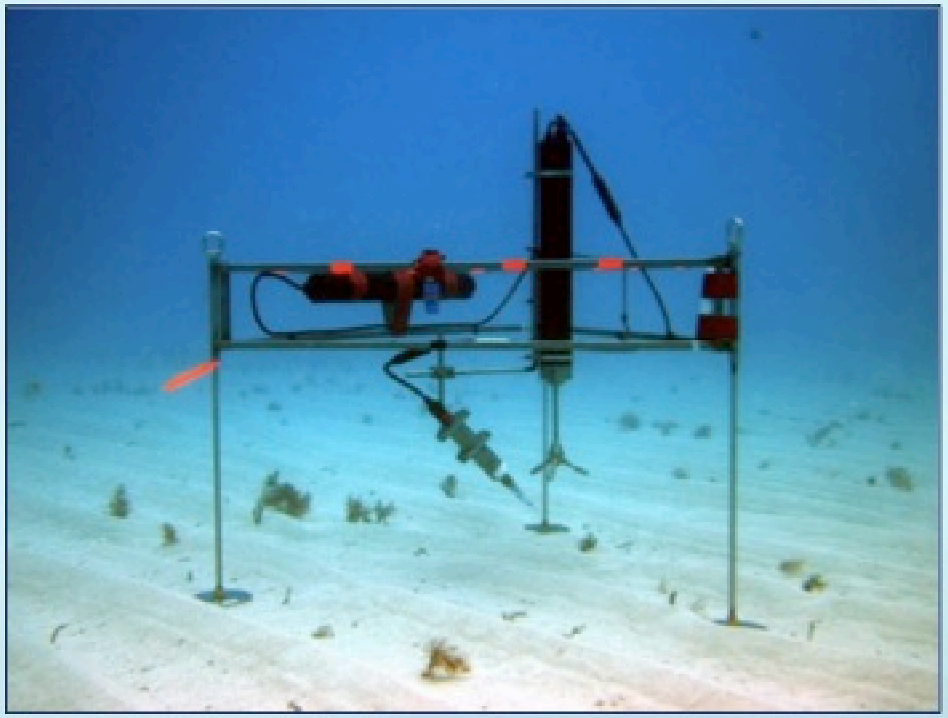

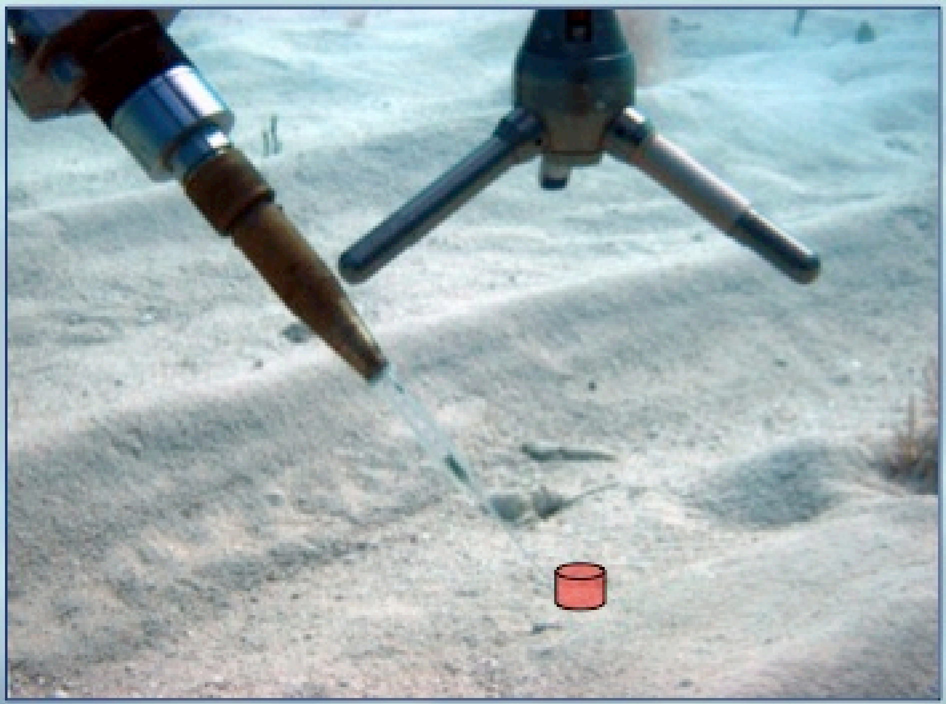

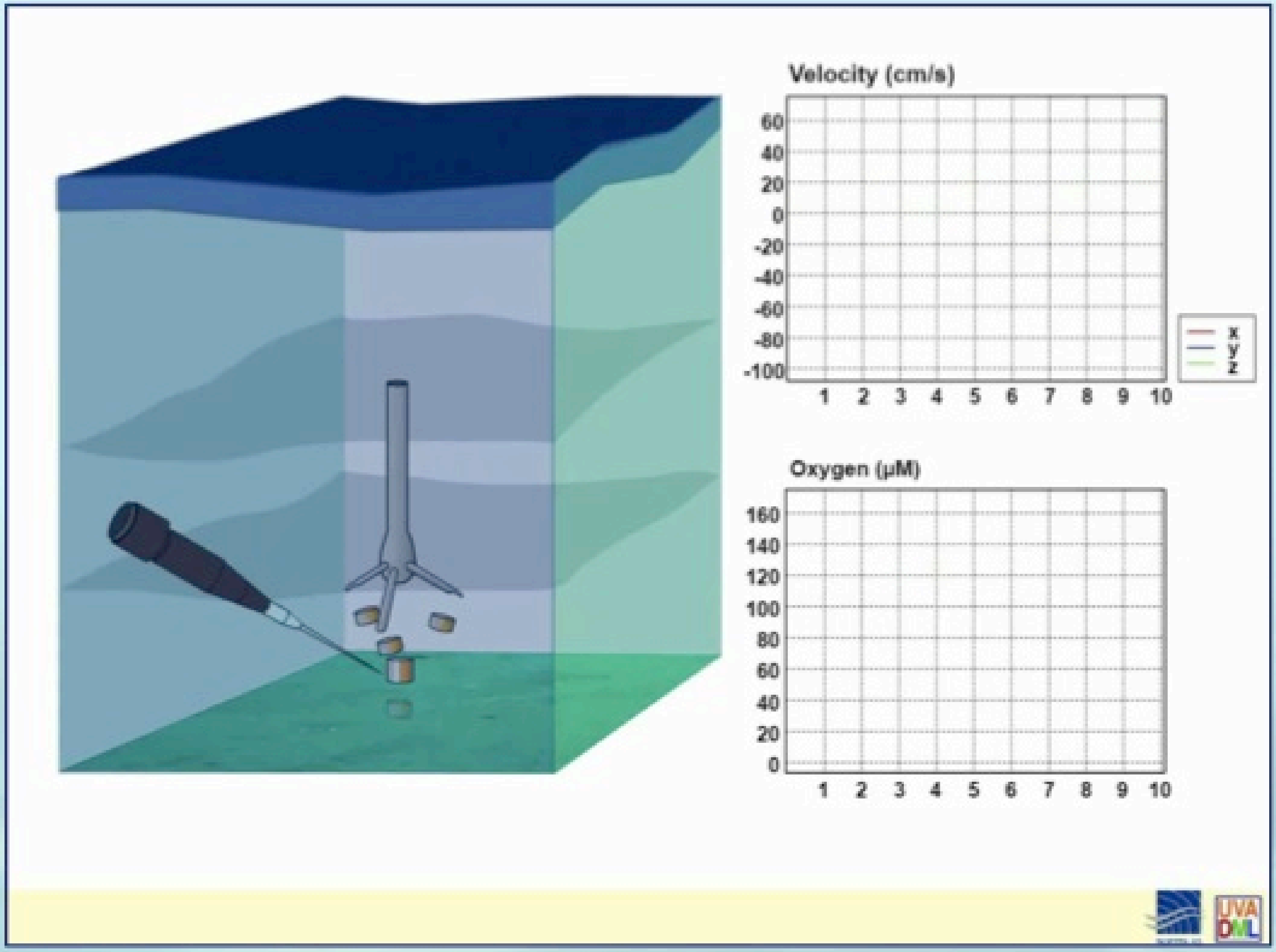

- Data typically recorded at 32 - 64 Hz and 5 - 30 cm above benthic surface

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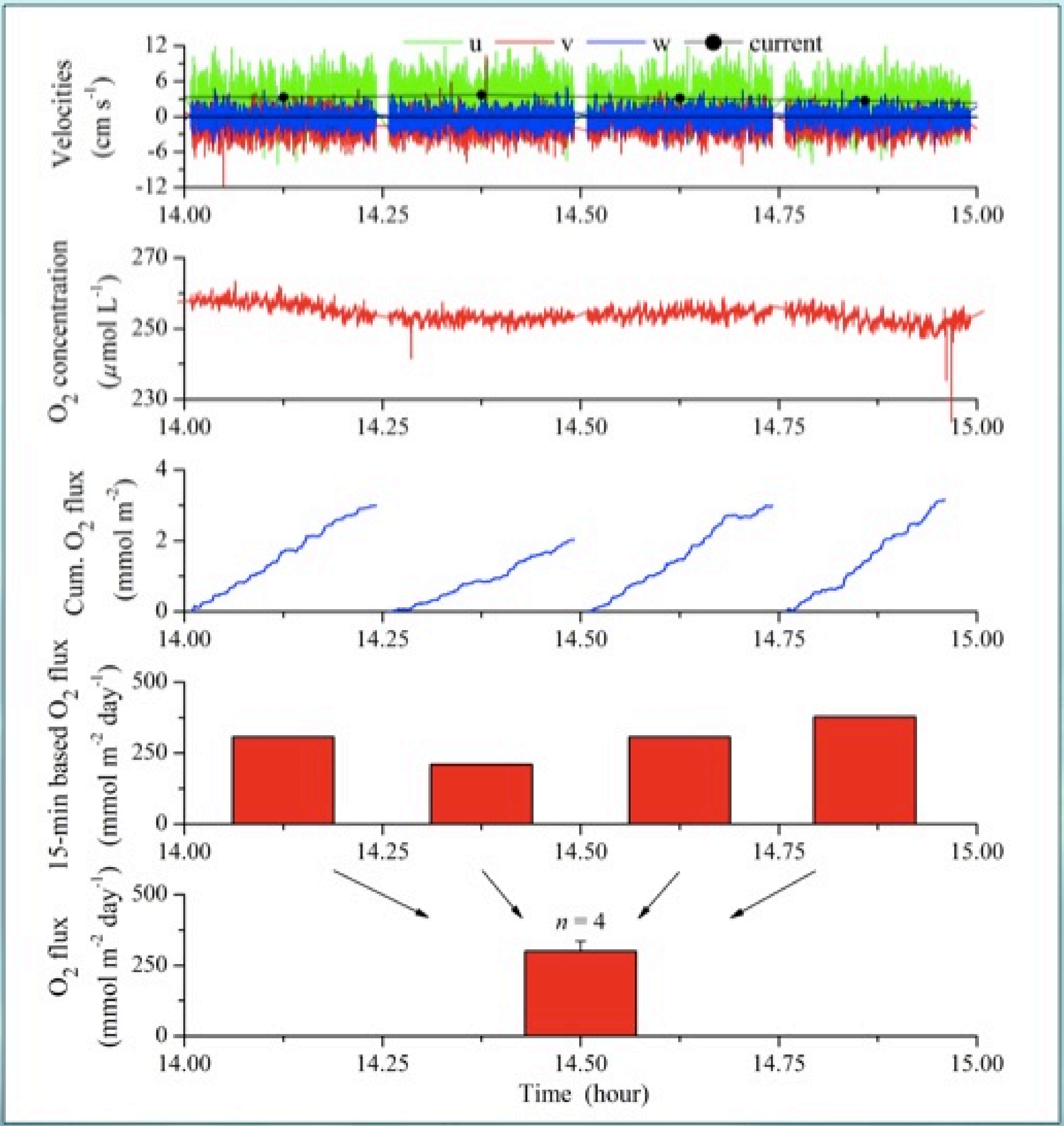
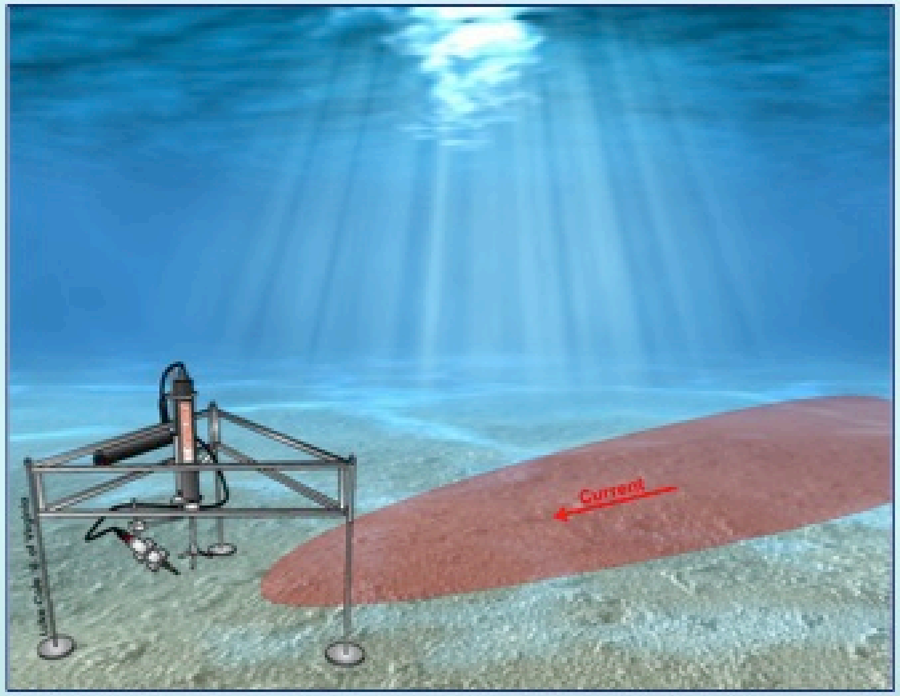
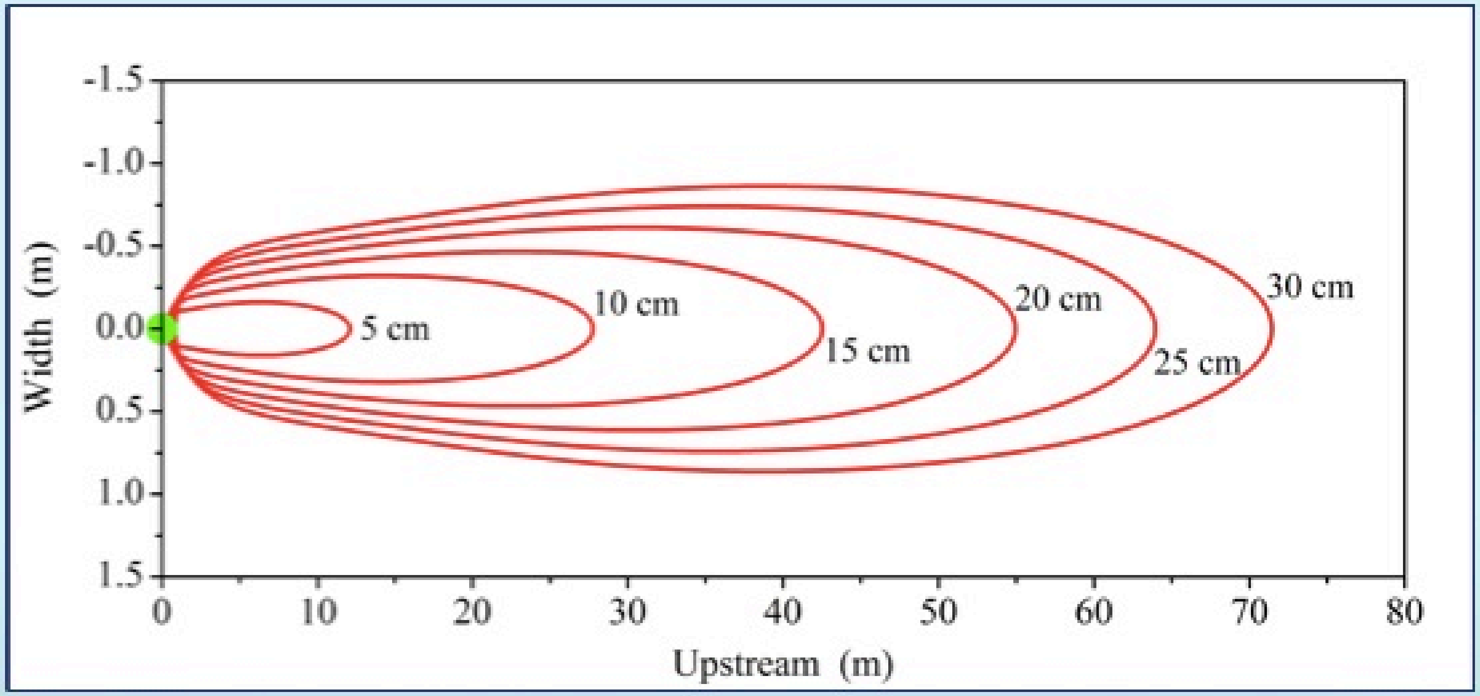
Basic principles of eddy covariance



Hume et al. (2011) L&O

Where does the eddy flux come from?





