pyroscience
sensor technology

White Paper

EVALUATING THE PERFORMANCE OF PYROSCIENCE AQUAPHOX LOGGERS WITH NEW ANTIFOULING SENSORS FOR LONG-TERM PH AND OXYGEN MONITORING IN COASTAL WATERS

Münevver Nehir, Christiane Pachernegg-Mair, Christoph Staudinger

Affiliation: PyroScience GmbH

TABLE OF CONTENT

1 INTRODUCTION

Real-time *in situ* monitoring of pH and dissolved oxygen (DO) with advanced sensor technology is essential for observing the biogeochemical processes and ecosystem dynamics in coastal, shallow and brackish waters. These environments are crucial habitats for diverse marine life and play a significant role in global carbon cycling and nutrient regulation. However, they are highly sensitive to human-induced changes, such as urban runoff, agricultural practices and industrial discharges, all of which can lead to nutrient overloading and pollution.

Accurate and continuous measurements of pH and DO are critical for understanding the impacts of these stressors, as well as climate-driven changes like ocean acidification, which alters the carbonate chemistry of the water and hypoxia, which is characterized by low oxygen levels that threaten aquatic organisms. Advanced sensor technology enables stand-alone *in situ* data collection, capturing temporal and spatial variations that traditional monitoring methods often miss.

Optical sensor technology, such as the **PyroScience AquapHOx©** stand-alone loggers and real-time transmitters, offers significant advantages for *in situ* monitoring. These devices are highly flexible, robust and designed for plug & play operation in various aquatic environments, from coastal monitoring to deep-sea explorations. Their advanced optical measurement principles ensure high precision and stability over time, making them well-suited for long-term deployments. A wide range of optical pH and oxygen sensors are compatible with the **AquapHOx©** devices.

However, long-term monitoring using sensors also faces significant challenges, including issues like biofouling. Biofouling occurs when microorganisms, algae, or invertebrates attach to sensor surfaces, causing sensor drift, reduced accuracy, and increased maintenance requirements. While biofouling can impact long-term data reliability, it can also develop over shorter periods. Beyond degrading sensor performance, biofouling increases operational costs and complicates efforts to maintain consistent data quality over time. Addressing these challenges requires continuous innovation in sensor materials, antifouling coatings and maintenance strategies to ensure data reliability over extended periods (Delauney et al. 2010).

In this study, we evaluated the performance of **PyroScience AquapHOx©** stand-alone loggers equipped with pH and oxygen sensor caps with a new antifouling material. To achieve this, deployments were carried out at two different locations: i) Kiel Fjord (Western Baltic Sea, Germany) and ii) Rovinj (Northern Adriatic Sea, Croatia) to assess the effectiveness of the antifouling solutions in preventing biofouling and ensuring long-term accurate sensor data collection in challenging coastal shallow water environments.

2 MATERIALS & METHODS

2.1 Sensor Overview

The **AquapHOx©-L-pH** and **AquapHOx©-L-O_2** loggers are advanced underwater instruments designed for long term, stand-alone monitoring of *in situ* pH and dissolved oxygen, respectively. Each logger is equipped with a pre-integrated rechargeable battery, a temperature sensor and a 4 GB data logger capable of storing ca. 40 million data points. When set to a sampling frequency of 1-minute, the loggers can operate in stand-alone mode for about 6 months, with longer durations possible by increasing the sampling interval.

The set-up consists of the loggers and easily exchangeable optical sensor heads, offering flexibility for use with either a pH sensor (e.g., **PHCAP-PK8T-SUB**) or an oxygen sensor (e.g., **OXCAP-SUB**). As the **AquapHOx©** device features a single port, only one sensor head can be connected at a time. To measure both pH and oxygen simultaneously, two devices are required.

PyroScience recently introduced optical pH and oxygen sensors with a novel antifouling layer that prevents biofouling in underwater applications, enabling longer deployments in challenging environments (e.g. nutrient-rich shallow waters). The **PHCAP-PK8T-AF-SUB** is designed for monitoring pH between 7 and 9 (±0.5) on the pH total scale, while the **OXCAP-AF-SUB** is used for monitoring DO. All pH and oxygen sensor caps, as well as **AquapHOx©** devices, can be combined with copper protection cages (**APHOX-CAGE-AF** and **APHOX-CAP-AF**), which can be easily attached as an additional protective layer to prevent sensor biofouling. These two copper protection cages will be referred to as **Cu cages** throughout the paper.

2.2 Field Deployments: Sampling Site and Data Collection

In this study, two long-term deployments took place: one in the Kiel Fjord, Germany, and another in Rovinj, Croatia.

2.2.1 Kiel Fjord, Western Baltic Sea, Germany

The first deployment took place in the Kiel Fjord, Germany, at the GEOMAR floating pontoon facility (54°19'48.78"N, 10°8'59.44"E) over eight weeks from July 4 to August 30, 2024. The Kiel Fjord, a brackish waterbody in the southwestern Baltic Sea, extends 9.5km in length. Its inner section is 250m wide with depths of 10–12m, while the outer fjord expands to 7.5km and exceeds 20m in depth. Freshwater inputs primarily originate from the Schwentine River and local precipitation, and during summer, the water column stratifies, except in the inner fjord, which remains mixed for most of the year (Nikulina et al., 2008).