Berg et al. (2007) L&O

- Footprint definition: smallest area on the bottom that contributes 90% of the measured flux
- Typical size: 5 to 100 m^2
- Footprint different (and as yet undetermined) at shallow-water sites with waves because of oscillatory wave motions

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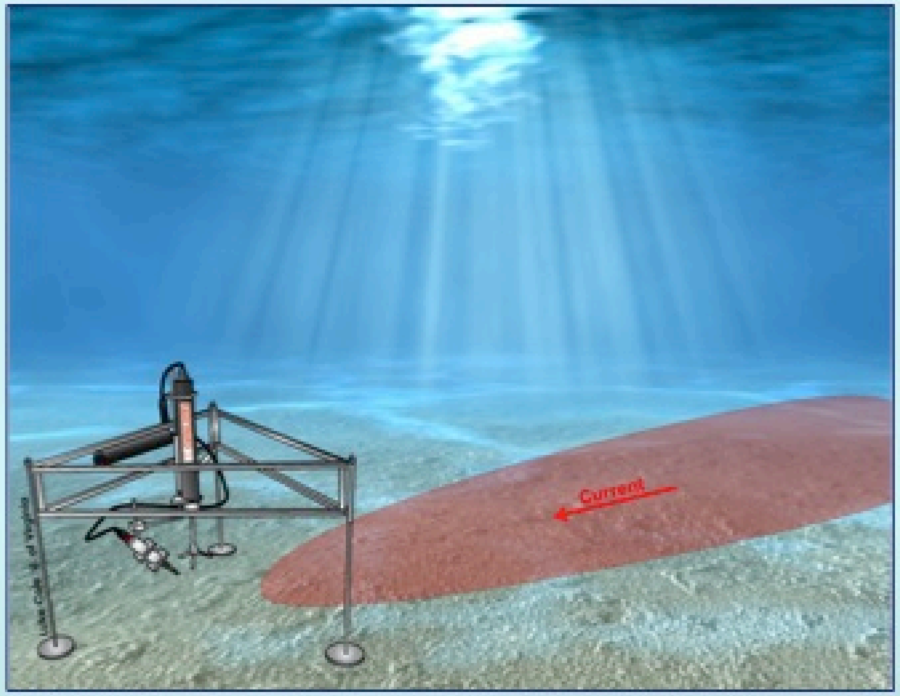
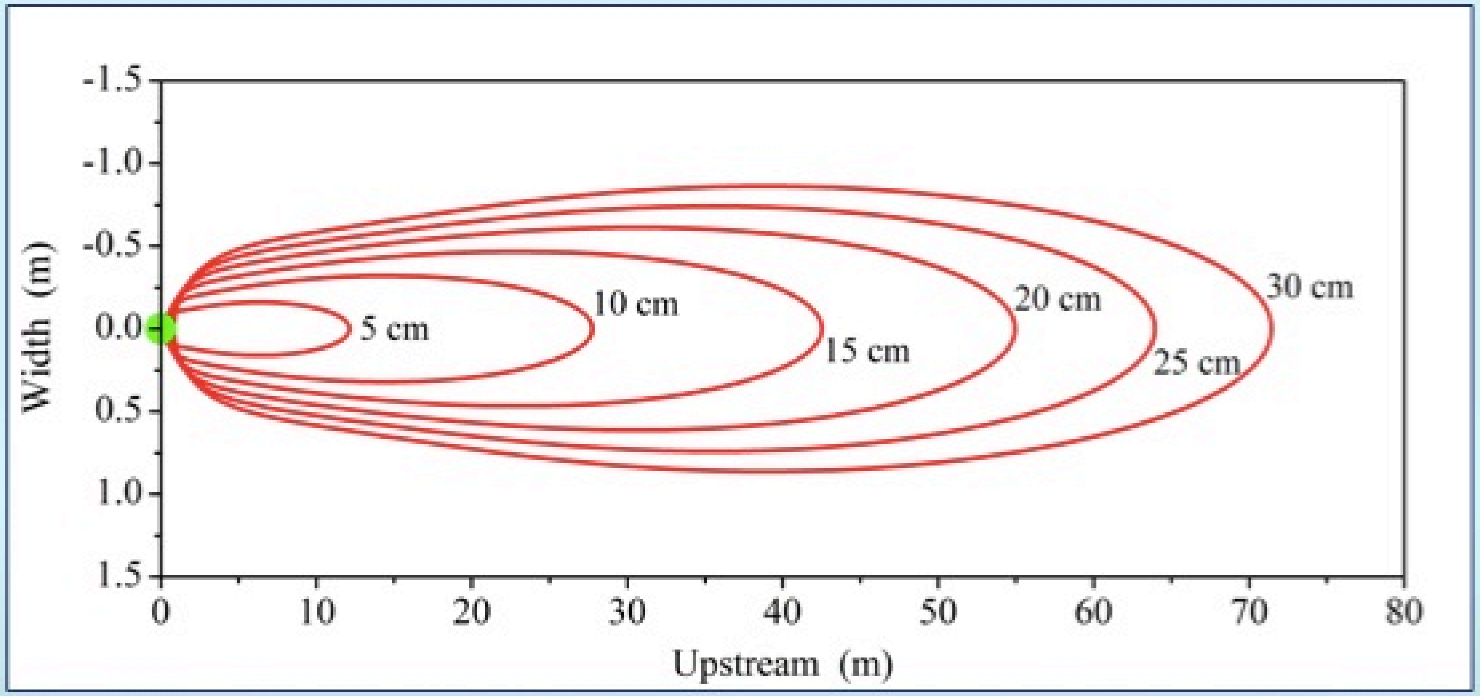
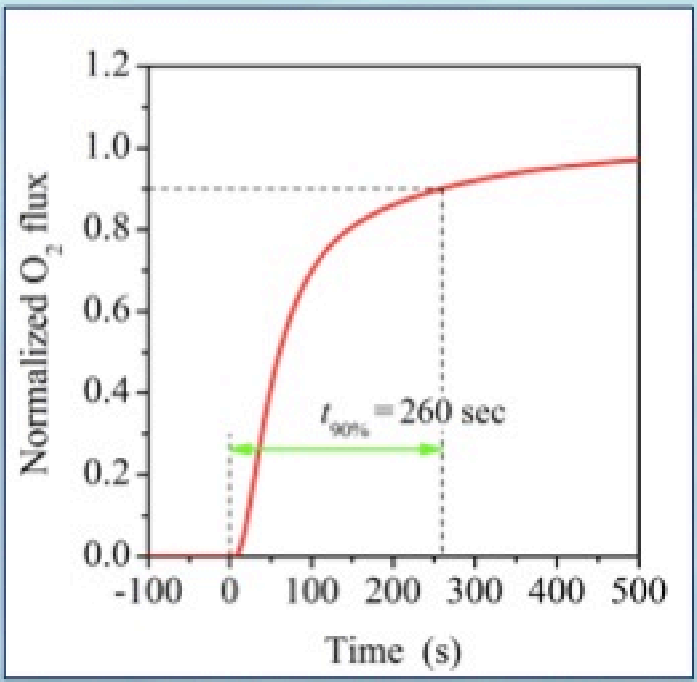
Where does the eddy flux come from?





Berg et al. (2007) L&O

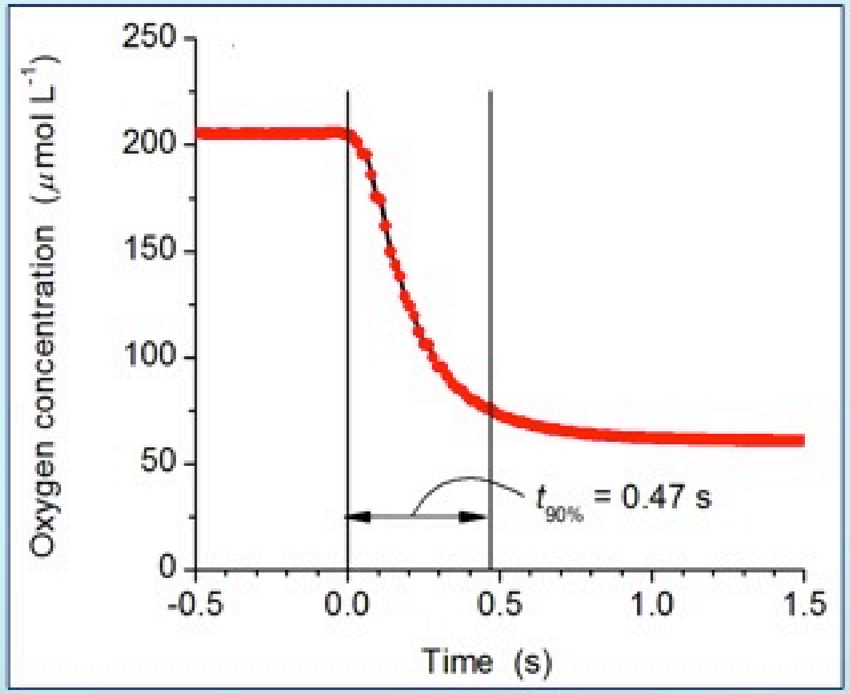


Rheuban and Berg (2013) L&O Methods

Requirements of approach

- Record velocity and oxygen data at > ~8 Hz
- Record velocity and oxygen data no more than 2 – 3 cm apart
- Sensor response time $t_{90\%}$ < ~0.5 s
- More complex to apply than other methods
- Full system price: $30,000 - $60,000

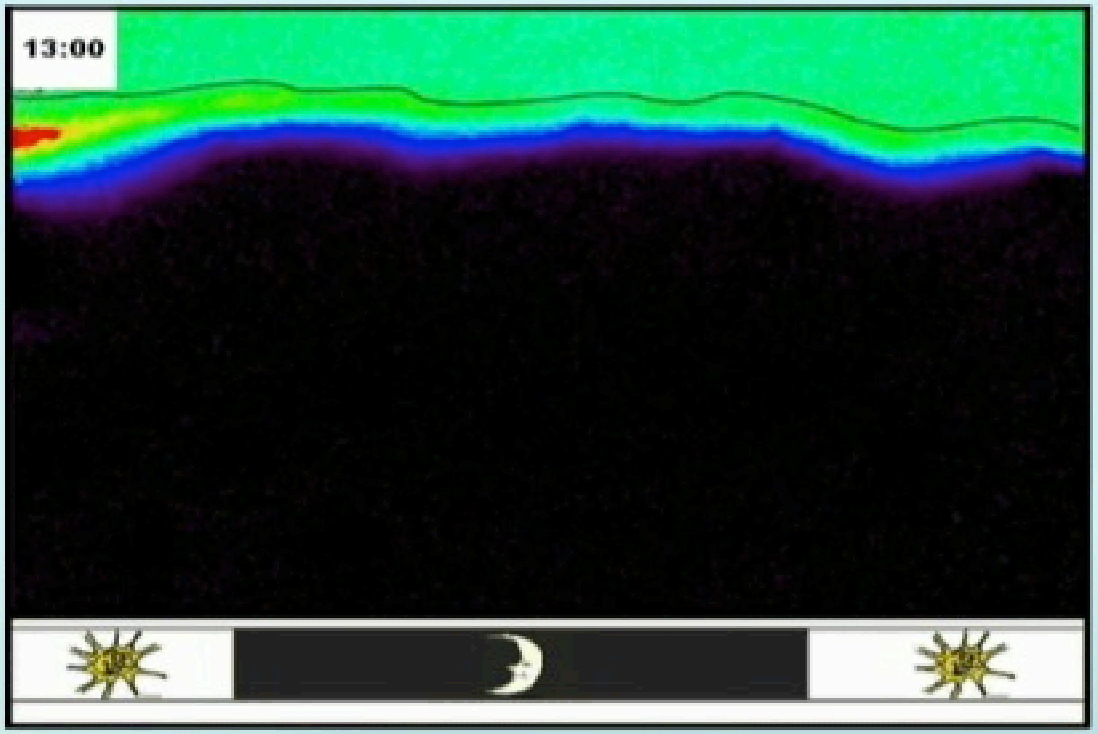
Why do all this?



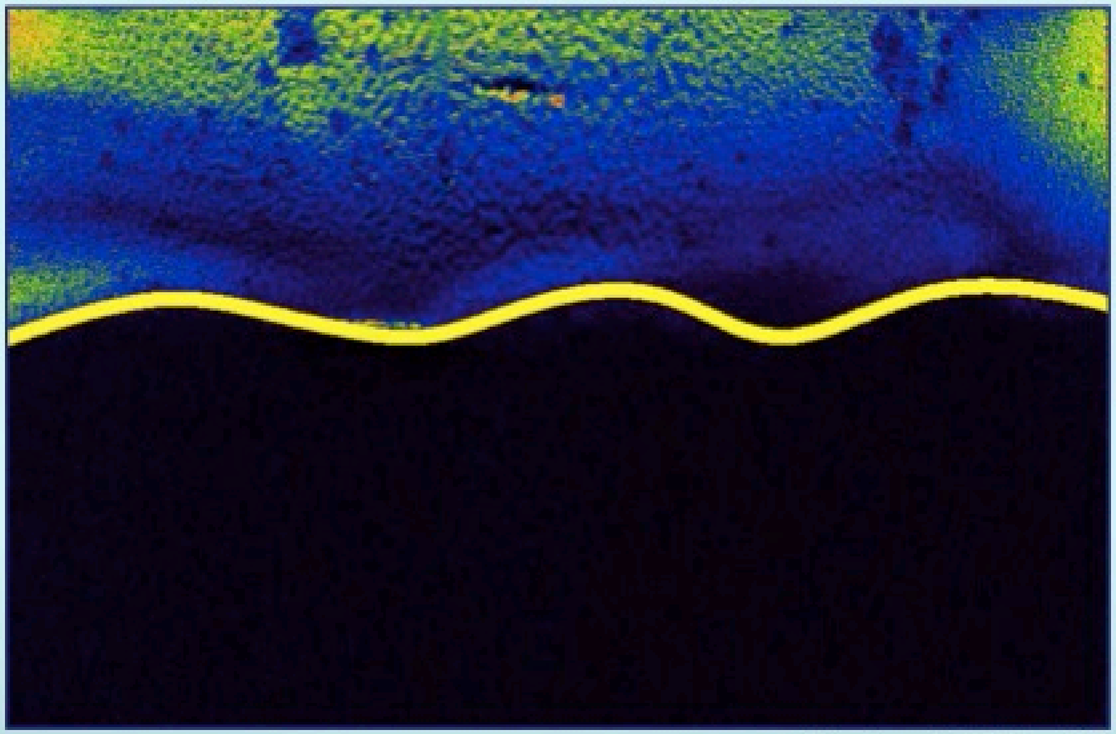
Berg et al. (2016). L&O Methods

doi: 10.1002/loe2.10005

Natural environment complex and dynamic

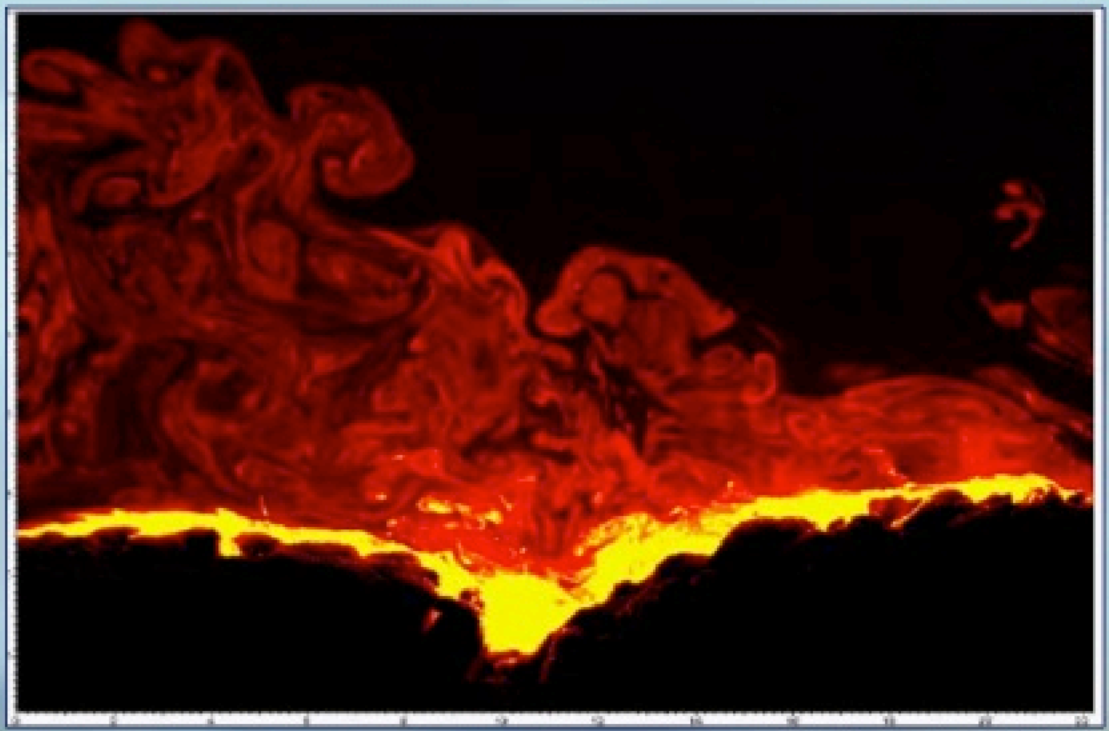


Wenzhofer and Glud (2004)



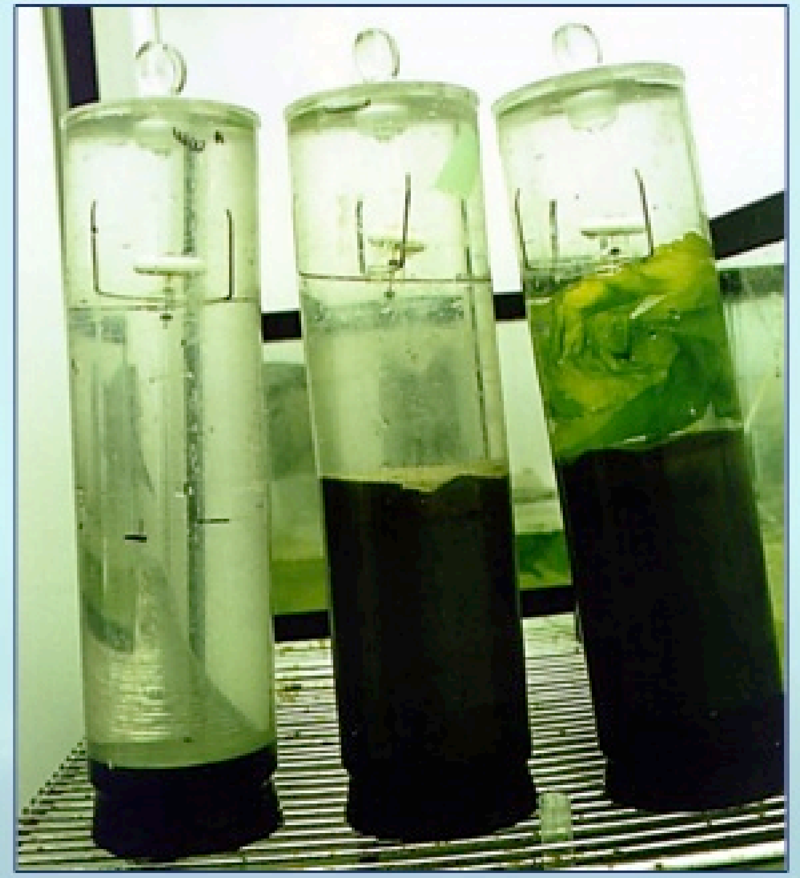
Kessler et al. (Unpubl.)

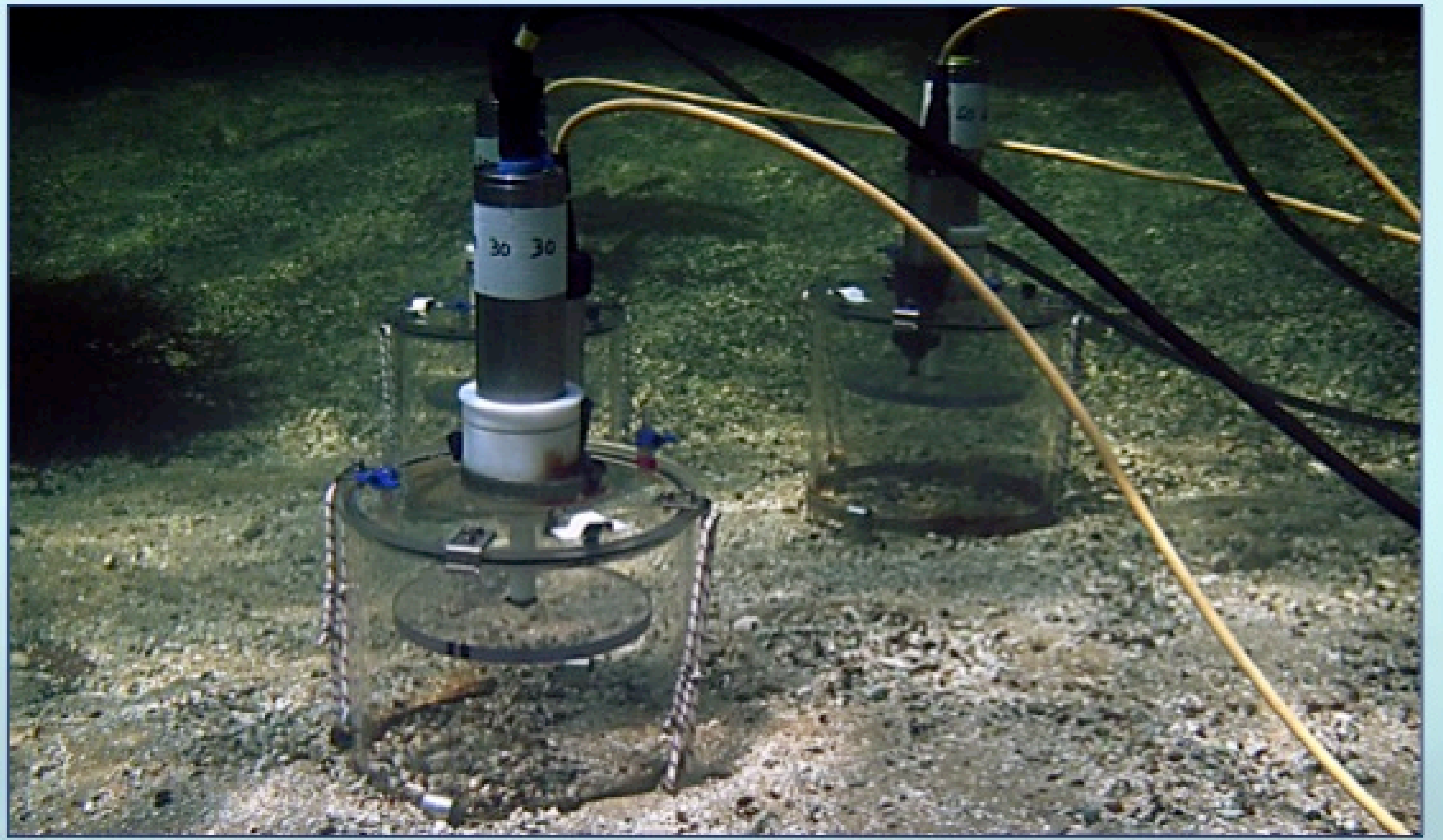
Reimers et al. (2004)



Reidenbach et al. (2007)

Traditional flux methods have limitations





Sediment core incubations and in situ chamber deployments:

- Exclude or seriously alter the most important drivers of flux (current flow, wave action, light, etc.)
- Disturb the sediment
- Cut off all exchange with the natural dynamic water column

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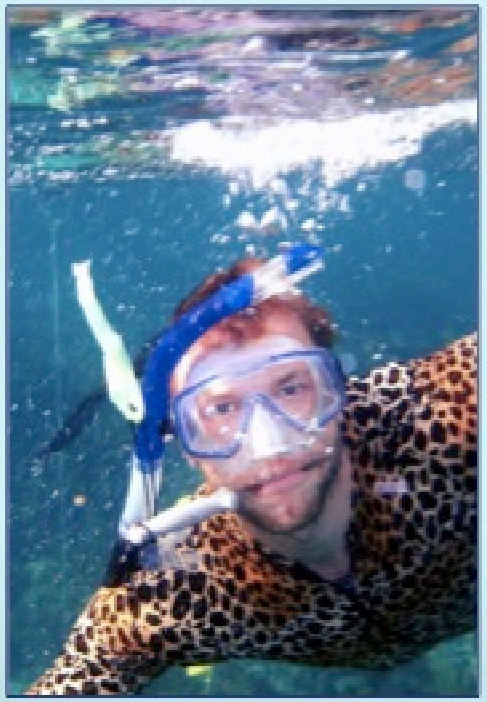
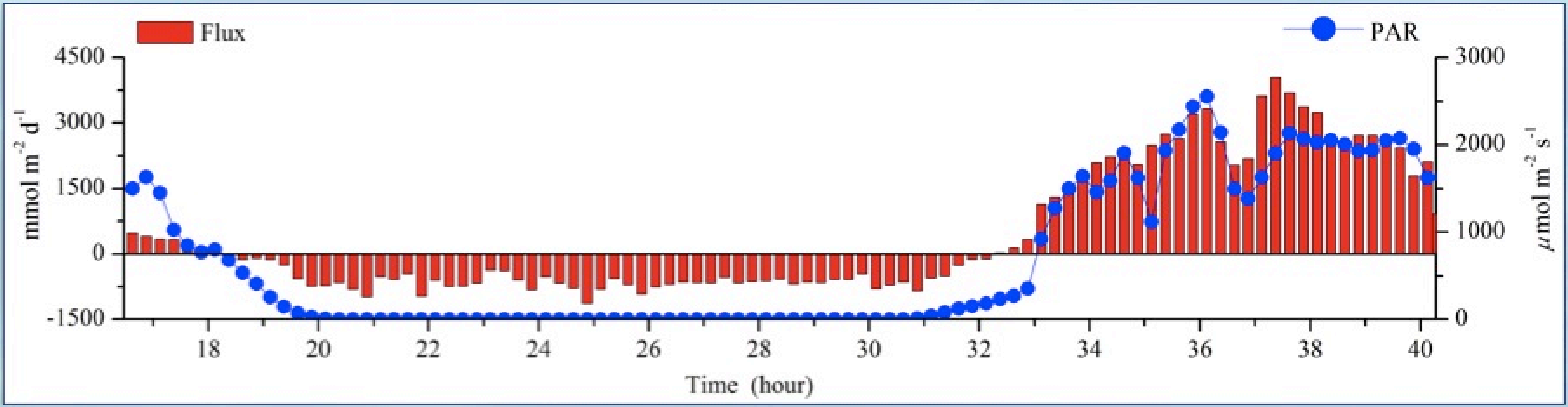
Effects of natural light







Long et al. (2013) PLoS ONE

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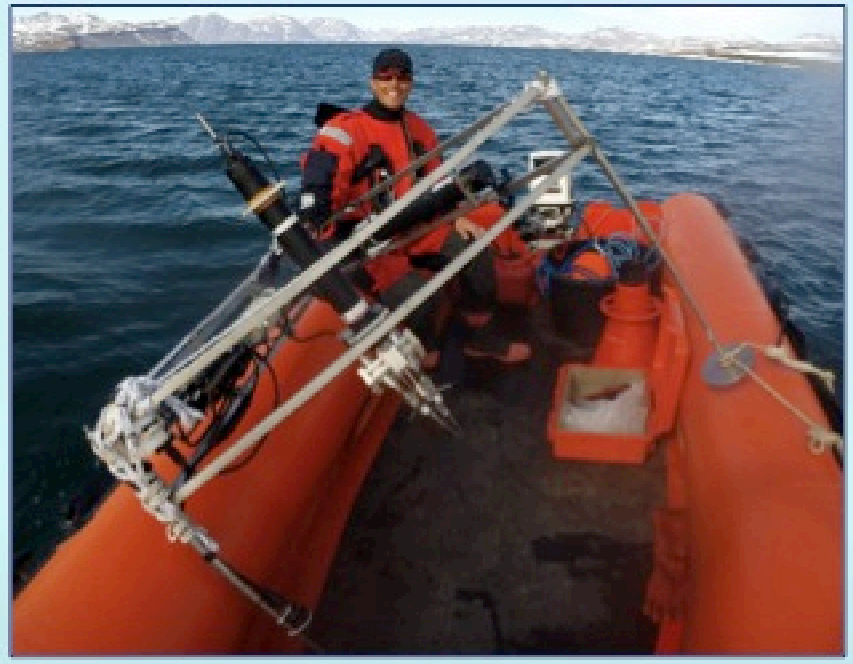
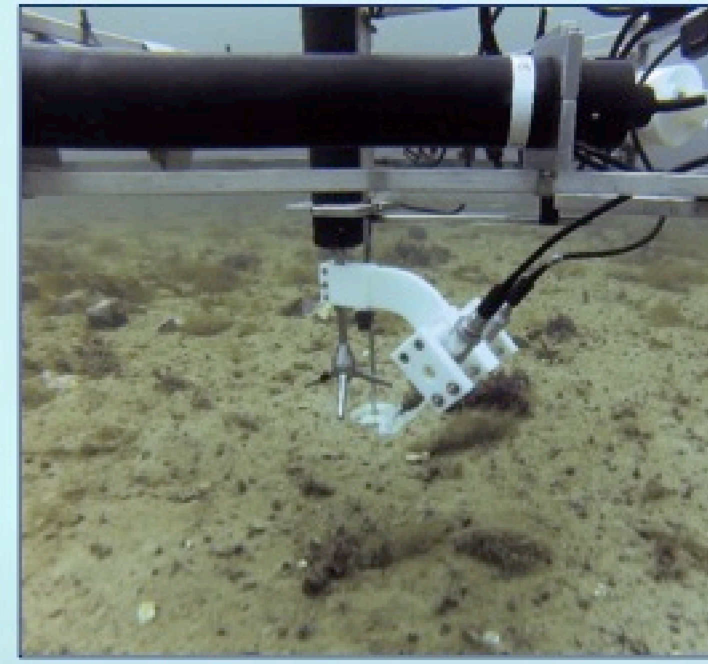
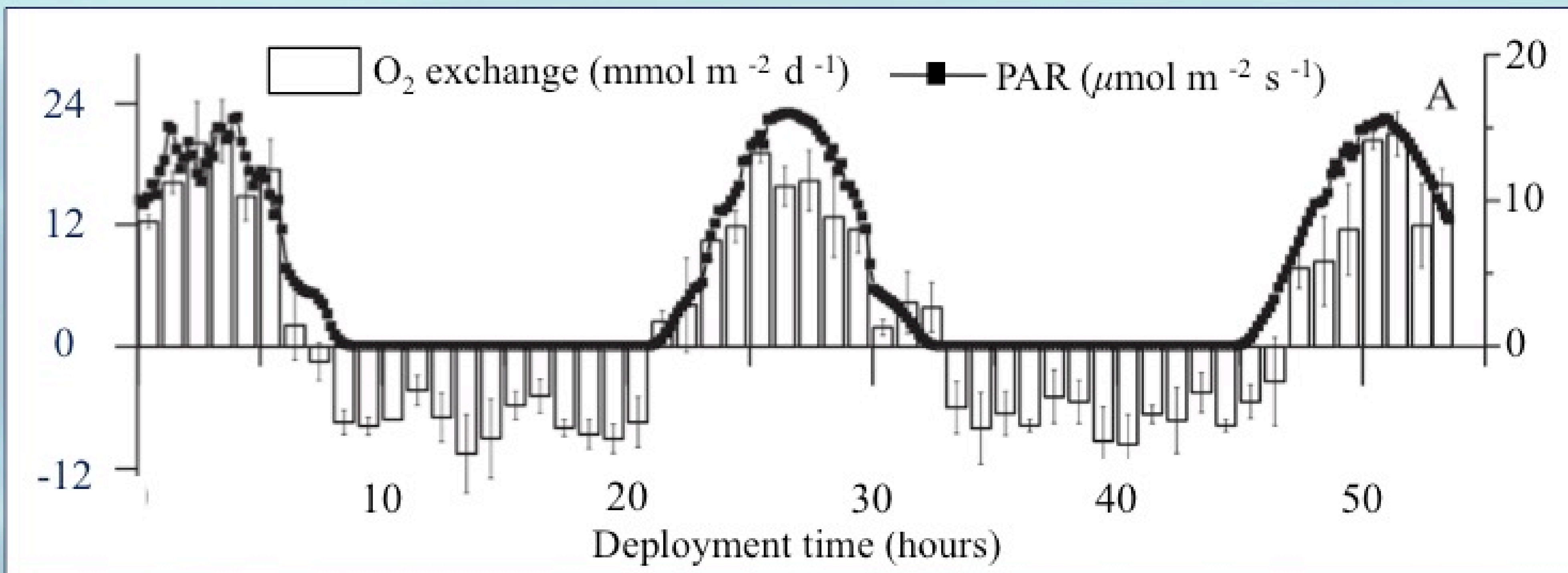


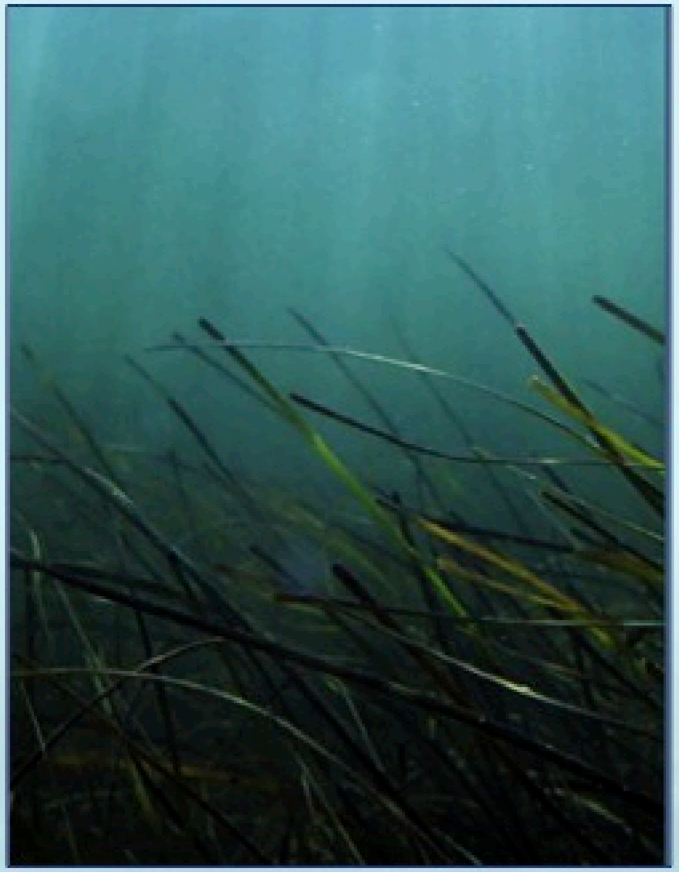




Attard et al. (2014) L&O

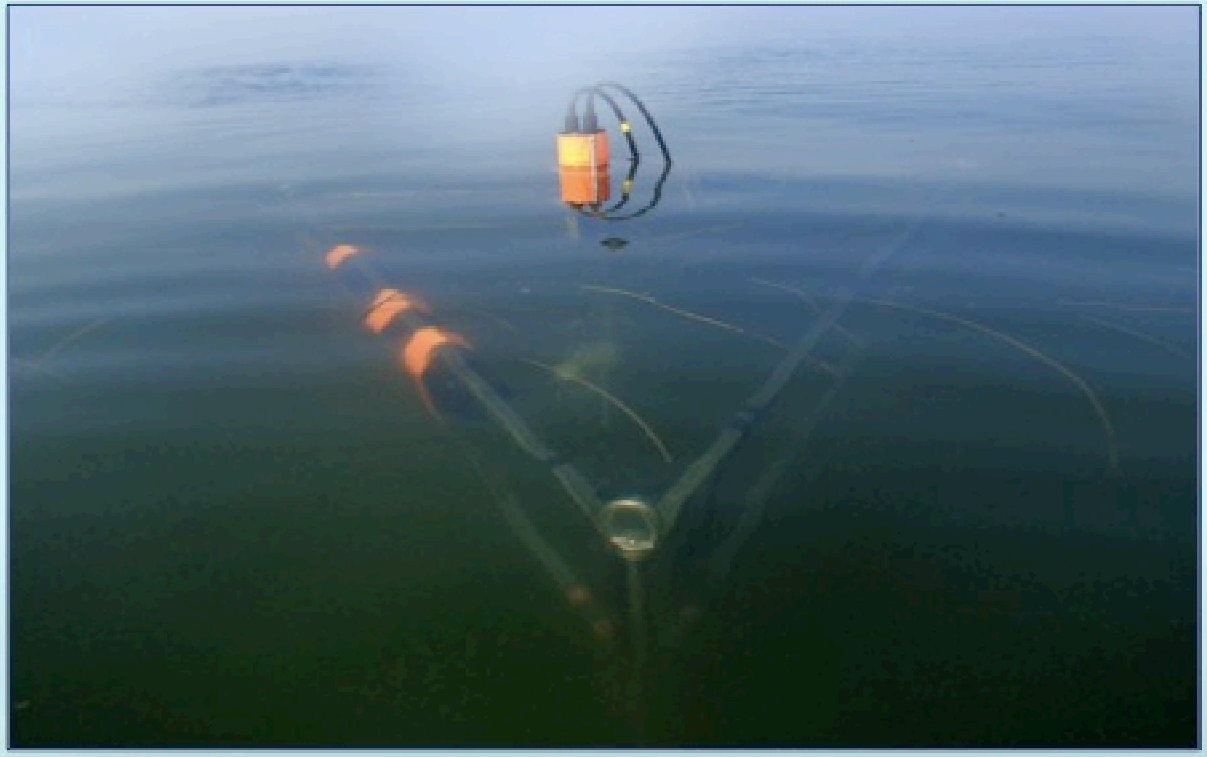
Seagrass at Virginia Coast Reserve LTER

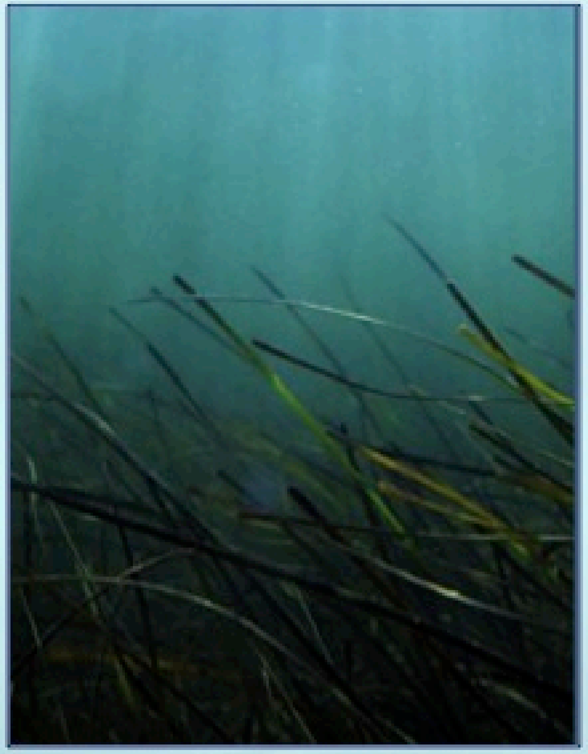
Map: M. Oreska & J.J. Orth

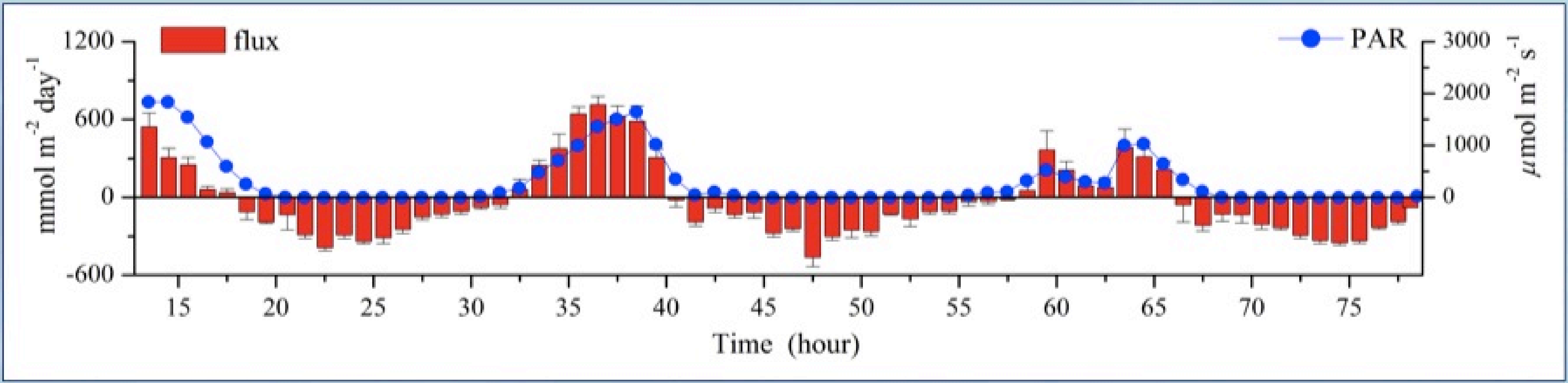


- Restored seagrass meadows – larger than 2500 ha
- Site of extensive aquatic eddy covariance work