A total of four **AquapHOx©** shallow water loggers, equipped with standard and with novel antifouling layer sensor caps, were deployed:

- 2 **AquapHOx©-L-pH** loggers: 1x **PHCAP-PK8T-SUB**, 1x **PHCAP-PK8T-AF-SUB**
- 2 **AquapHOx©-L-O_2** loggers: 1x **OXCAP-SUB**, 1x **OXCAP-AF-SUB**

These loggers were mounted on a stainless-steel frame and positioned at ca. 1.5m below the water surface. pH and oxygen levels were recorded at 1-minute intervals, ensuring high-resolution data collection.

To provide additional biofouling protection, the loggers and sensor caps were equipped with an antifouling cage (**APHOX-CAGE-AF**) and a protective cap (**APHOX-CAP-AF**).

2.2.2 Rovinj, Northern Adriatic Sea, Croatia

The second deployment was conducted 1.5km north of Rovinj, Croatia, at a landing stage. The loggers were mounted on pillars at a water depth of ca. 2m. The water near the pier is nutrient-rich and reaches a depth of about 3m. During the measurement period in June 2024, mucilage aggregate formation occurred in the Adriatic Sea. Throughout the summer, water temperatures increased significantly, reaching up to 29°C.

Between April 2024 and October 2024, a total of six **AquapHOx©** shallow water loggers were deployed (Fig. 1):

- 3 **AquapHOx©-L-pH** loggers: 2x **PHCAP-PK8T-SUB**, 1x **PHCAP-PK8T-AF-SUB**
- 3 **AquapHOx©-L-O_2** loggers: 1x **OXCAP-SUB**, 2x **OXCAP-AF-SUB**

One of the **PHCAP-PK8T-SUB**, the **PHCAP-PK8T-AF-SUB**, and all of the oxygen sensors were protected from biofouling additionally with copper cages (**APHOX-CAGE-AF**, **APHOX-CAP-AF**). The measurement interval for all pH and oxygen sensors was set to 1-minute.

Fig. 1 ***AquapHOx-L-pH*** *and* ***AquapHOx-L-O₂*** *loggers mounted on pillars near Rovinj, Croatia.*

2.3 Sensor Maintenance and Calibration

For both deployments in Kiel and Rovinj, all oxygen and pH sensors were calibrated prior to deployment using **PyroScience** buffer capsules and the **PyroScience PyroWorkbench** software. The oxygen sensors were calibrated with ambient air (100%) and an **OXCAL** (0%) solution, while the pH sensors were calibrated using pH 2 (**PHCAL2**) and pH 11 (**PHCAL11**) buffer solutions.

After retrieval, the pH sensors were recalibrated with a pH 2 calibration buffer to assess potential drift over time. Throughout this paper, we use the terms 'prospective' and 'interpolated' drift correction for pH. The prospective drift correction applies drift parameters determined under optimal laboratory conditions, while the interpolated drift correction calculates drift based on calibrations performed before, during, and after deployment using Python. However, this correction can also be performed using **PyroWorkbench** software from **PyroScience**. In the software, 'prospective' and 'interpolated' drift correction for pH are referred to as 'automatic drift compensation (default)' and 'interpolated (advanced)', respectively.

The sensors deployed in Kiel were not serviced until the end of the deployment, while the sensors deployed in Rovinj were serviced in July 2024 due to the longer deployment period. All sensors in Rovinj were then recalibrated, with pH sensors calibrated in pH 2

and pH 11 buffer solutions and oxygen sensors calibrated in ambient air and with **OXCAL**. The copper cages were reused.

The oxygen as well as the pH measurements for both deployments are automatically temperature compensated using the temperature sensor of the **AquapHOx©** device. The salinity influence on the pH reading (**-PK8T** sensors) is negligible between 30-40 PSU. The salinity in Rovinj is in the range of 36-38 PSU (Urbini et al. 2020, Table 1); therefore, salinity compensation is not necessary. However, the pH data from the Kiel deployment was compensated for salinity using Python, as the Kiel Fjord is characterized by lower salinity (<20 PSU) during the deployment period. For this experiment, DO is given in % air saturation; so, salinity compensation of the data is not required. In this paper, our focus is on comparing the absolute difference between two sensor versions (one with and one without antifouling layer). Any additional data processing would affect both sensors in the same degree, and therefore, it has been neglected here.

Sensor set-up, measurement configuration, and data logging were performed using **PyroWorkbench** software (version V1.5.0.2415). All data were processed and analyzed using Python (version 3.12.7).

3 RESULTS AND DISCUSSION

3.1 Kiel Fjord Deployment

3.1.1 Biofouling Observations

Photos taken before and after the deployment clearly show significant biofouling on the sensor surfaces (Fig. 2). The accumulation of microorganisms and marine organisms indicates that Kiel Fjord is highly conducive to biological growth, which can lead to sensor drift and measurement inaccuracies over time. Despite the presence of biofouling, the antifouling protection cages appear to have provided some level of resistance, although friction with the metal deployment frame throughout the entire deployment period caused physical damage to the bottom part of the copper cages.

*Fig. 2 Four **AquapHOx** pH and oxygen loggers before and after the deployment in Kiel Fjord, Germany.*

3.1.2 Time Series Data Analysis

Figure 3 presents time series data of pH, dissolved oxygen (DO), temperature, and salinity recorded in Kiel Fjord over an eight-week period from July 4 to August 30, 2024.

pH measurements from two different sensors (**PHCAP-PK8T-AF-SUB and PHCAP-PK8T-SUB**) show fluctuations between 7.4 and 8.4. Periods of relatively higher pH, particularly in mid-July, suggest enhanced primary production, potentially due to algal activity. Notable pH drops indicate possible upwelling events, mixing or biological processes such as respiration-driven CO_2 accumulation.