Effects of natural light



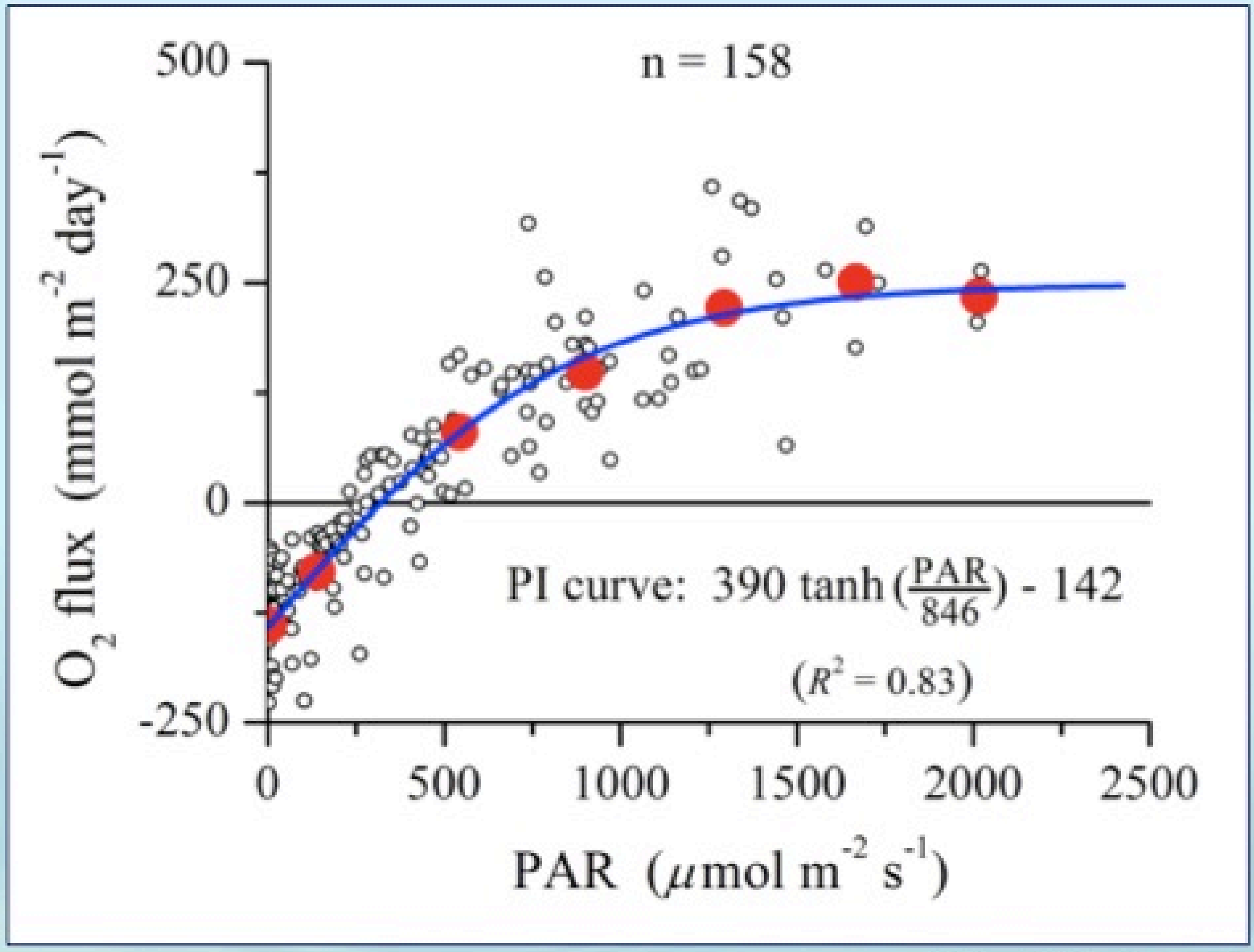




Delgard et al. (In prep A)

doi: 10.1002/loe2.10005

Effects of natural light



Delgard et al. (In prep A)

- Averaged system-scale response to light
- Integrated horizontally and vertically (through canopy)

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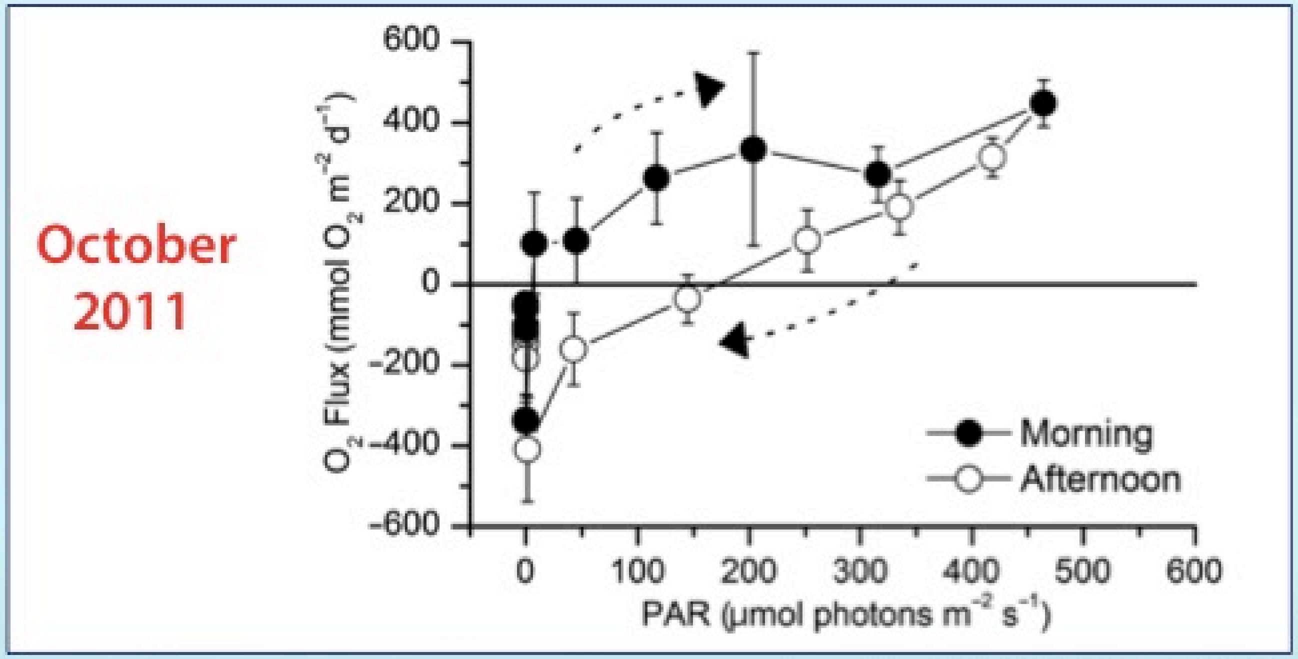
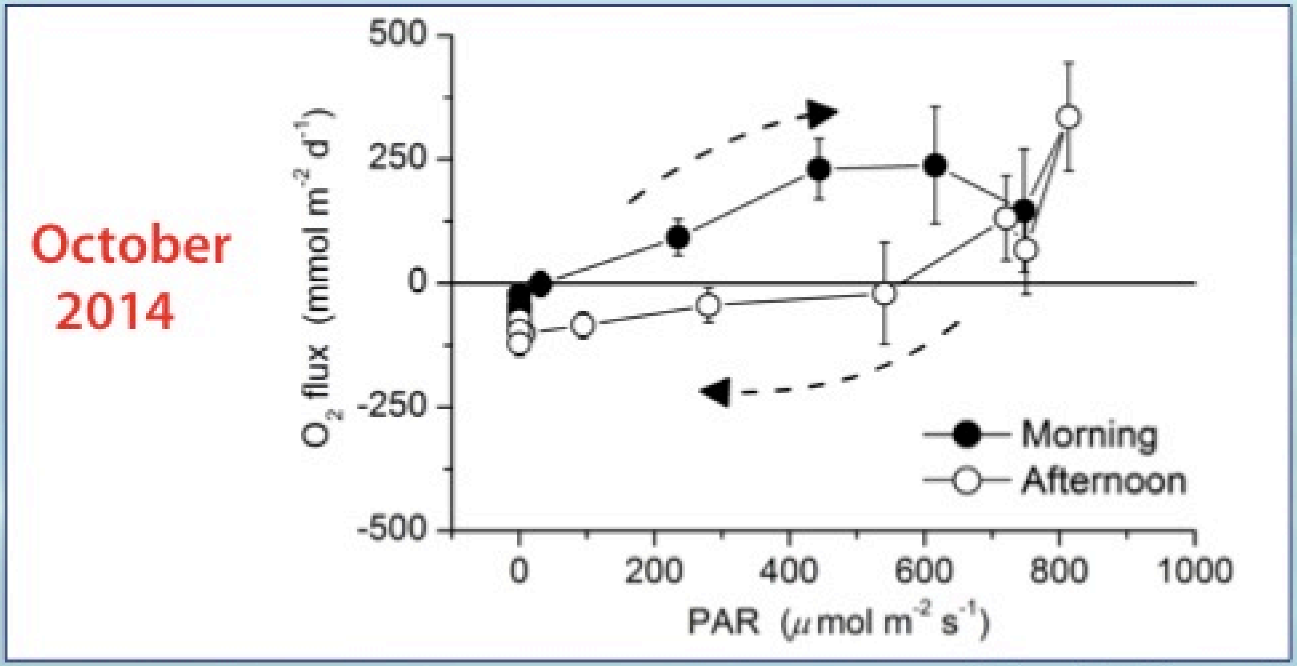
Effects of natural light



Rheuban et al. (2014) MEPS



Delgard et al. (In prep A)

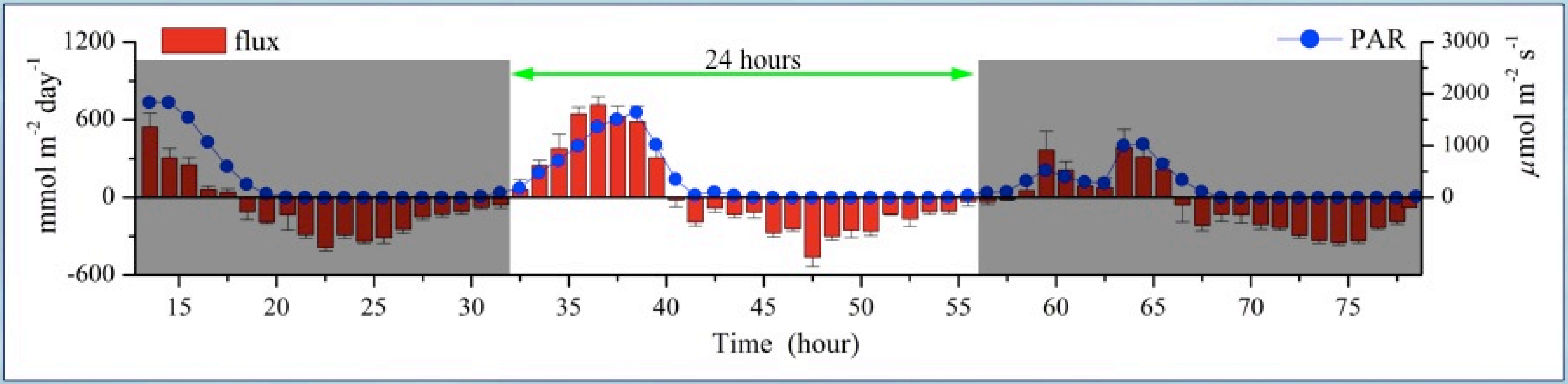
doi: 10.1002/loe2.10005

Seagrass metabolism

- $R = \frac{1}{24}\left(\sum \text{flux}_{\text{dark}} + \frac{\sum \text{flux}_{\text{dark}}}{h_{\text{dark}}} h_{\text{light}}\right)$

- $GPP = \frac{1}{24}\left(\sum \text{flux}_{\text{light}} + \frac{\left|\sum \text{flux}_{\text{dark}}\right|}{h_{\text{dark}}} h_{\text{light}}\right)$

Hume et al. (2011) L&O



Delgard et al. (In prep A)

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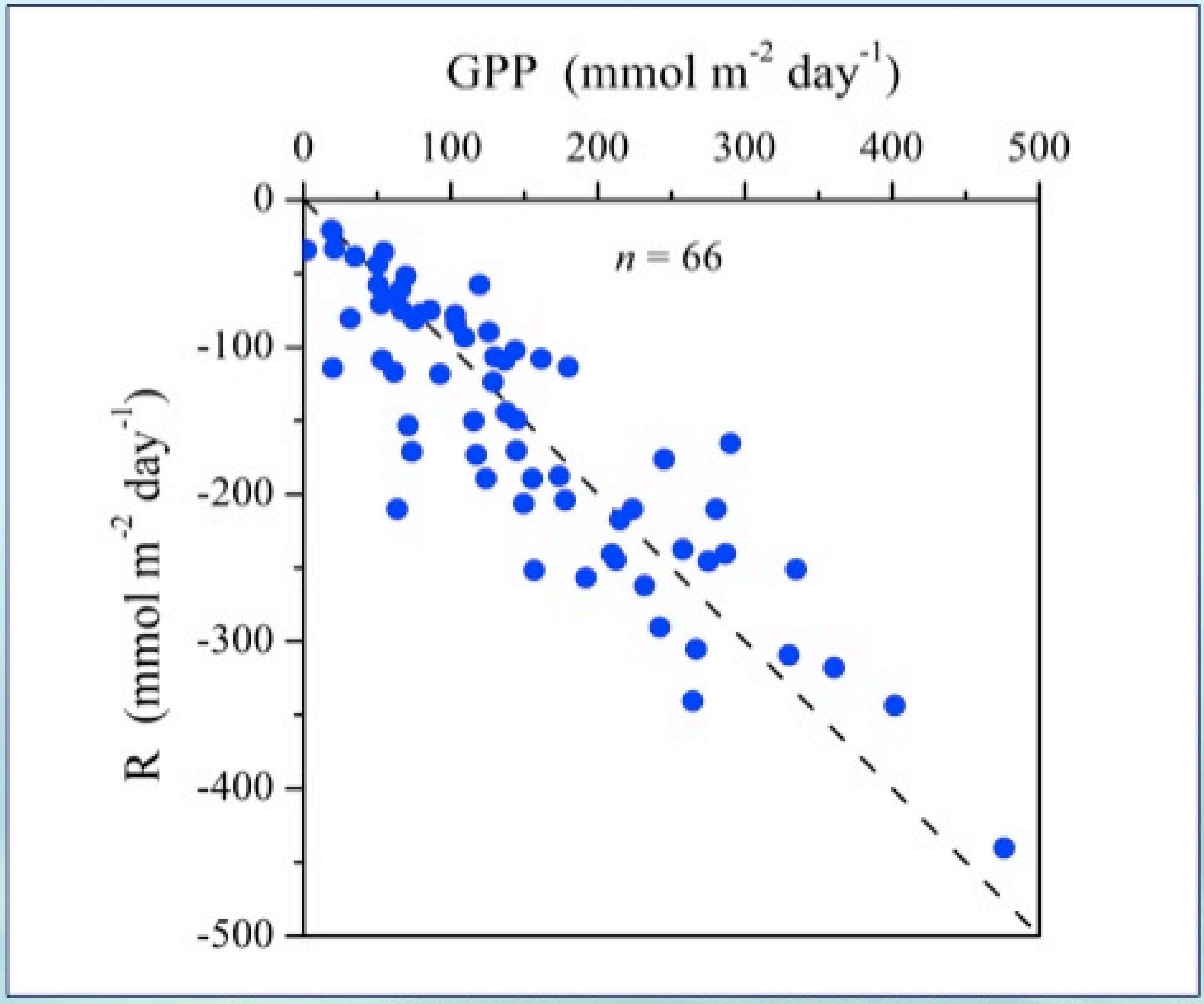

Hume et al. (2011) L&O; Rheuban et al. (2014) MEPS; Delgard et al. (In prep B)

- Tight coupling between R and GPP
- System in metabolic balance

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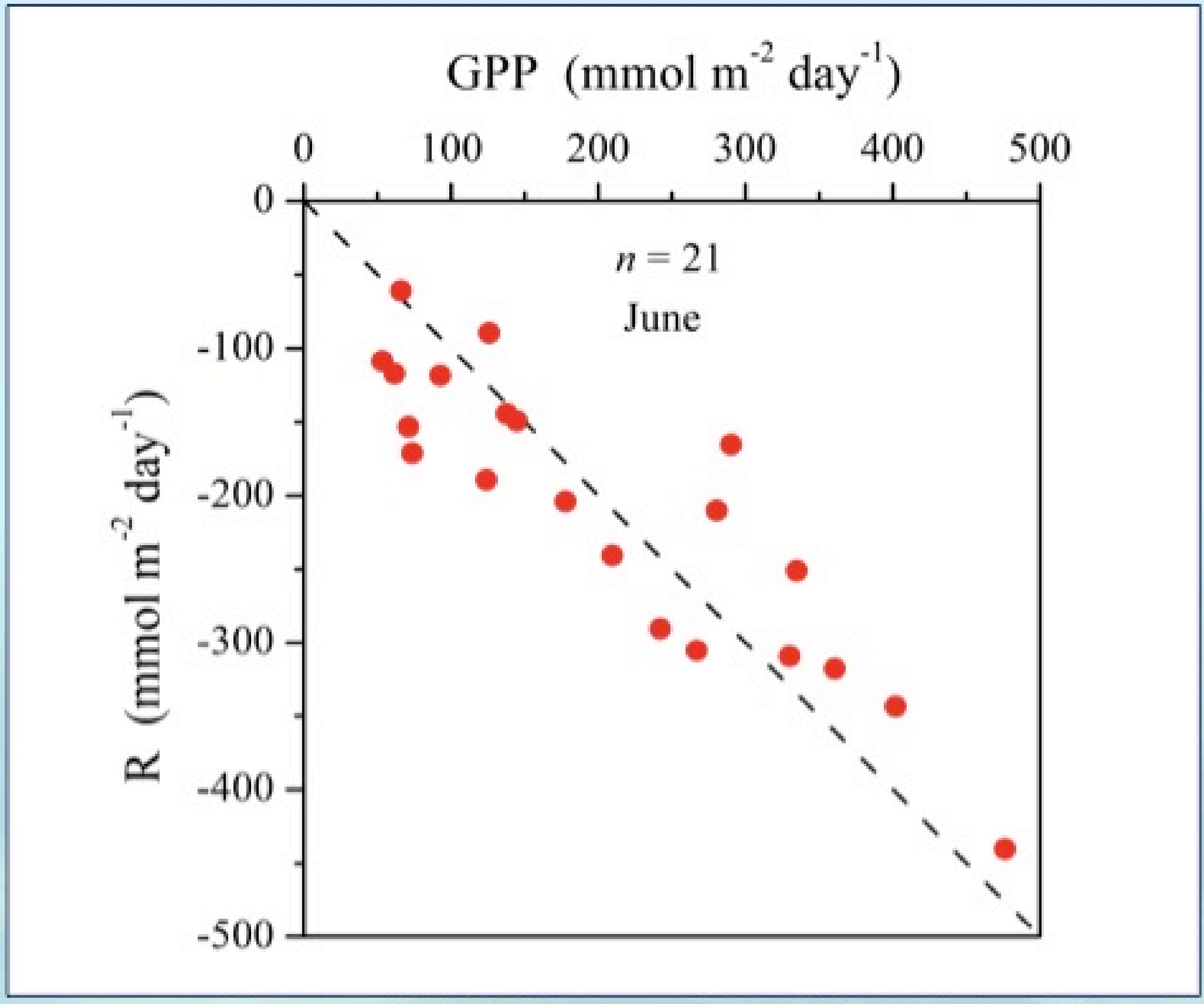
Seagrass metabolism



Hume et al. (2011) L&O; Rheuban et al. (2014) MEPS; Delgard et al. (In prep B)

- Variation in R and GPP in June is almost as large as over entire year
- Challenging to find “good” mean values

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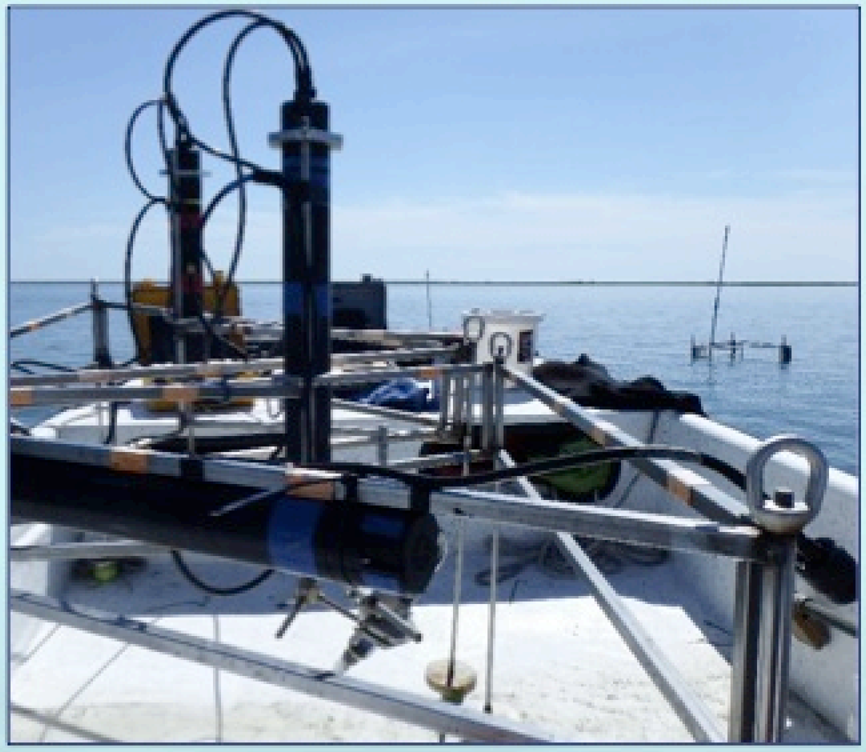
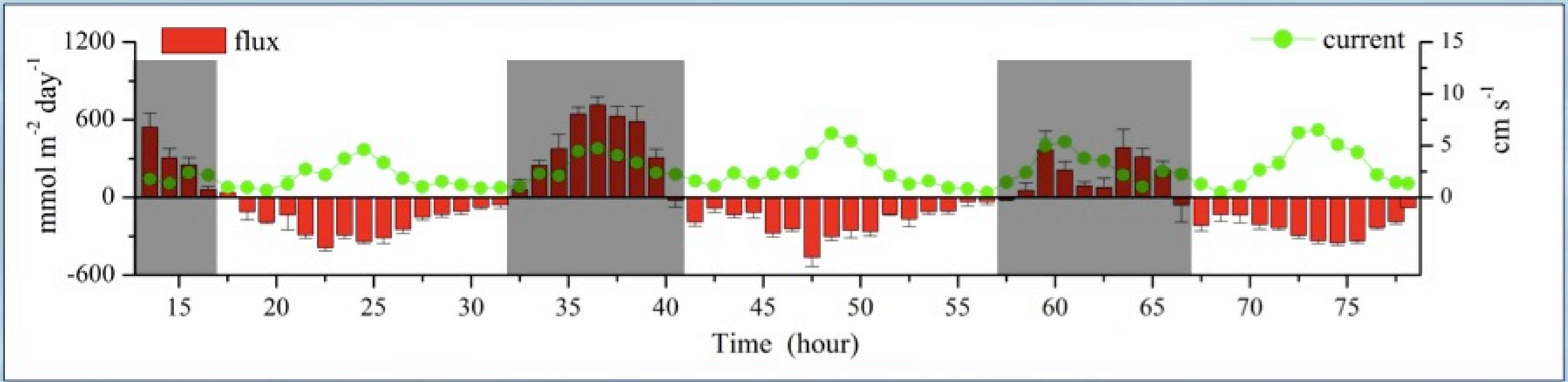
Effects of natural flow





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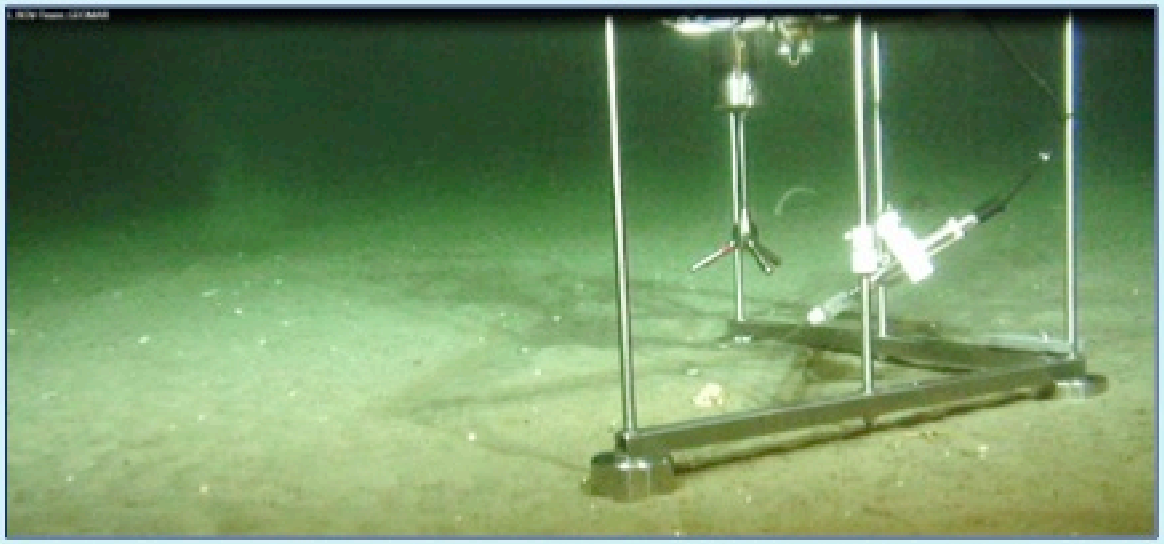
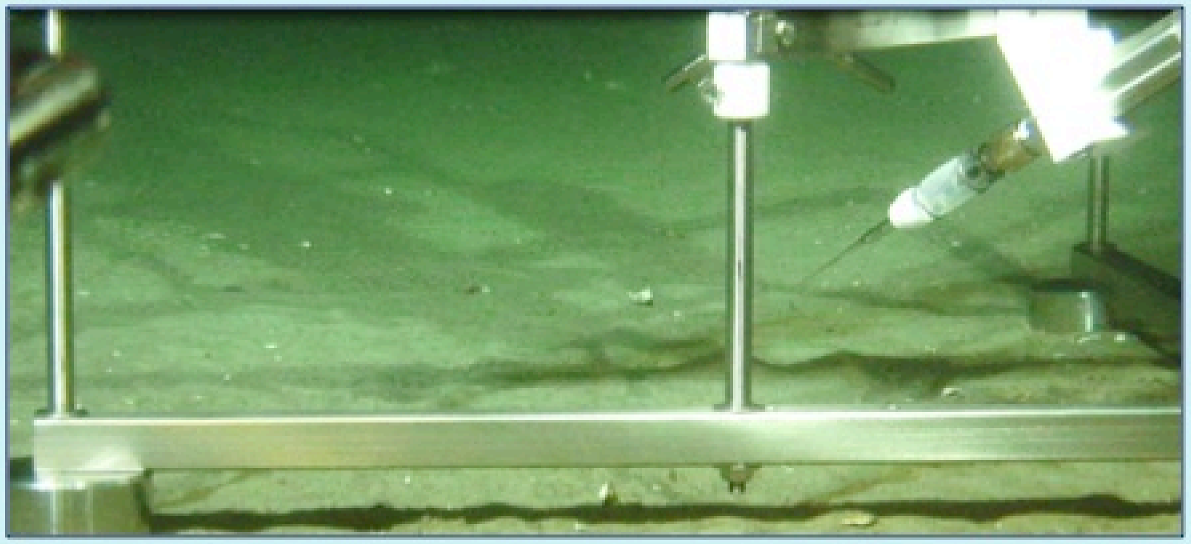
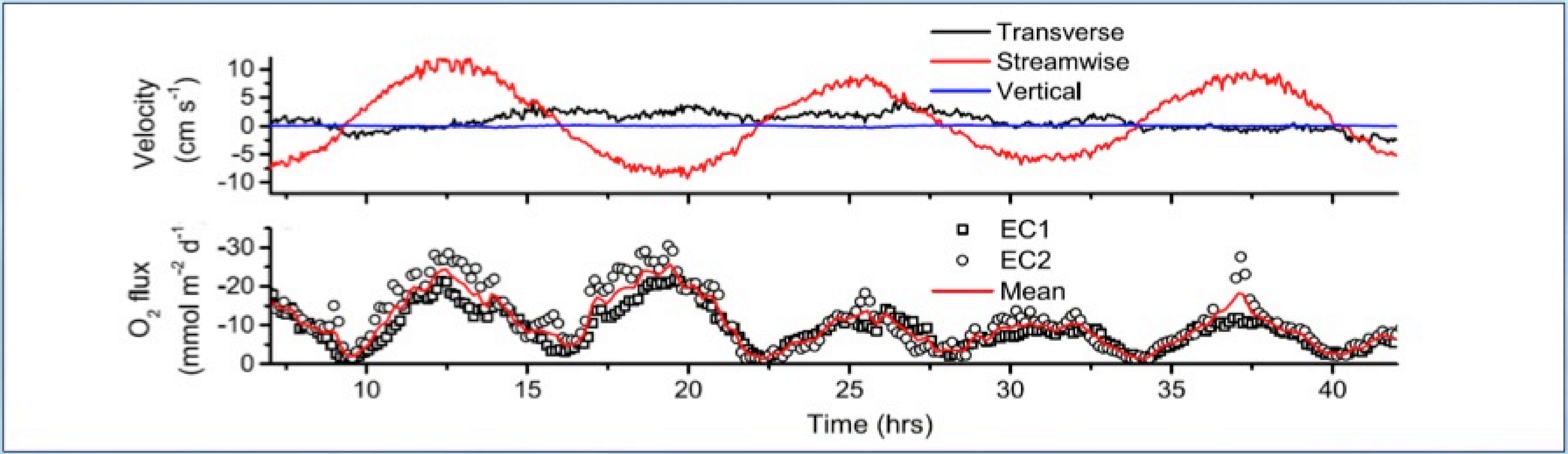




Photos: GEOMAR ROV Team



McGinnis et al. (2014)

- Flow over permeable sands can stimulate O_2 flux, here up to 25-fold

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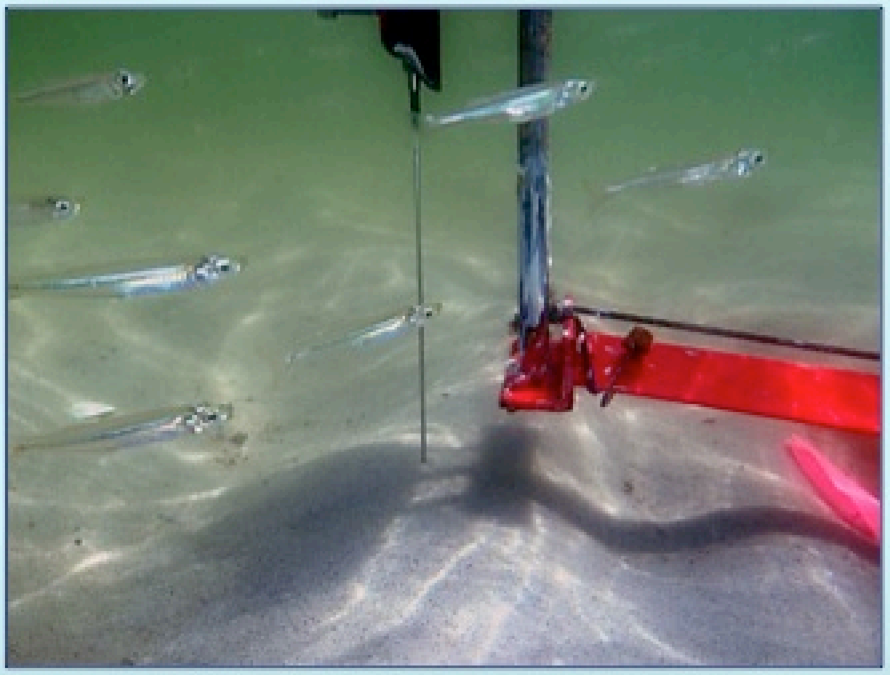
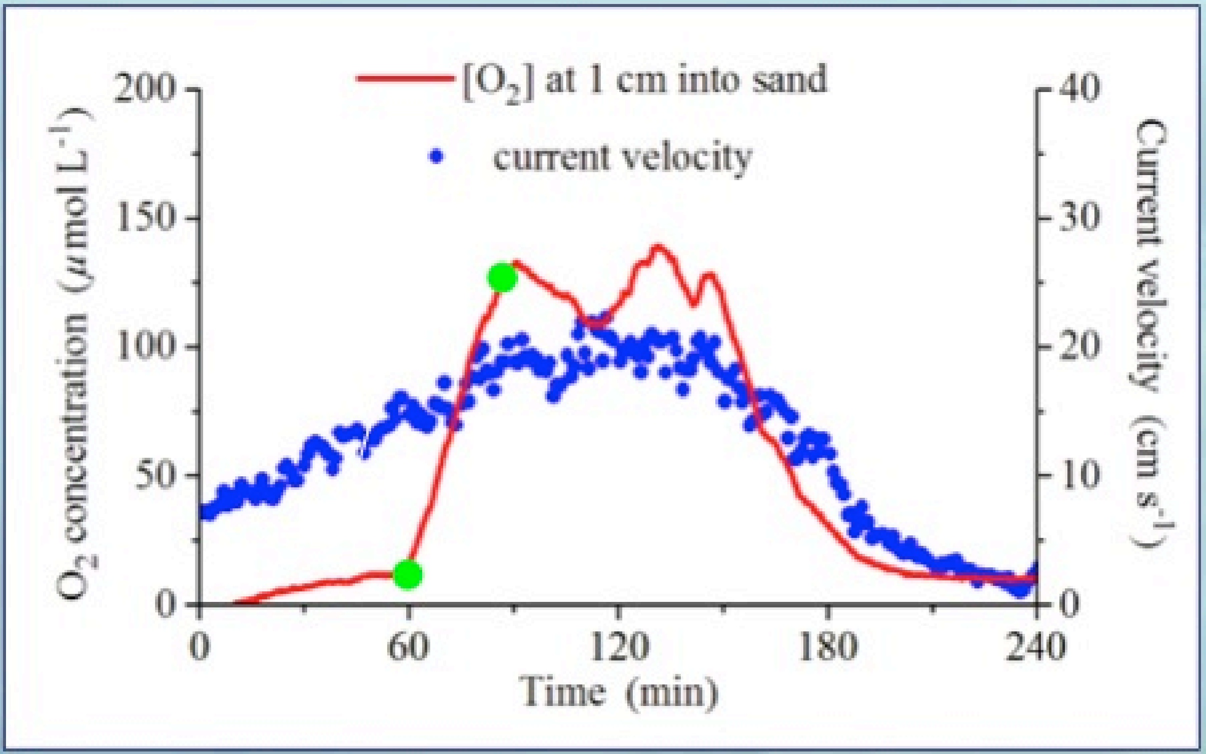
Effects of natural flow



- Flushing of anoxic pore water out of sediment equals flux of ~ -50 mmol m^{-2} day^{-1}
- Flushing of reduced compounds (e.g., H_2S, Fe^{2+}, Mn^{2+}) reacting with oxygen adds to this flux



Berg et al. (2013) L&O

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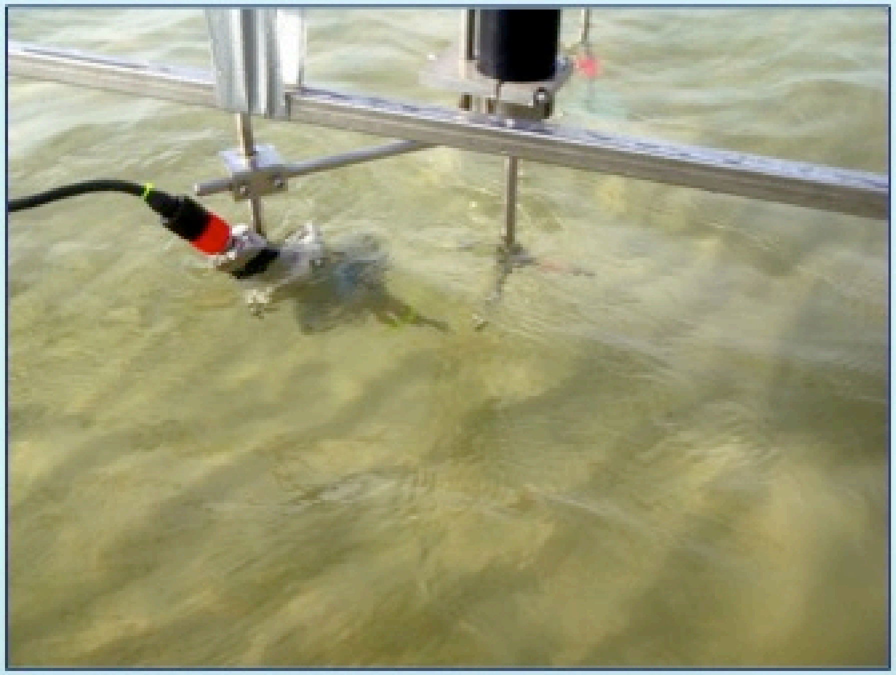
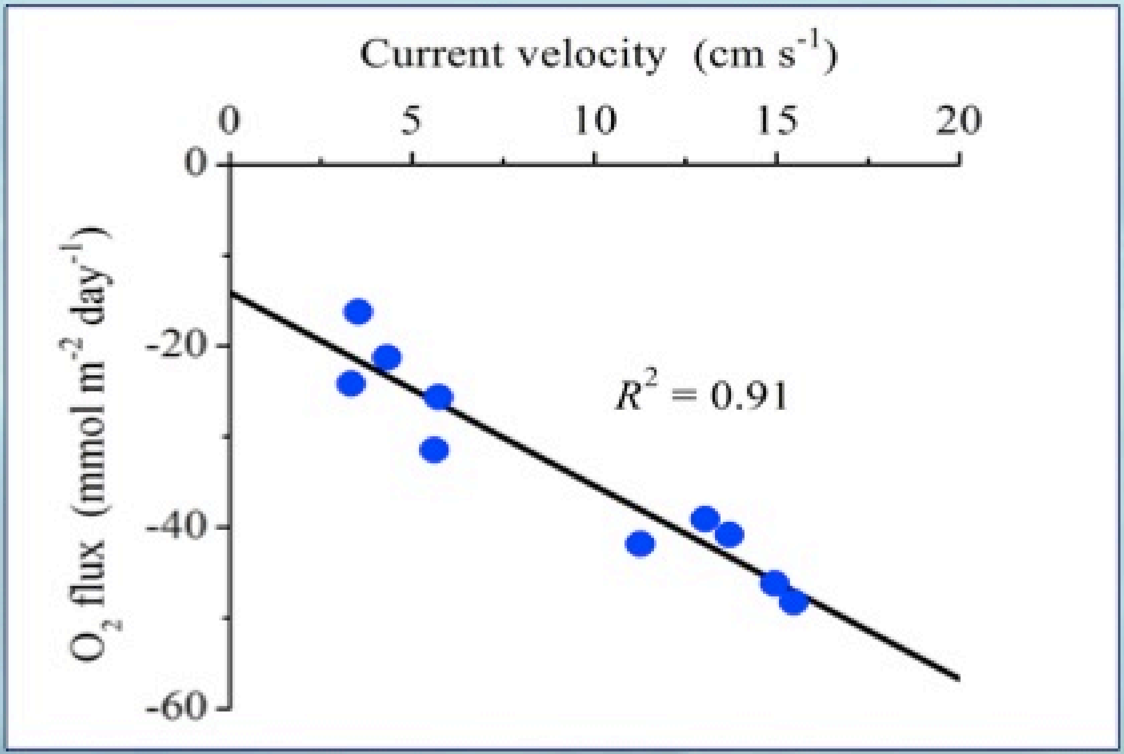


- Fluxes averaged over several hours still contain strong current flow signal
- Fluxes increase ~4-fold with flow increase from 1 to 20 cm s^{-1}