DO (% air saturation), recorded by **OXCAP-AF-SUB** and **OXCAP-SUB**, fluctuates significantly, reaching values >100%, which indicate strong photosynthetic oxygen production. Sharp declines later in the record suggest oxygen depletion due to respiration or shifts in water masses.

Temperature trends reveal gradual warming from early July to mid-August, peaking around 20°C, followed by cooling. These variations likely reflect seasonal atmospheric changes and hydrodynamic mixing.

Salinity, measured by the Exo1 Sonde (YSI, Xylem brand), ranges from 12 to 20 PSU. Early fluctuations correspond to freshwater inputs from precipitation and river discharge, whereas later stabilization suggests reduced freshwater influence or increased mixing with more saline waters from the Baltic Sea.

The correlation between pH, DO, temperature and salinity reflect the hydrographic characteristics of Kiel Fjord. Saltwater intrusions, driven by water exchange between the bay, the Schwentine River, and the Baltic Sea, cause fluctuations in temperature, salinity, DO, and pH (Nehir et al. 2022). These intrusions typically lead to simultaneous decreases in temperature, DO and pH, emphasizing their interconnected nature. Warmer water holds less oxygen, but photosynthesis can temporarily increase DO. Later, DO declines despite cooling, indicating respiration-driven oxygen loss.

The pH and DO data exhibit a strong correlation throughout the deployment period. Periods of lower pH values align closely with lower DO levels, suggesting the influence of biogeochemical processes such as respiration and organic matter decomposition. Both pH and DO show rapid short-term fluctuations and multi-day trends, reflecting the system's high-frequency dynamics. These fluctuations could be driven by changes in biological activity, water mass movement and local hydrodynamic conditions. Such time series data are valuable for understanding short-term environmental changes and long-term trends in coastal ecosystems.

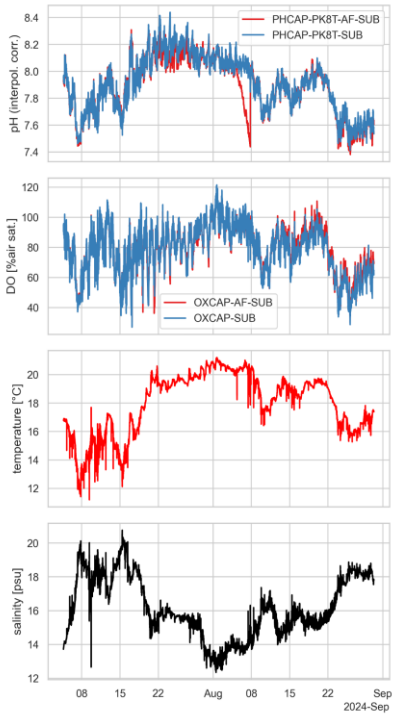

Fig. 3 Time series data of pH, DO, temperature (°C), and salinity (psu) in Kiel Fjord, July 4 to August 30, 2024.

3.1.3 pH Drift Compensation and Sensor Performance

A comparison of the raw pH data (no correction) and the effects of two drift correction approaches– interpolated and prospective –is presented in Fig. 4 for both sensors with the antifouling layer (**PHCAP-PK8T-AF-SUB**) and without (**PHCAP-PK8T-SUB**, standard sensor).

At the beginning of the deployment, both sensors show minimal differences between raw and drift corrected data. However, as the deployment progresses, drift becomes more evident. For the antifouling coated sensor (**PHCAP-PK8T-AF-SUB**), by August 2, the interpolated correction is 0.04 pH lower than the raw data, while the prospective correction is 0.01 pH lower. By the end of the deployment, the interpolated correction deviates by -0.17 pH, while the prospective approach stays closer to the uncorrected data at -0.05 pH.

For the standard sensor (**PHCAP-PK8T-SUB**), a similar trend is observed. By August 2, the interpolated correction is 0.06 pH lower than the raw data, while the prospective correction is only 0.01 pH lower. At the end of the deployment, the interpolated correction deviates by -0.28 pH while the prospective correction remains at -0.05 pH.

The results indicate that the antifouling layer coated sensor experiences less drift over time compared to the standard sensor, suggesting that the antifouling layer effectively reduces the accumulation of biofouling-related artifacts, though it does not completely eliminate them. Overall, the interpolated correction (blue) appears to stabilize the measurements more effectively than the prospective drift correction method (green), suggesting it may be a more reliable approach for compensating sensor drift.