Berg et al. (2013) L&O

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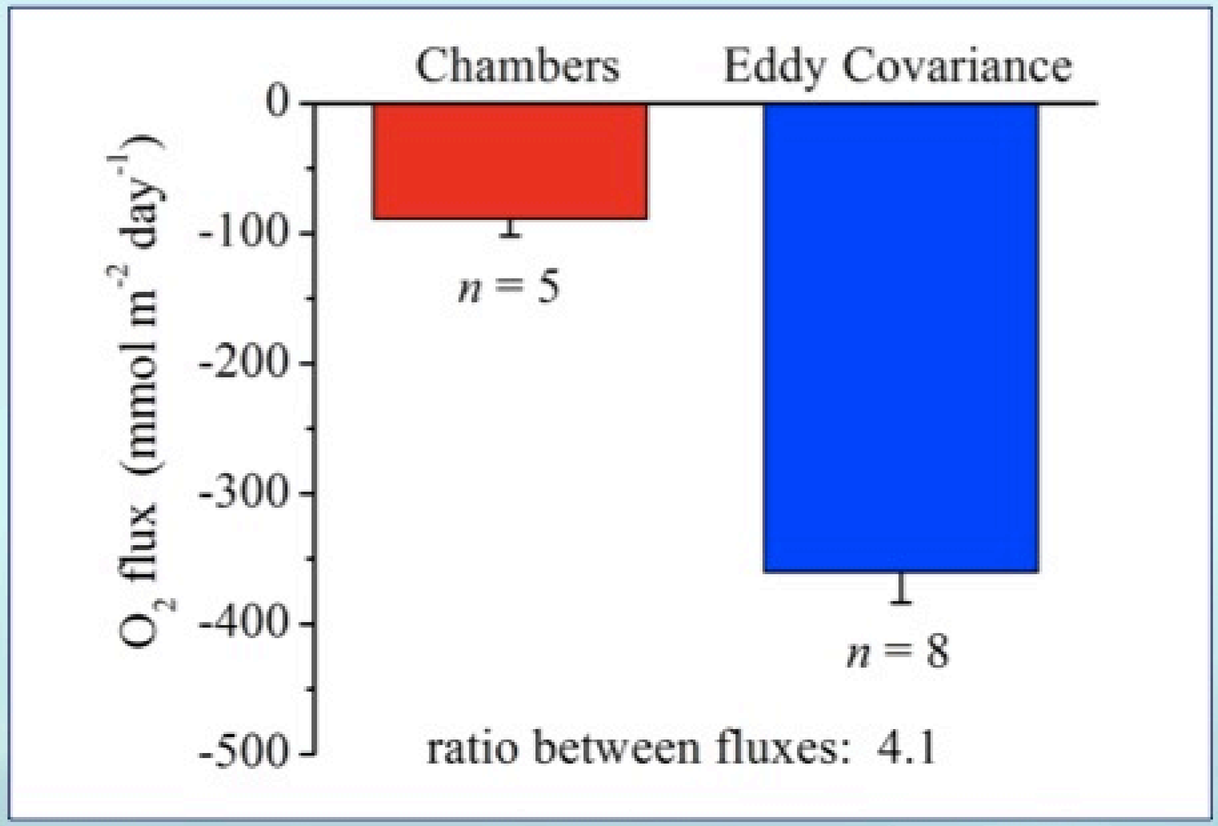
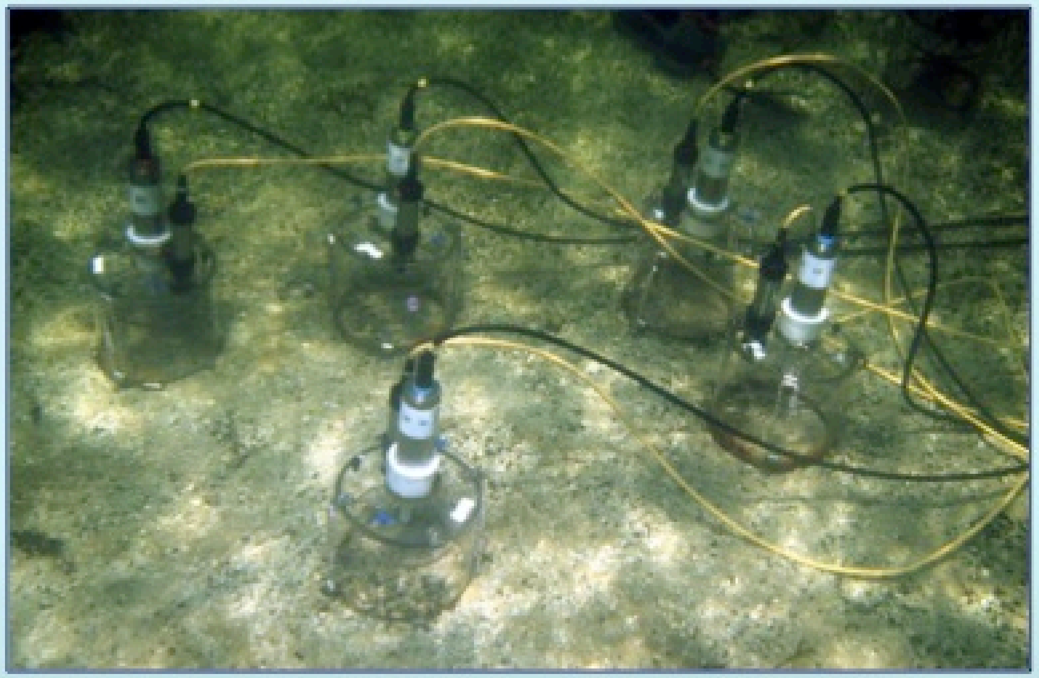
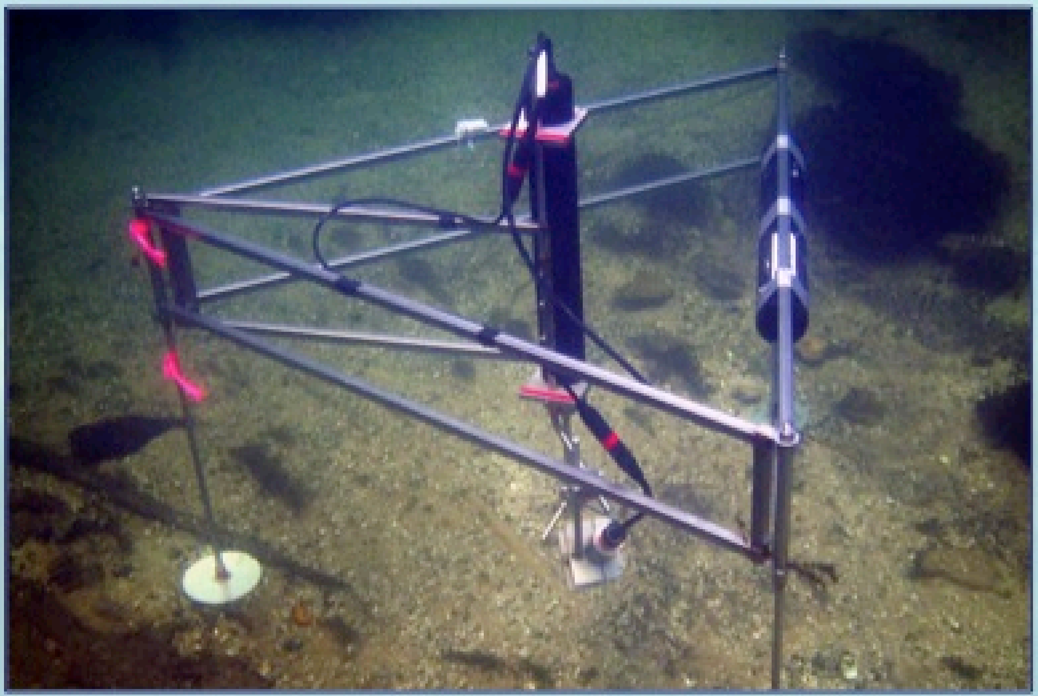


Berg et al. (2013) L&O





- Permeability of sand: 2.3×10^{-10} m^2
- Current velocity: 31 cm s^{-1}
- Use chambers with caution in highly permeable sands at high current flows

Berg, Delgard, Glud, Huettel, Reimers, Pace

doi: 10.1002/loe2.10005

Sensors for eddy covariance

Clark-type glass microelectrode:

- Great, well-tested sensor
- Used in almost all studies published so far
- But fragile and difficult to work with
- Expensive ($700)
- Often a microelectrode is broken or the tip fouled within a 24-hour deployment
- Stirring sensitive

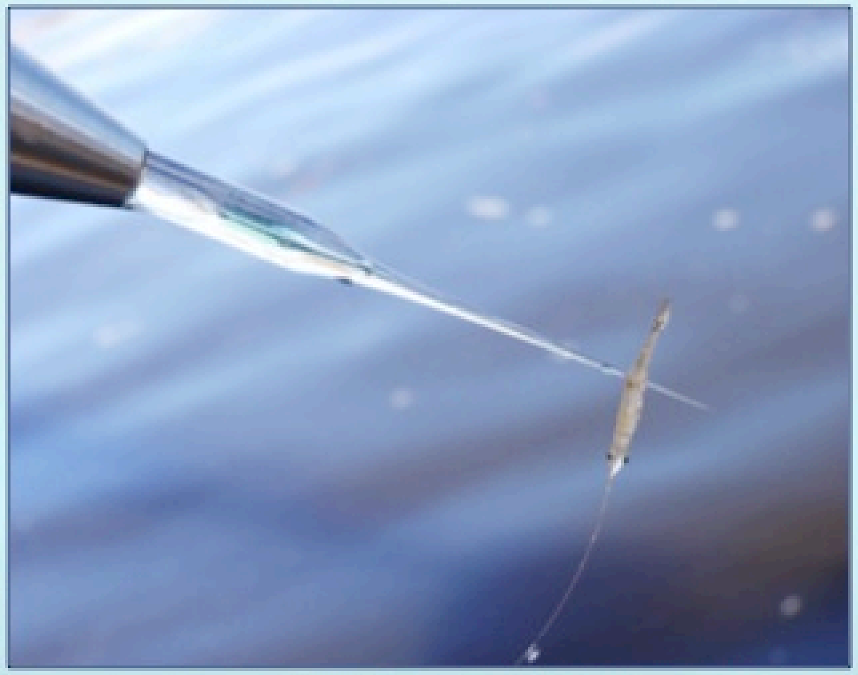
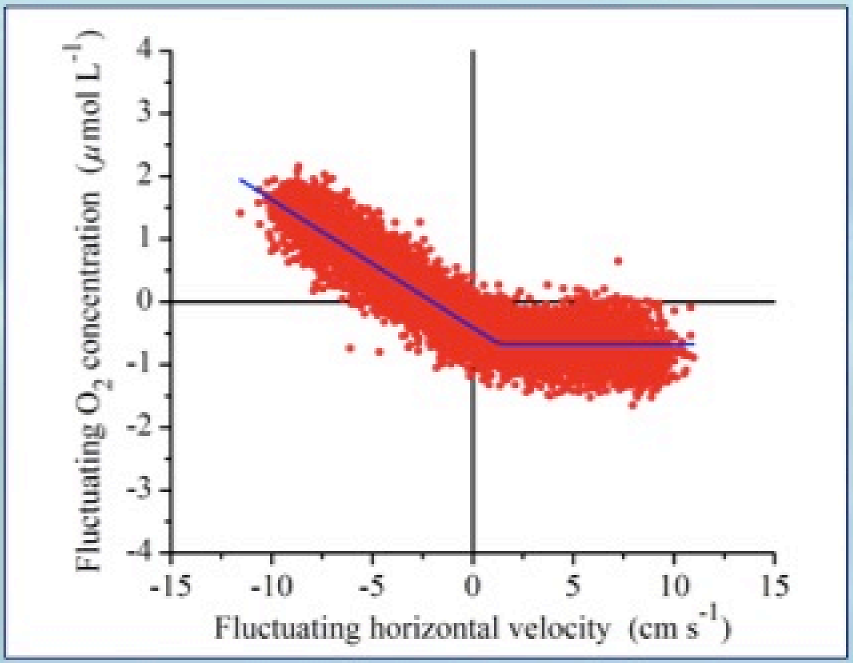


Photo: Sarah Larsen, Dan McGinnis



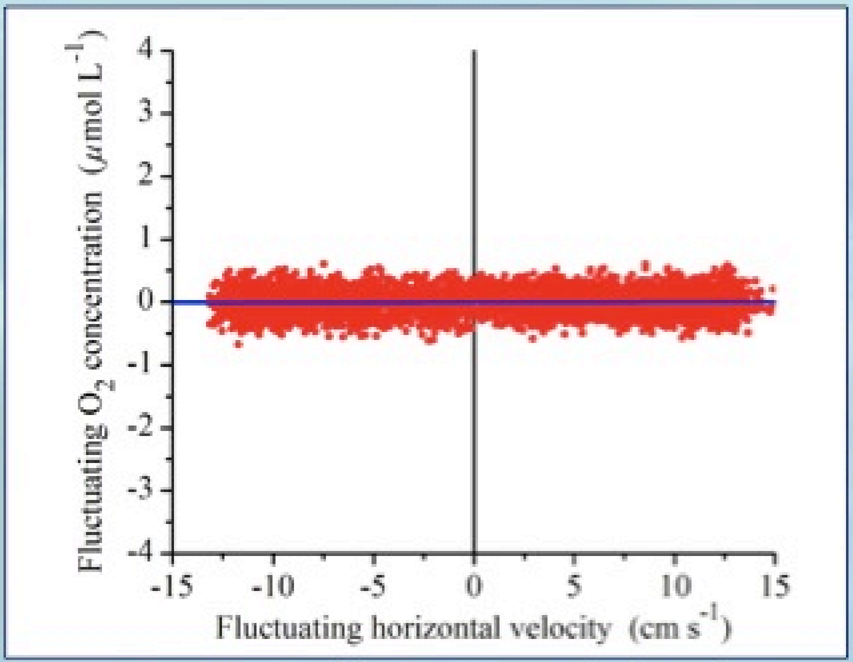
Berg et al. (2016). L&O Methods

doi: 10.1002/loe2.10005

Sensors for eddy covariance

RINKO micro sensor:

- New dual sensor (oxygen and temp.)
- Developed specifically for eddy covariance (Berg et al. 2015. L&O methods)
- 10mm tip size, robust
- Disturbs flow for some flow directions
- Has not shown signs of stirring sensitivity in tests



Berg et al. (2016). L&O Methods

doi: 10.1002/loe2.10005

Sensors for eddy covariance

Fiber optode:

- Used in a few new studies
- More robust than Clark-type electrodes
- Still only lasts a few days due to breakage or bleaching
- Somewhat expensive ($360)
- Can apparently be stirring-sensitive. More work is needed to understand why.

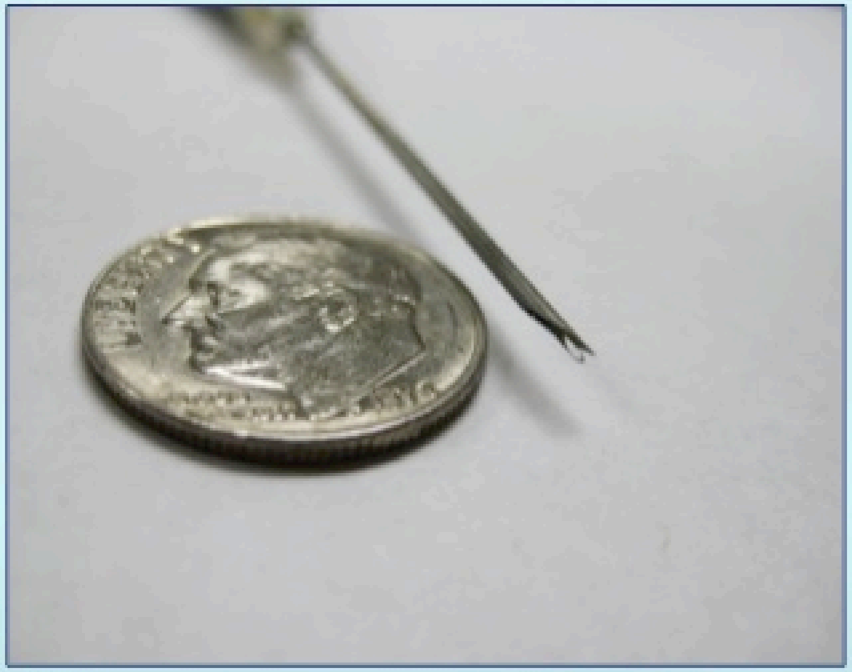
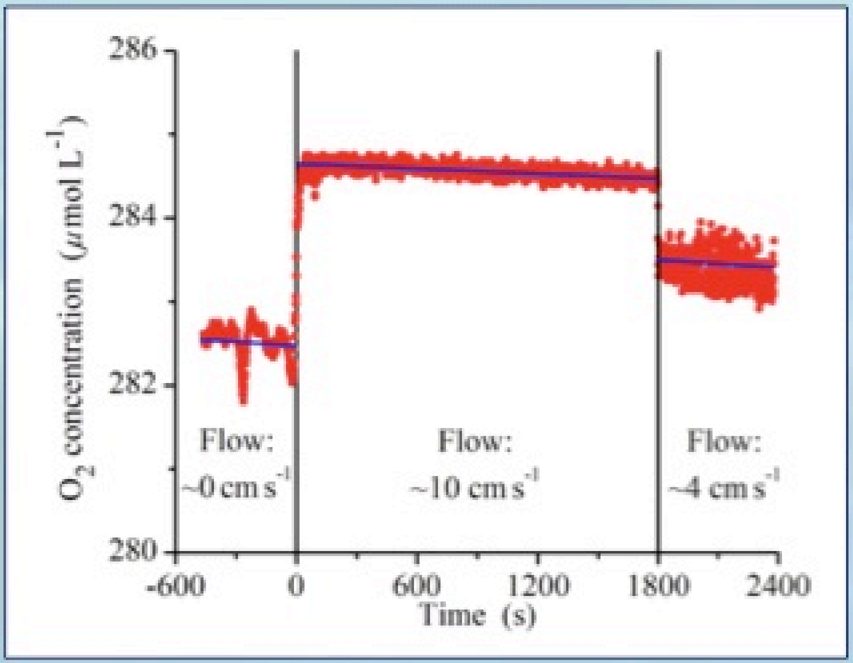


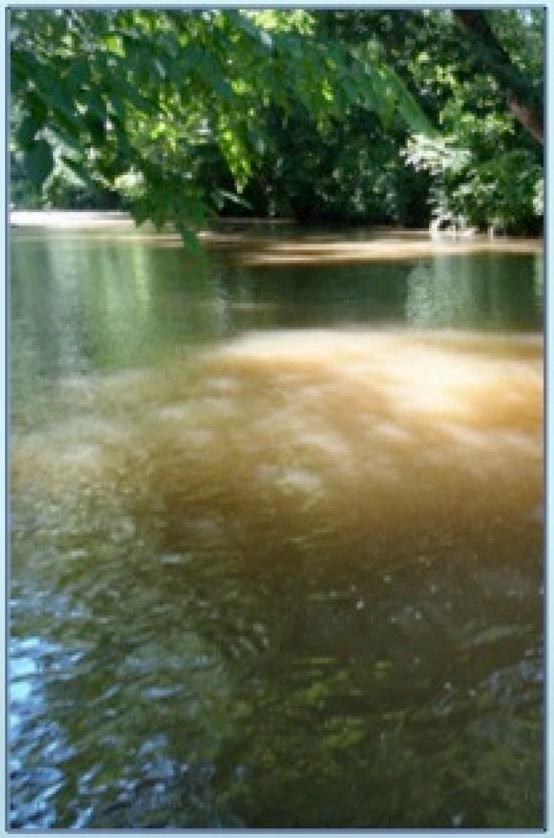
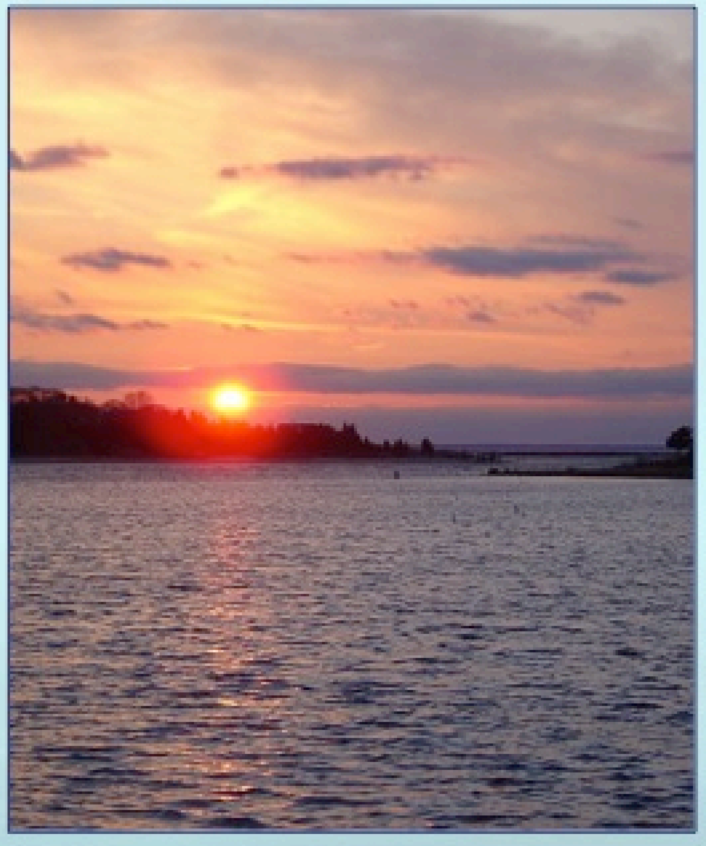
Photo: Dirk Koopmans



Glud, et al. (unpubl)

doi: 10.1002/loe2.10005

New applications – air-water exchange

Air-water exchange of gases (O_2, CO_2, and CH_4) for lakes, rivers, and estuaries is critical for whole-system estimates of:

- Primary production and respiration
- Carbon budgets
- Emission of greenhouse gases

$$\text{Flux} = k\,(C_{air} - C_{water})$$

doi: 10.1002/loe2.10005

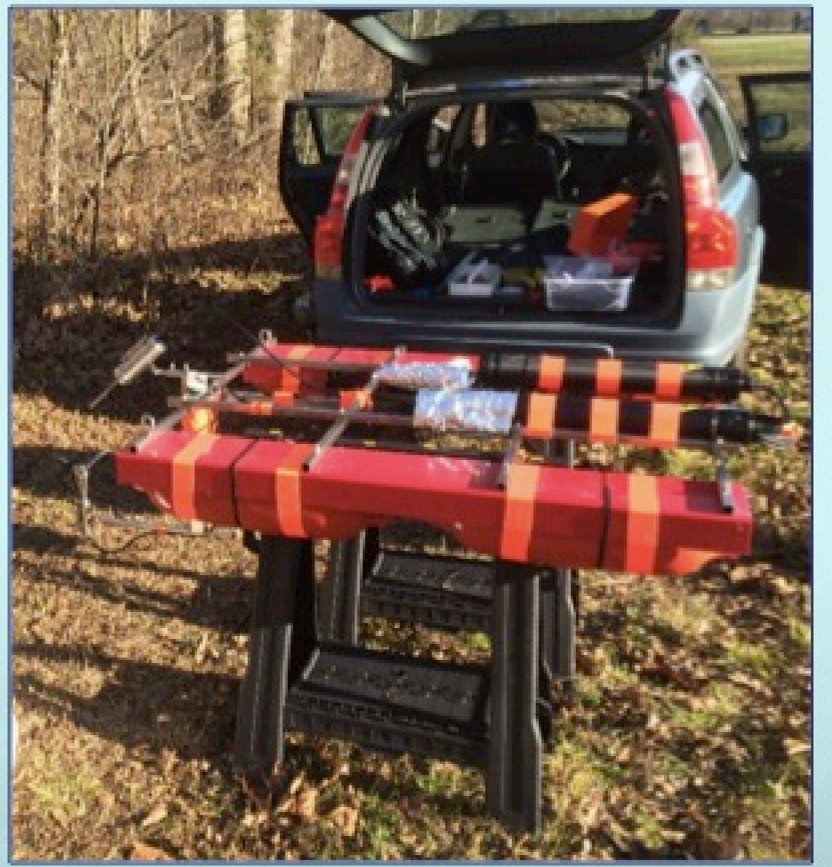
New applications – air-water exchange

$$\text{Flux} = k\,(C_{air} - C_{water})$$

- Means of C_{air} and C_{water} are easy to measure (or calculate) for gases of interest
- Values for *k* are difficult to assess
- Uncertainty in *k* is often huge

New idea:

- Measure eddy fluxes of oxygen under air-water interface along with means of C_{air} and C_{water}
- Determine *k* for oxygen (k_{02})
- Convert k_{02} to gases of interest (CO_2, CH_4, etc.)



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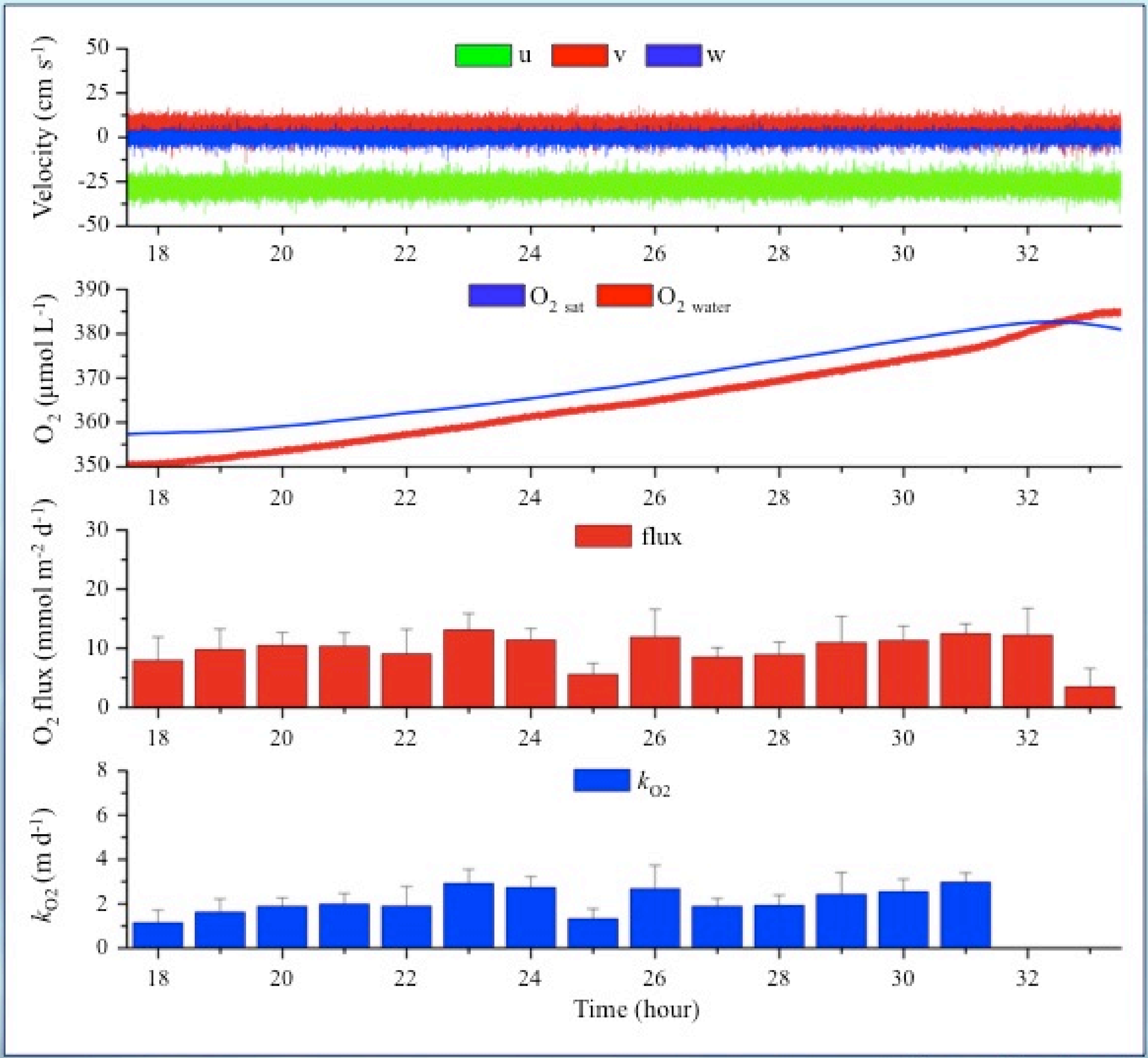
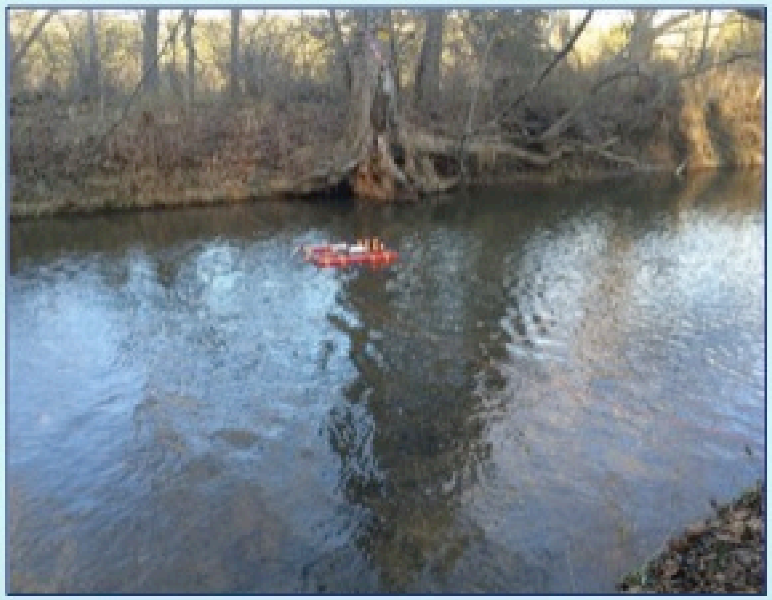
New applications – air-water exchange

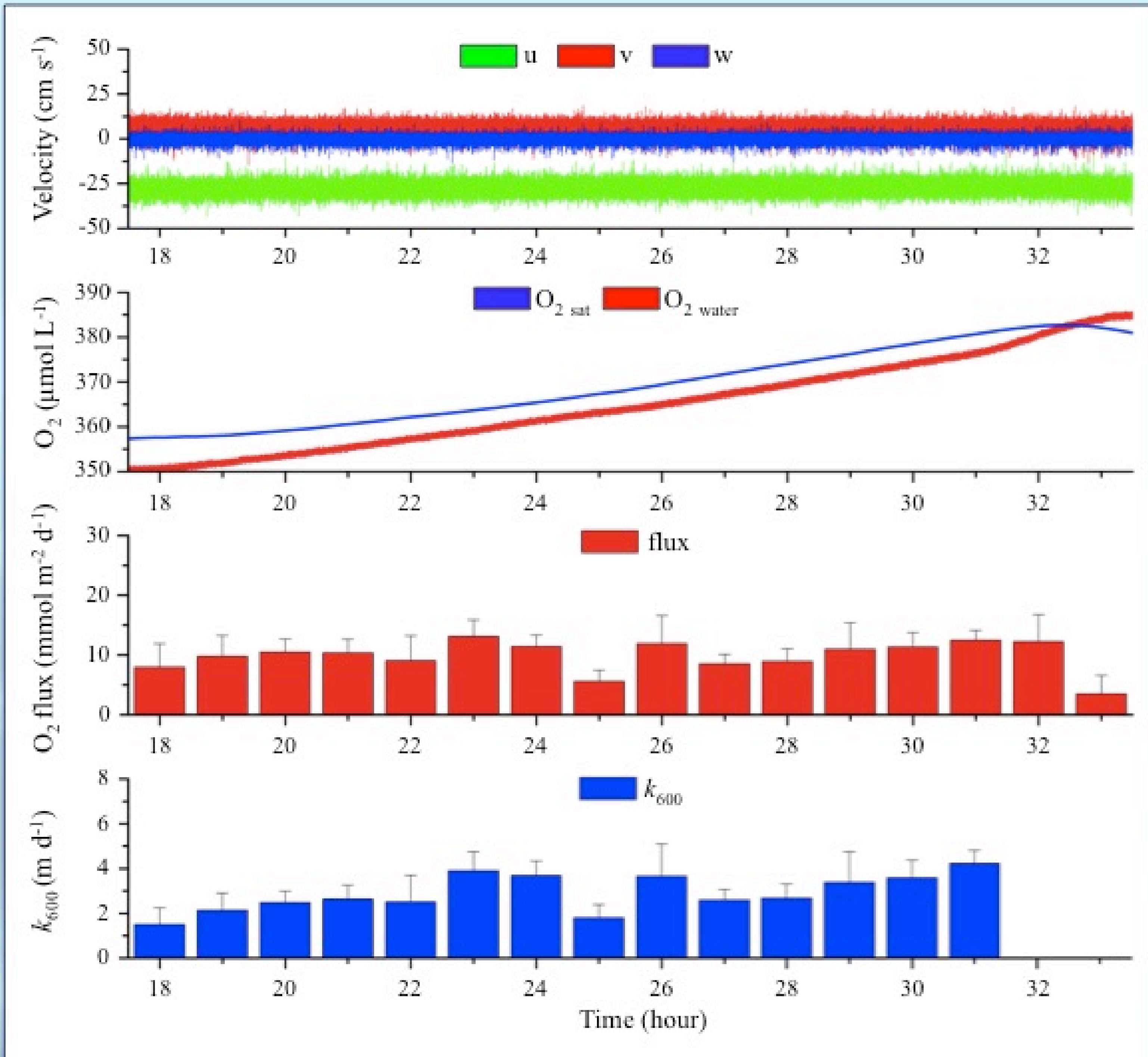


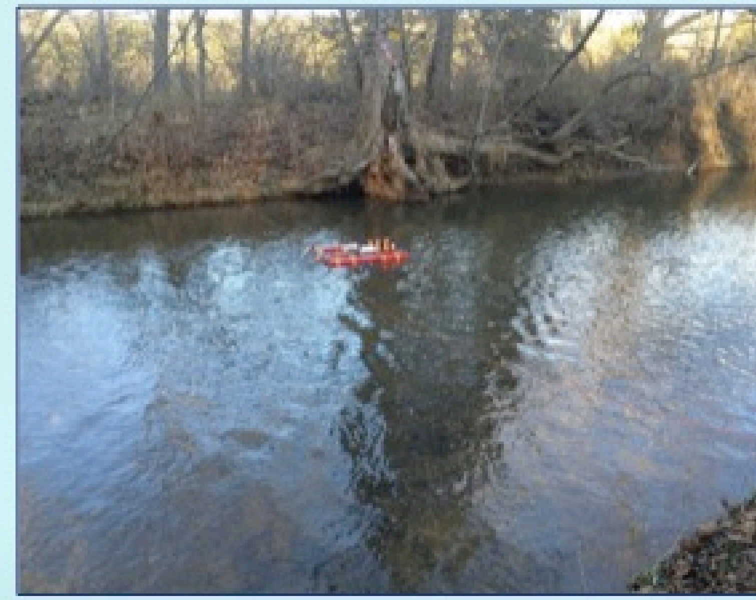


Berg and Pace (In prep)

doi: 10.1002/loe2.10005

New applications – air-water exchange





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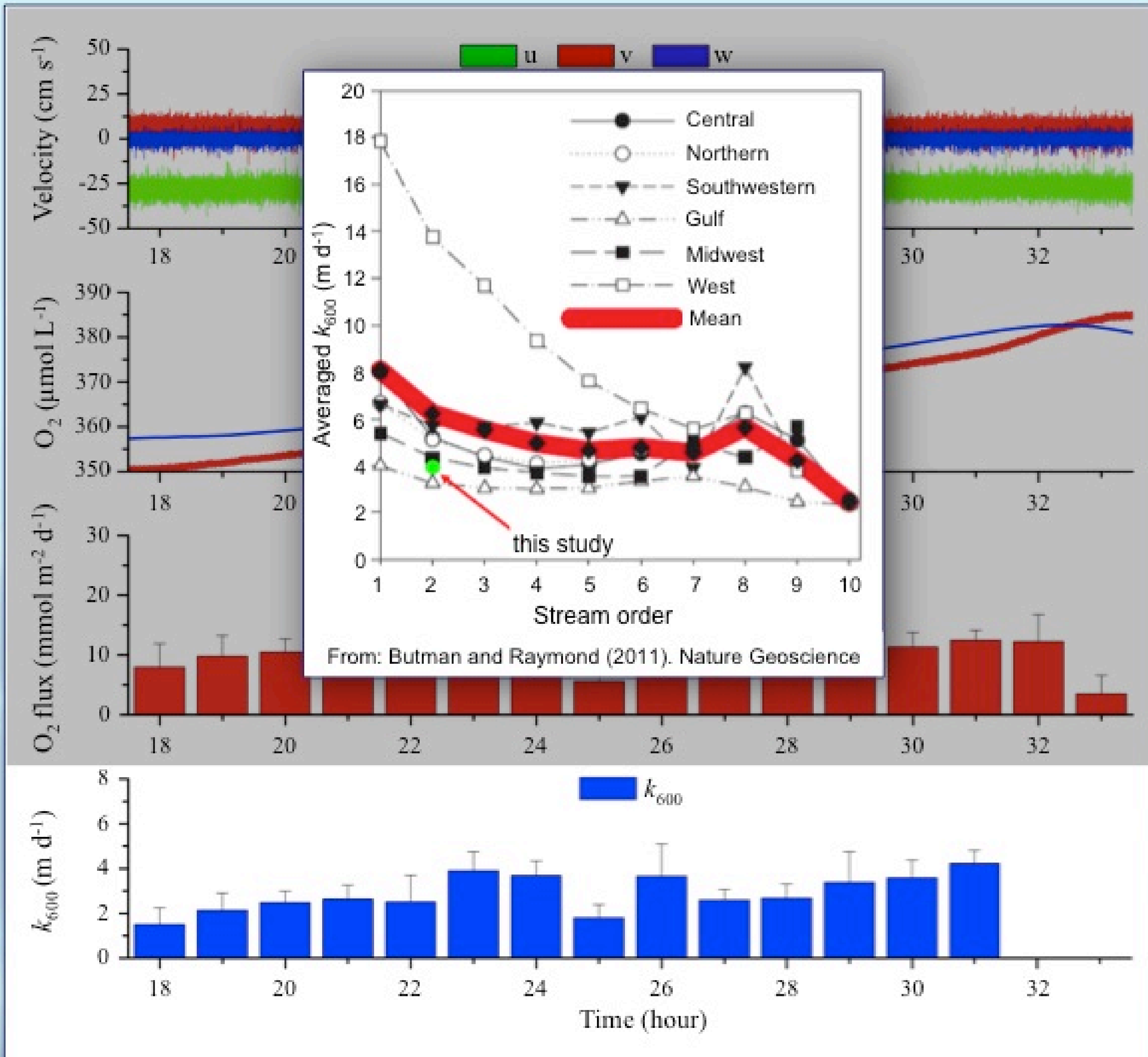
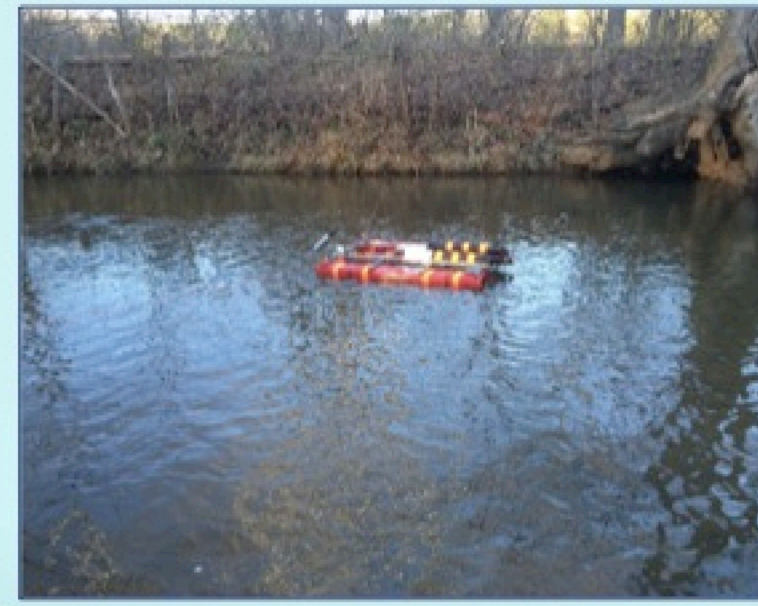
New applications – air-water exchange