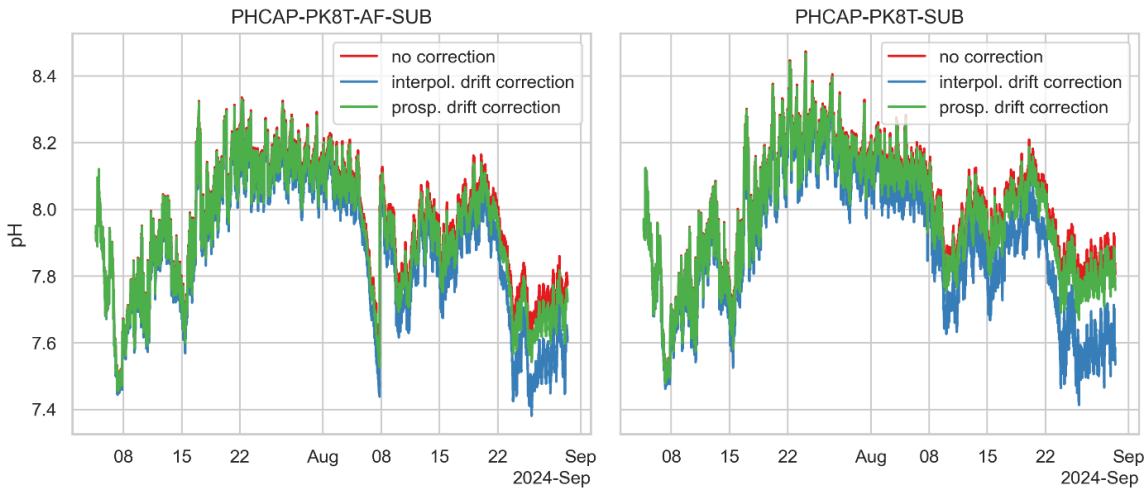

Fig. 4 Comparison of pH data (raw, interpolated and prospective drift compensated) from 2 sensors: (i) with an antifouling layer (left) and (ii) without the antifouling layer (right) from the Kiel deployment.

Building on this, Fig. 5 presents the same dataset as Fig. 4 but focuses solely on the interpolated drift corrected pH data. This allows for a clearer comparison of the two sensors' behavior. While the corrected data from both sensors follow similar trends, some

deviations remain, particularly in specific time intervals. The gray-shaded regions highlight periods where differences between the two sensors become more pronounced.

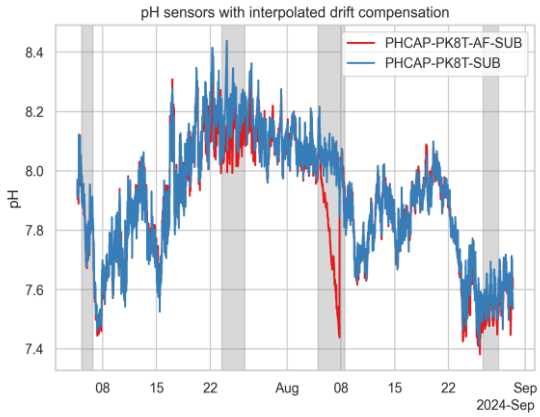

Fig. 5 Interpolated drift compensated data for both pH sensors, Kiel deployment.

To further investigate these discrepancies, Fig. 6 zooms in on the shaded regions from Fig. 5, providing a closer look at critical phases of the deployment. At the start of the deployment, both sensors are in good agreement, capturing even very small pH fluctuations simultaneously. However, three weeks later, in the first middle region, the standard sensor exhibits larger fluctuations compared to the novel antifouling sensor. Some events appear only in one sensor or even point in opposite directions, suggesting early signs of fouling.

After four weeks, in the second middle region, a notable divergence appears, with the antifouling sensor showing a gradual decline in pH while the standard sensor remains more stable. This difference raises the possibility that a large organism may have obstructed the sensor, temporarily blocking water exchange. On August 7, this obstruction disappeared, and the sensor returned to normal operation. Although the sensor is not perfectly protected from biofouling, but the data suggests that full recovery is possible.

At the end of the deployment, both sensors once again exhibit similar trends, and pH spikes are detected in a comparable manner. However, noticeable offsets (ca. ±0.05 pH) remain, indicating that while drift correction methods improve data reliability, further refinement is needed to fully align the measurements. The effect of biofouling on pH (e.g., on the **PHCAP-PK8T-SUB** sensor without the novel antifouling layer) is expected to cause an artificial rise, and the data confirms this trend.

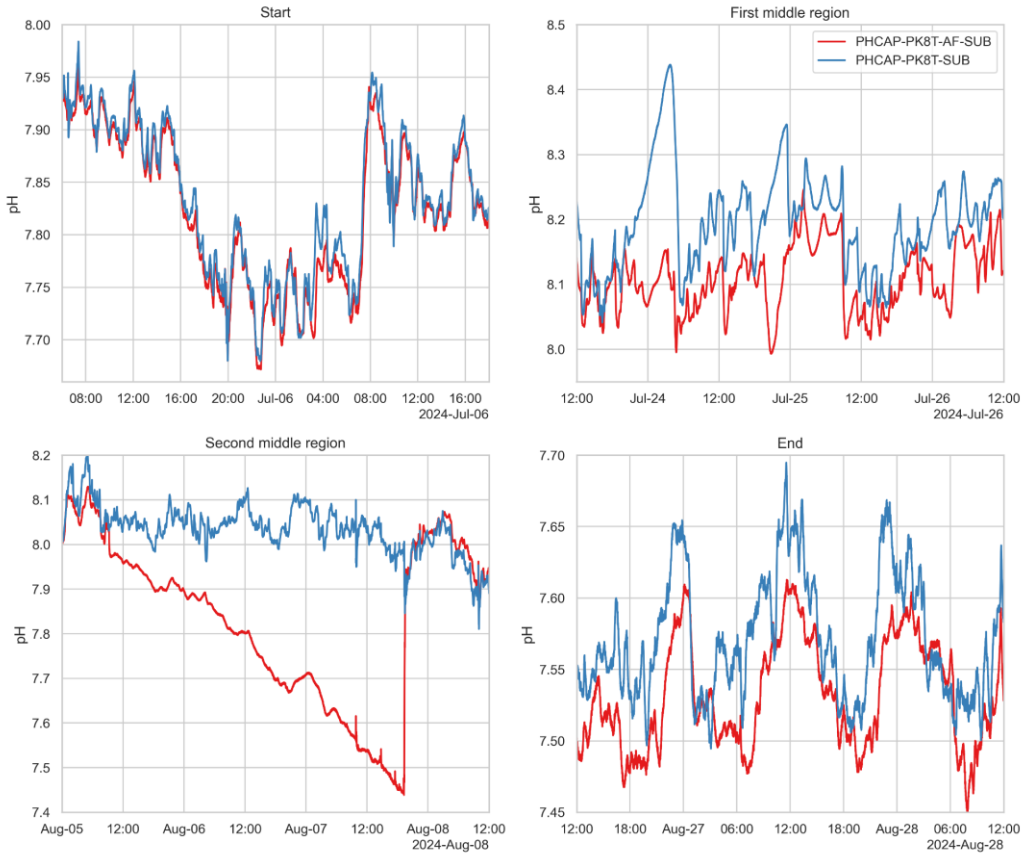

Fig. 6 Zooms on interesting regions of the pH data. The pH data is corrected for both sensors with the interpolated drift correction, Kiel deployment.

3.1.4 Oxygen Sensor Performance

Figure 7 presents the full dataset of dissolved oxygen (% air saturation) recorded by two oxygen sensors during the Kiel deployment. The dataset includes measurements from an oxygen sensor with an antifouling (AF) layer (**OXCAP-AF-SUB**) and one without it (**OXCAP-SUB**). The time series reveals variations in oxygen levels, with notable fluctuations throughout the deployment period. No drift correction was applied to the data. Shaded areas highlight specific periods of interest, which are further examined in Fig. 8.

During more than half of the experiment, the sensors are in good agreement, capturing oxygen variations similarly. However, around August 10, the **OXCAP-SUB** sensor without the novel antifouling layer begins to show lower oxygen values compared to the fouling-protected sensor. This discrepancy is likely caused by the growth of organisms on the standard sensor, affecting its readings. By the end of the deployment, the offset between the two sensors has increased to approximately 5% air saturation, indicating a potential biofouling effect.

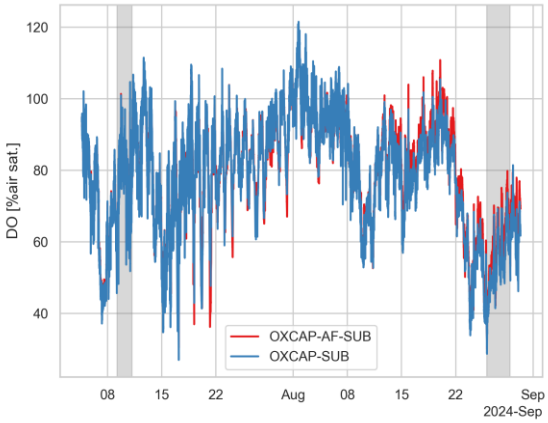

Fig. 7 DO (%air sat.) data for both oxygen sensors with and without antifouling layer, Kiel deployment from July 4 to August 30, 2024. No drift correction was applied.

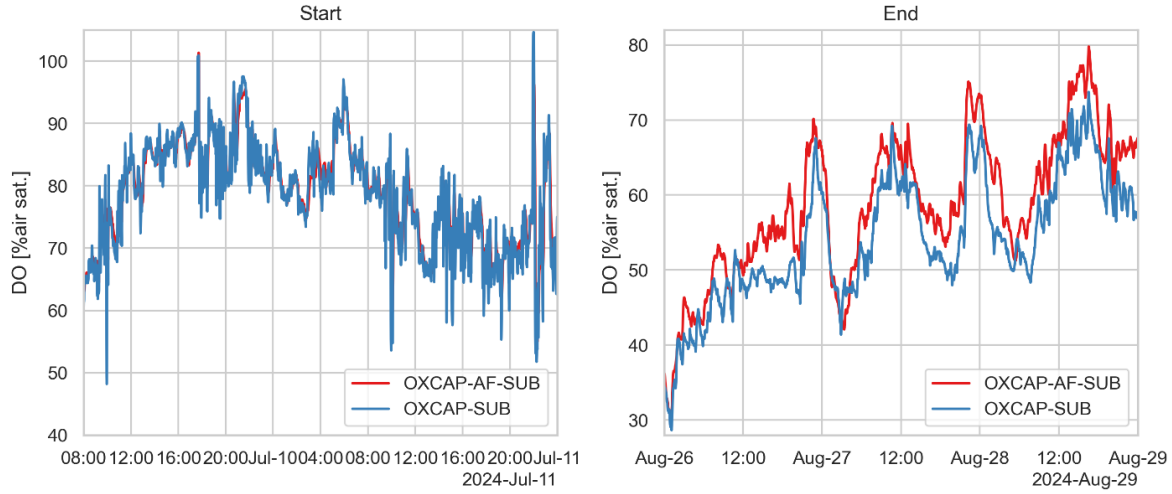

Fig. 8 Zooms on interesting regions of the DO data, Kiel deployment.

Figure 8 provides a closer look at two distinct timeframes: the start (July 10–11) and the end (August 26–29) of the deployment. In the early phase, both sensors exhibit near-identical measurements, capturing even small fluctuations simultaneously and without any offset. This suggests that, at the beginning of the experiment, both sensors functioned optimally. However, near the end of the deployment, a clear offset develops, accompanied by differences in measurement kinetics. While both sensors still detect large changes in dissolved oxygen, they do so with discrepancies in timing and magnitude. Biofouling on the **OXCAP-SUB** sensor appears to have interfered with its ability to accurately measure oxygen levels, highlighting the impact of sensor contamination over prolonged deployments.

3.2 Rovinj Deployment

3.2.1 Biofouling Observations and Time Series Data Analysis

Figure 9 shows the **AquapHOx**© loggers after the deployment in Rovinj. The loggers are overgrown with mussels and other organisms. This proves the strong biofouling conditions during the deployment.