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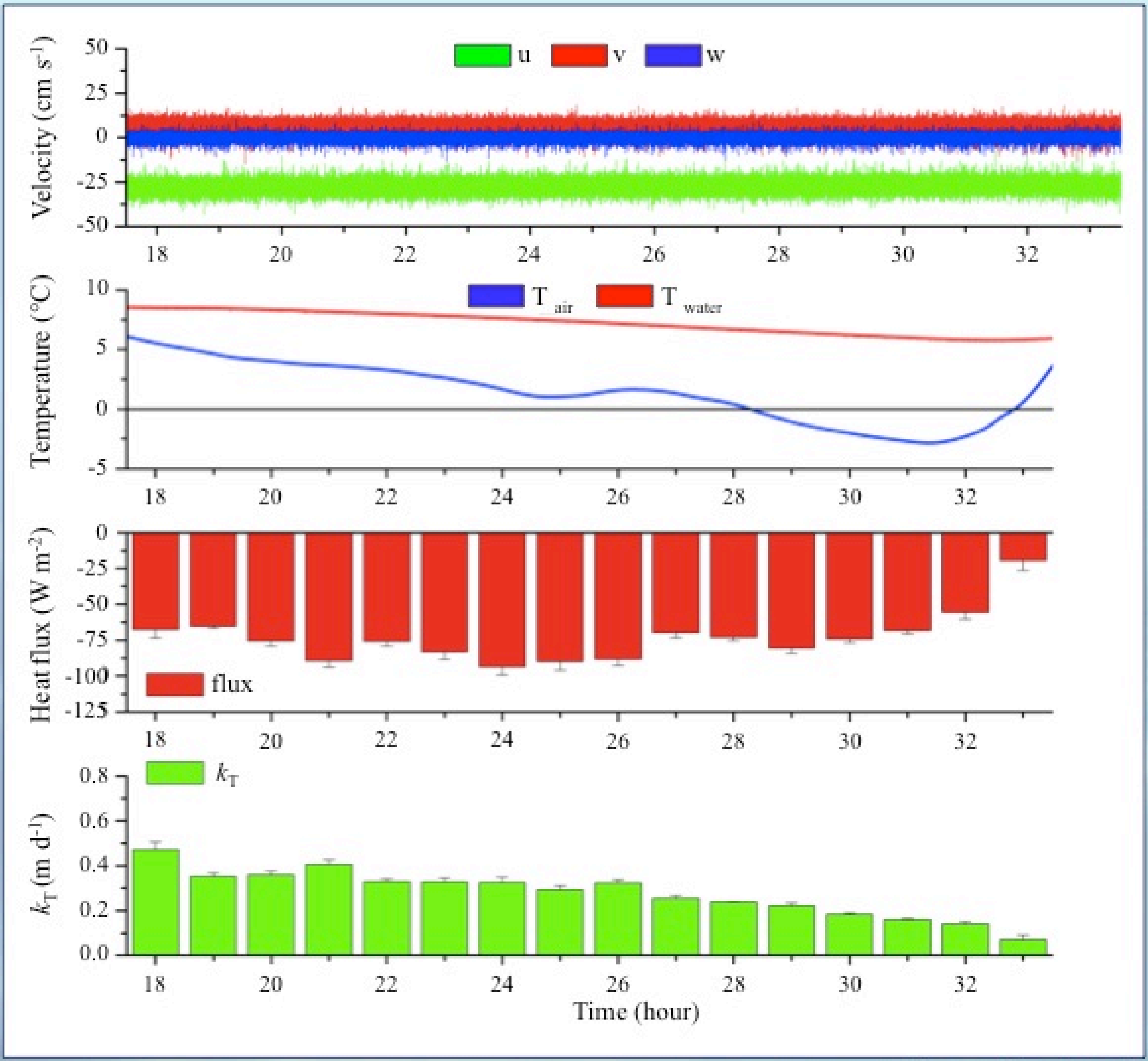

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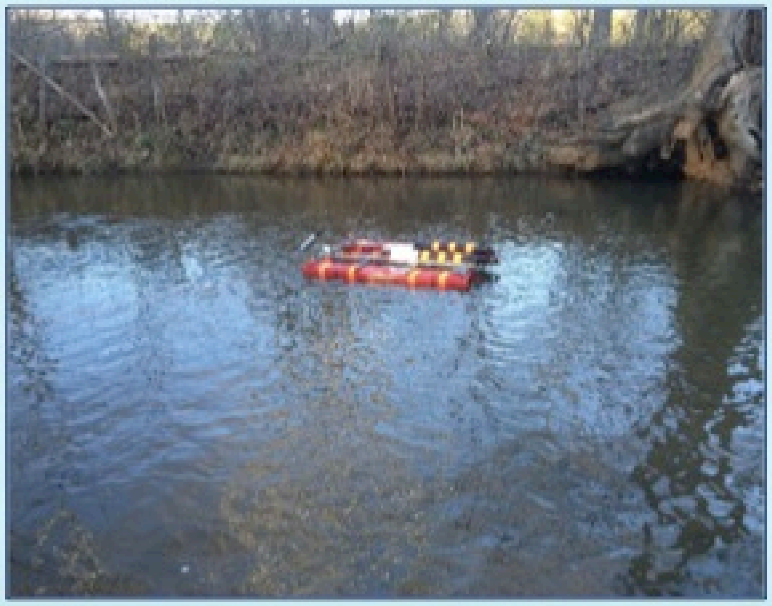

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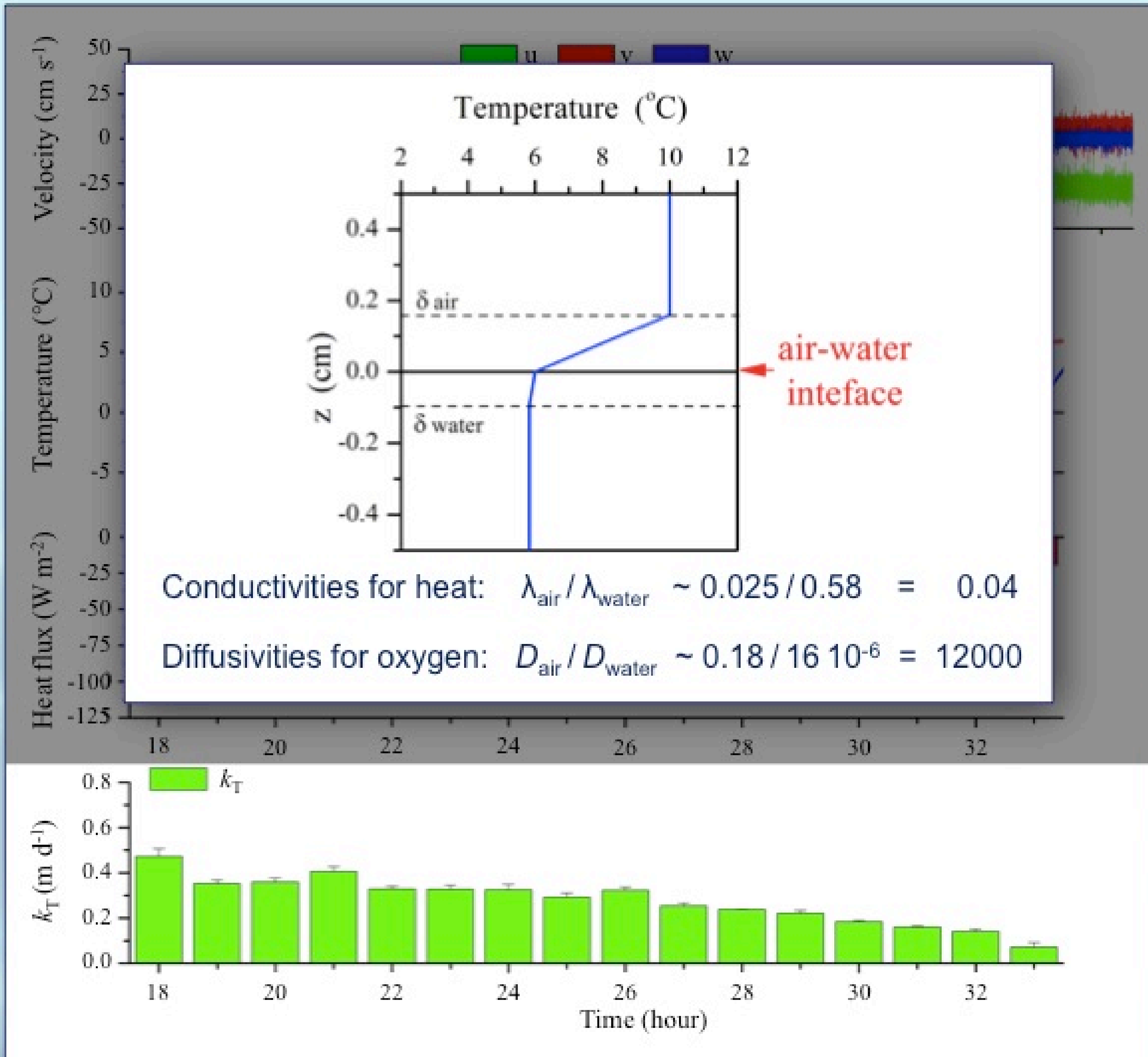

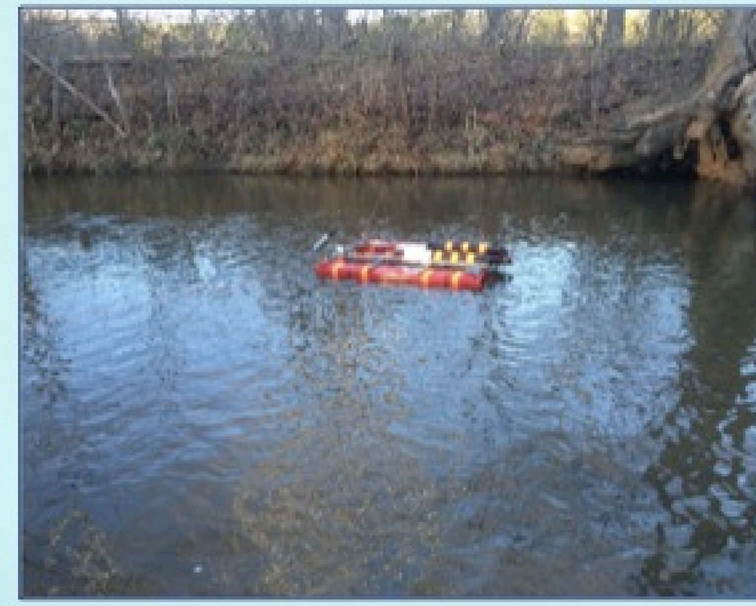

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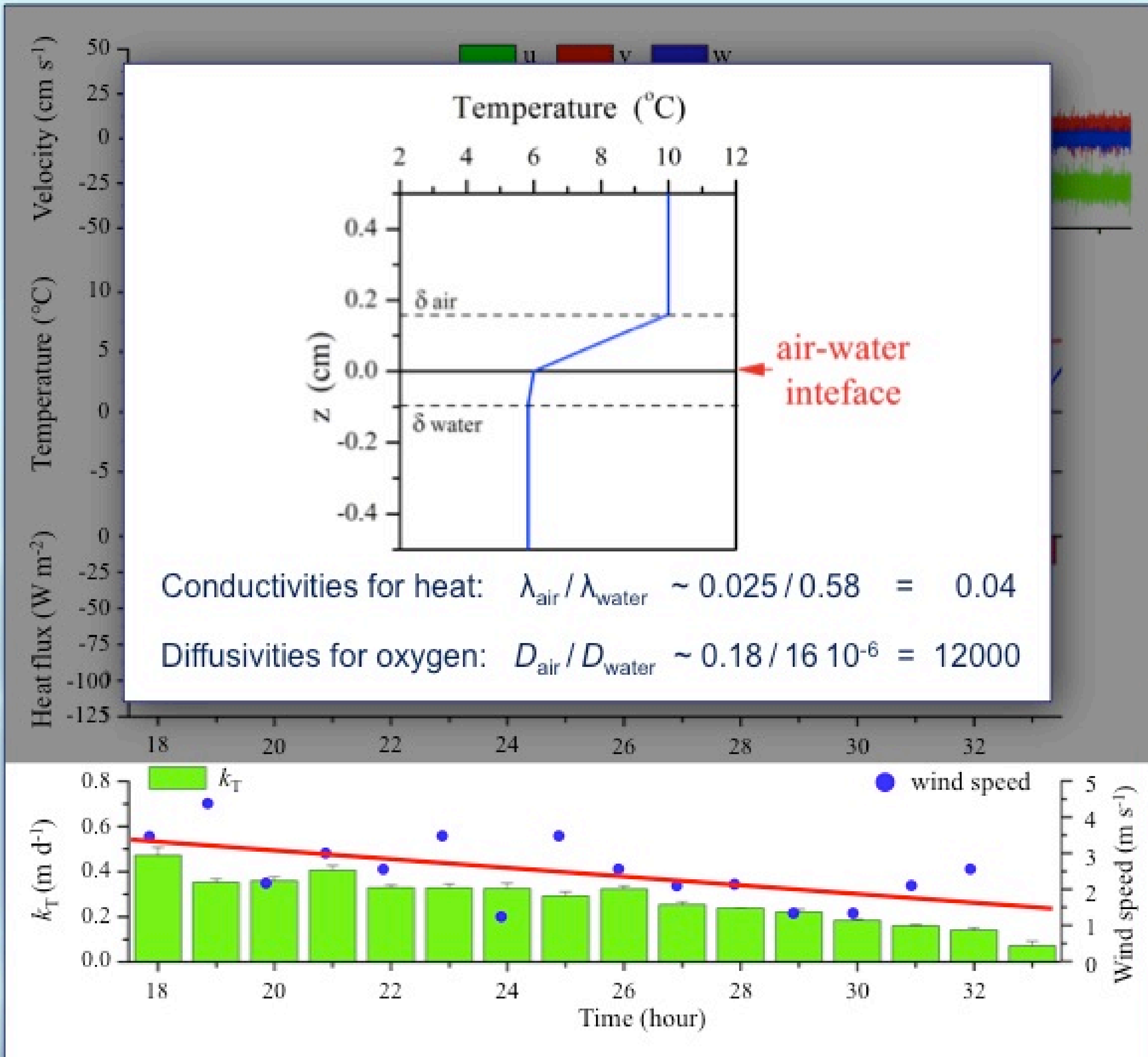

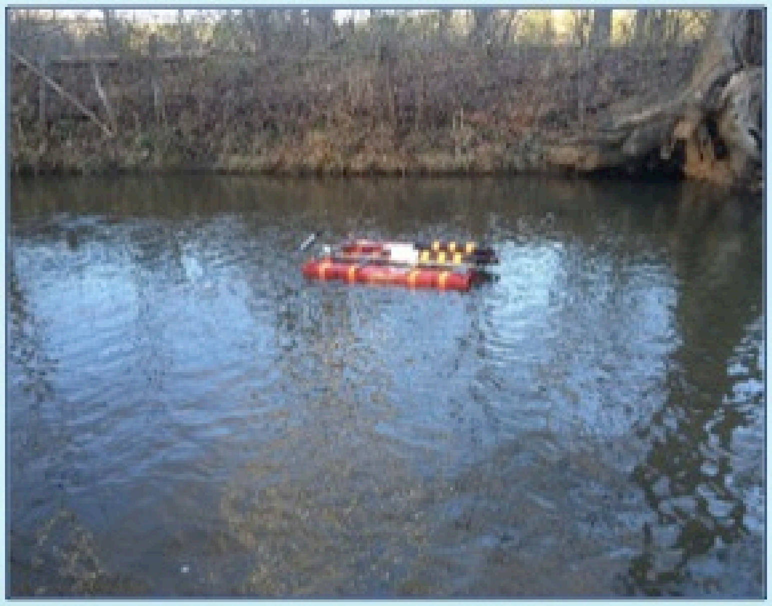

Berg and Pace (In prep)

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New applications – "fly-over"

LI-COR Biosciences

Bluefin Robotics

- Fly-over eddy covariance measurements in air are common today
- A possibility under water? "Fly" over the seafloor or under the air-water interface to get fluxes and exchange coefficients? Maybe…

doi: 10.1002/loe2.10005

Summary and next steps

Main point: Aquatic eddy covariance measures fluxes at high temporal resolution under true in situ conditions. Allows studies of whole-system in situ fluxes at a level of detail not possible before.

Specific foci - develop:

- New more robust sensors – including for other constituents than oxygen
- Plug-and-play instruments
- Flux extraction procedures for imperfect field conditions
- New applications, mobile platforms, and observatory systems
- Courses and workshops to discuss issues and developments, and to train new users
- Open access databases

doi: 10.1002/loe2.10005

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Teamwork

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References

Attard, K. M., R. N. Glud, D. F. McGinnis, and S. Rysgaard. 2014. Seasonal rates of benthic primary production in a Greenland fjord measured by aquatic eddy correlation. Limnol. Oceanogr. 59: 1555-1569.

Berg, P., D. Koopmans, M. Huettel, H. Li, K. Mori, and A. Wüest. 2016. A new robust dual oxygen-temperature sensor for aquatic eddy covariance measurements. Limnol. Oceanogr.: Methods 14: 151–167.

Berg, P., M. H. Long, M. Huettel, J. E. Rheuban, K. J. McGlathery, R. W. Howarth, K. H. Foreman, A. E. Giblin, and R. Marino. 2013. Eddy correlation measurements of oxygen fluxes in permeable sediments exposed to varying current flow and light. Limnol. Oceanogr. 58: 1329–1343.

Berg, P., and M. L. Pace. In prep. Air-water gas exchange measured by eddy covariance on the water side of the interface. Limnology and Oceanography: Methods.

Berg, P., H. Roy, and P. L. Wiberg. 2007. Eddy correlation flux measurements: The sediment surface area that contributes to the flux. Limnol. Oceanogr. 52: 1672-1684.

Delgard, M. L., P. Berg, and K. J. Mcglathery. In prep A. In situ effects of light, flow and temperature on seagrass metabolism measured by aquatic eddy covariance. Marine Ecology Progress Series.

---. In prep B. Seagrass metabolism measured by aquatic eddy covariance – seasonal, annual and interannual variability. Limnol. Oceanogr.

Hume, A. C., P. Berg, and K. J. McGlathery. 2011. Dissolved oxygen fluxes and ecosystem metabolism in an eelgrass (Zostera marina) meadow measured with the eddy correlation technique. Limnol. Oceanogr. 56: 86-96.

Kessler, A., R. N. Glud, M. B. Cardenas, and P. L. M. Cook. Unpubl.

Long, M. H., P. Berg, D. de Beer, and J. C. Zieman. 2013. In situ coral reef oxygen metabolism: An eddy correlation study. Plos One 8: e58581. doi:58510.51371/journal.pone.0058581.

doi: 10.1002/loe2.10005

References

McGinnis, D. F., S. Sommer, A. Lorke, R. N. Glud, and P. Linke. 2014. Quantifying tidally driven benthic oxygen exchange across permeable sediments: An aquatic eddy correlation study. Journal of Geophysical Research: Oceans 119: 6918-6932.

Reidenbach, M. A., J. R. Koseff, and S. G. Monismith. 2007. Laboratory experiments of fine-scale mixing and mass transport within a coral canopy. Physics of Fluids 19: 075107, doi:075110.071063/075101.2752189.

Reimers, C. E., H. A. Stecher III, G. L. Taghon, C. M. Fuller, M. Huettel, A. Rusch, N. Ryckelynck, and C. Wild. 2004. In situ measurements of advective solute transport in permeable shelf sands. Continental Shelf Research 24: 183–201.

Rheuban, J. E., and P. Berg. 2013. The effects of spatial and temporal variability at the sediment surface on aquatic eddy correlation flux measurements. Limnology And Oceanography: Methods 11: 351–359.

Rheuban, J. E., P. Berg, and K. J. McGlathery. 2014. Multiple timescale processes drive ecosystem metabolism in eelgrass (Zostera marina) meadows. Marine Ecology Progress Series 507: 1–13.

Wenzhofer, F., and R. N. Glud. 2004. Small-scale spatial and temporal variability in coastal benthic O_2 dynamics: Effects of fauna activity. Limnol. Oceanogr. 49: 1471-1481.

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