Fig. 9 ***AquapHOx*** *pH and oxygen loggers after the deployment in Rovinj.*

The graphs (Fig. 10–16) below show the measured DO, pH and temperature at the landing stage at the diving center in Rovinj. The three oxygen sensors detect reliable oxygen values over the entire measurement period of more than 6 months. The oxygen concentrations match each other very well. There are some rare events where the oxygen readings do not match each other. In the time period from May 11 until 15 (Fig. 11) the **OXCAP-SUB** sensor detects higher oxygen concentrations than the two **OXCAP-AF-SUB**. During this period, 2 pH sensors also show higher pH values than usual. This indicates that the different sensor readings are caused by a biological event. But in total the oxygen sensors monitor DO over more than 6 months without exchange of sensor caps and one recalibration after 3 months in nutrient-rich and warm sea water. The standard oxygen sensors and the oxygen sensors with the novel antifouling layer both show very low drift and are not influenced by biofouling, with all oxygen sensors being protected from biofouling by a copper mesh. The copper meshes were not exchanged in the service but reached the end of their lifetime after 6 months.

The pH plotted in the diagrams below (Fig. 10–16) is drift corrected. We performed the interpolated drift correction using the calibrations before, during and after the deployment with Python. Before the service, we compared two pH sensors without antifouling layer with and without copper meshes and a sensor with antifouling layer and copper mesh. The pH sensor without any antifouling protection stops to monitor pH after

2.5 months. The pH sensor shows high drift that cannot be compensated completely. Also, the day and night dynamics of the pH sensor without antifouling protection is significantly smaller. This comes from organisms growing on the sensor. These organisms are also the reason for the high drift and the early end of life of 2.5 months. Both pH sensors protected with copper meshes monitor the pH reliable for 3 months without recalibration. The pH sensor without copper mesh and without antifouling layer was exchanged for a pH sensor without copper mesh and with antifouling layer. One of the serviced sensors shows about 0.4 pH higher pH within the first 10 days after service (Fig. 13). It is presumed that pH was increased due to photosynthetic activity or due to the formation of calcium carbonate by marine organisms. After 10 days all 3 pH sensors monitor similar pH values. The new sensor shows an offset of 0.1 pH for about a month (Fig. 13 & 14). In the following months the sensor with antifouling layer and copper mesh shows lower pH and higher dynamics while the sensors with copper mesh and without anti fouling layer and the new sensor with antifouling layer, but without copper mesh, show similar, but higher pH. It is not possible to be sure which of the sensors measure the pH of the surrounding seawater but it is presumed that the sensor with antifouling layer and copper mesh monitors the pH in the surrounding sea water because of the higher dynamics and the other two sensors are partially overgrown by marine organisms leading to lower pH fluctuations.

Historical data from the northern Adriatic Sea highlight notable seasonal fluctuations in DO, pH and temperature levels. The period between April and October, spanning spring to autumn, is especially dynamic, influenced by factors such as riverine discharges, nutrient influx, phytoplankton blooms, and thermal stratification (Urbini et al. 2020).

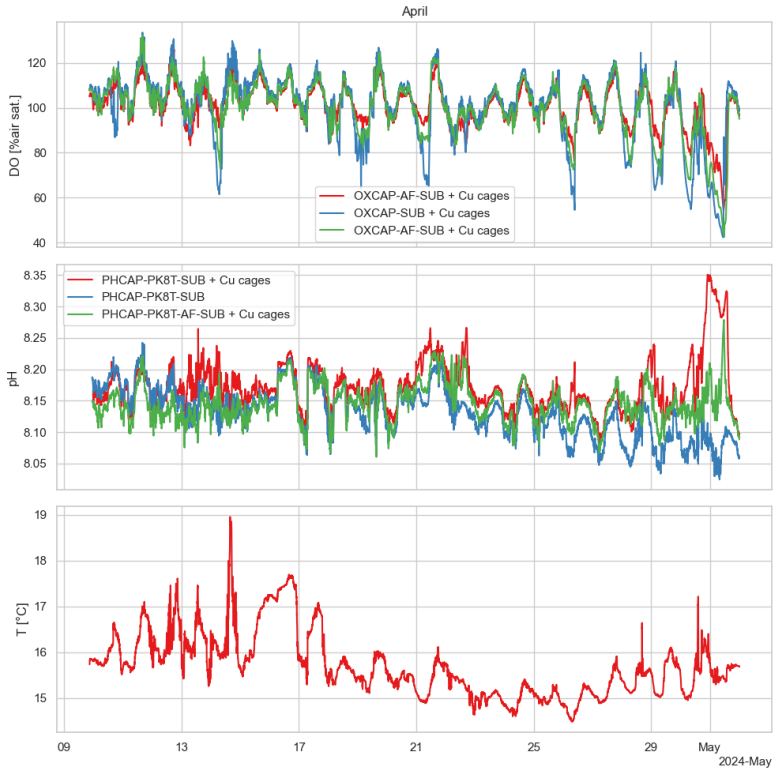

Fig. 10 Time series data of pH, DO (%air sat.) and temperature (°C) in April 2024 in Rovinj.

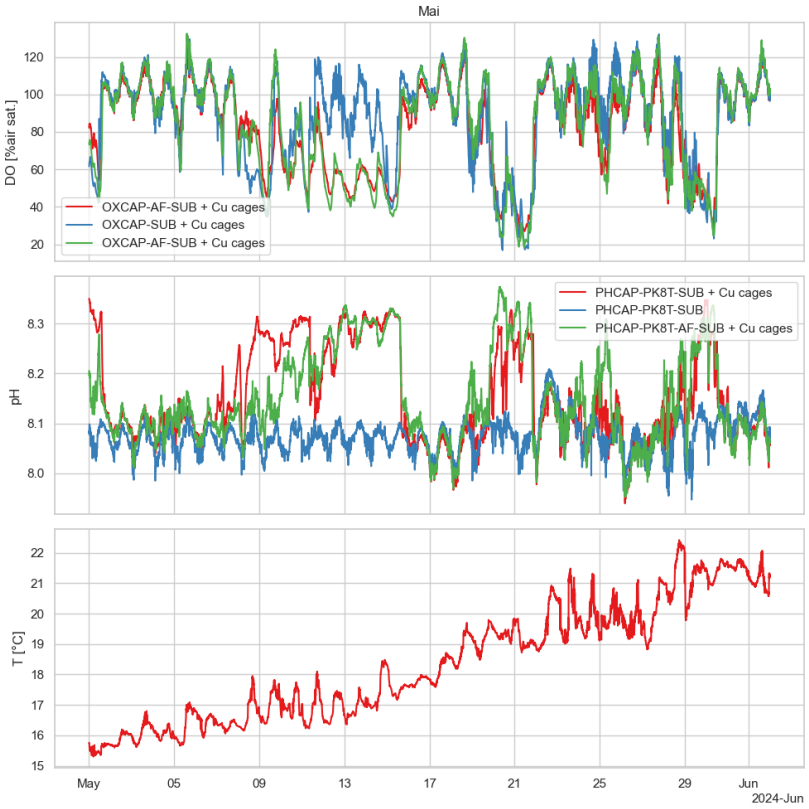

Fig. 11 Time series data of pH, DO (%air sat.) and temperature (°C) in May 2024 in Rovinj.

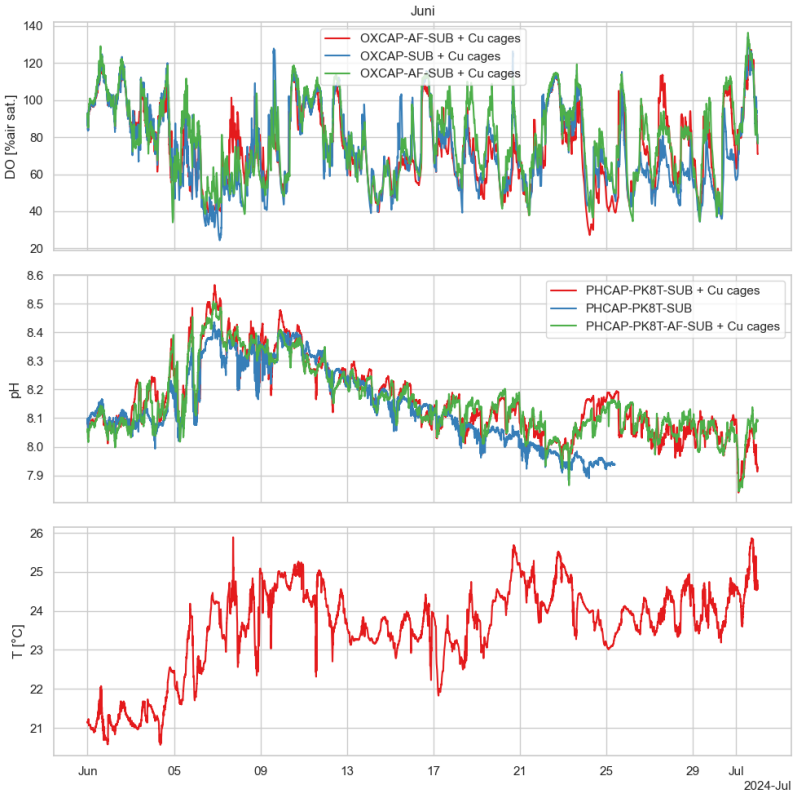

Fig. 12 Time series data of pH, DO (%air sat.) and temperature (°C) in June 2024 in Rovinj.

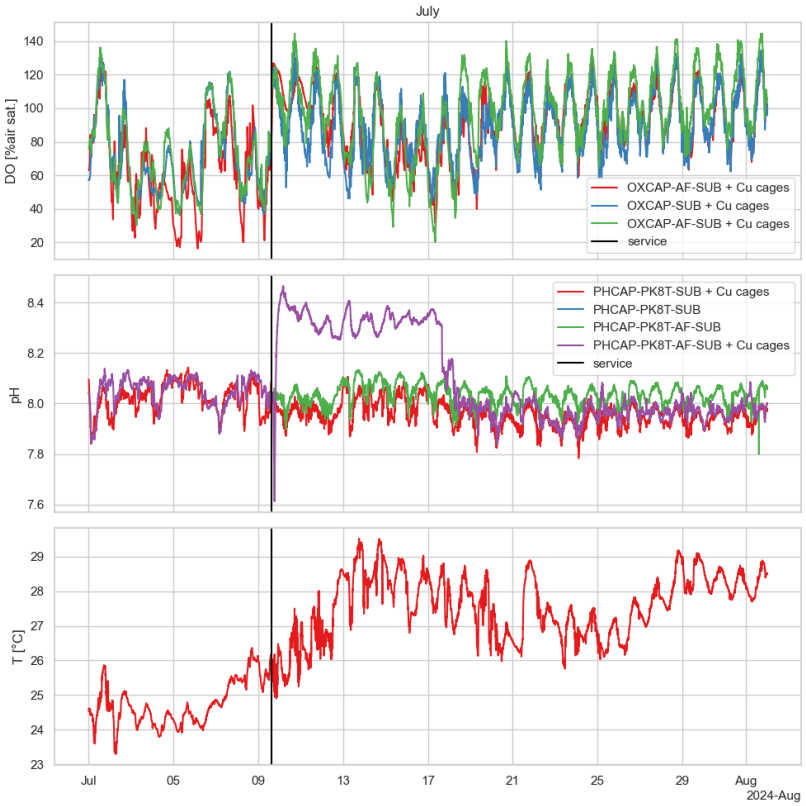

Fig. 13 Time series data of pH, DO (%air sat.) and temperature (°C) in July 2024 in Rovinj.

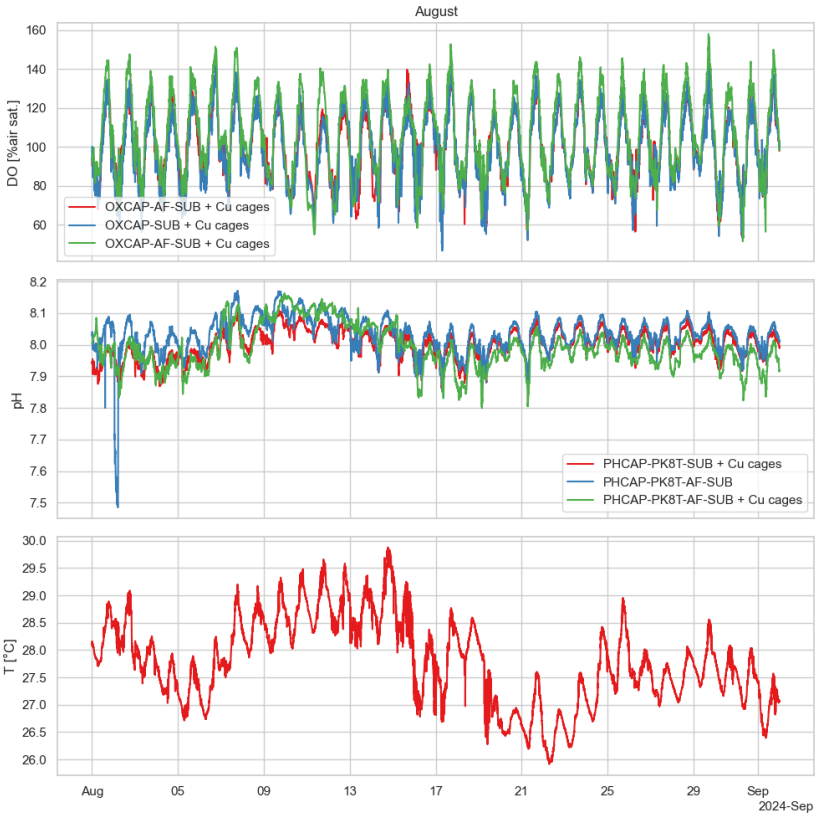

Fig. 14 Time series data of pH, DO (%air sat.) and temperature (°C) in August 2024 in Rovinj.

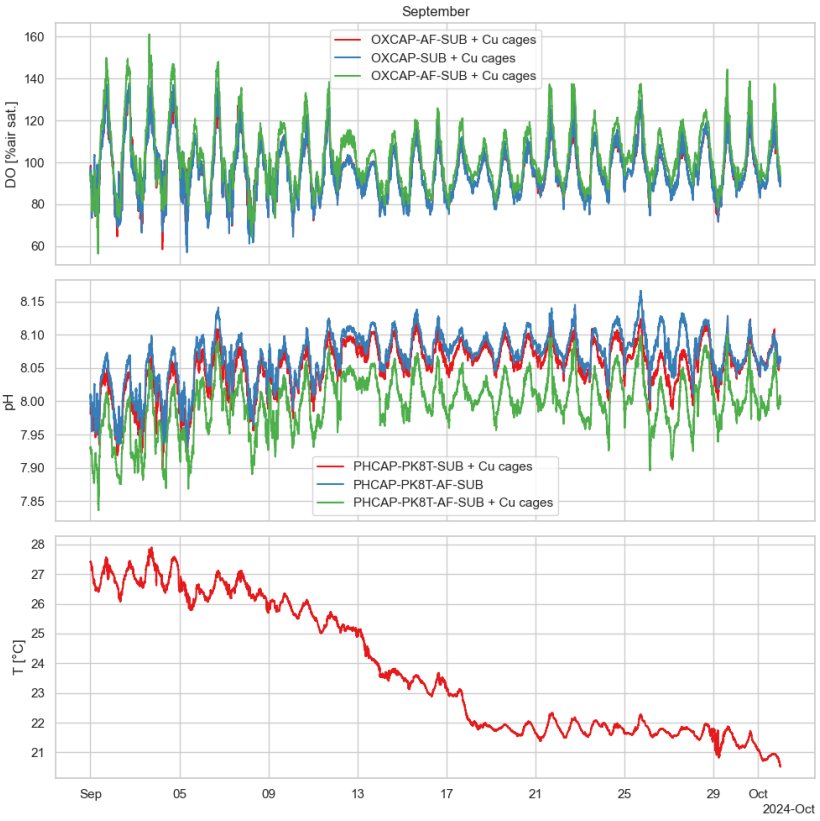

Fig. 15 Time series data of pH, DO (%air sat.) and temperature (°C) in September 2024 in Rovinj.

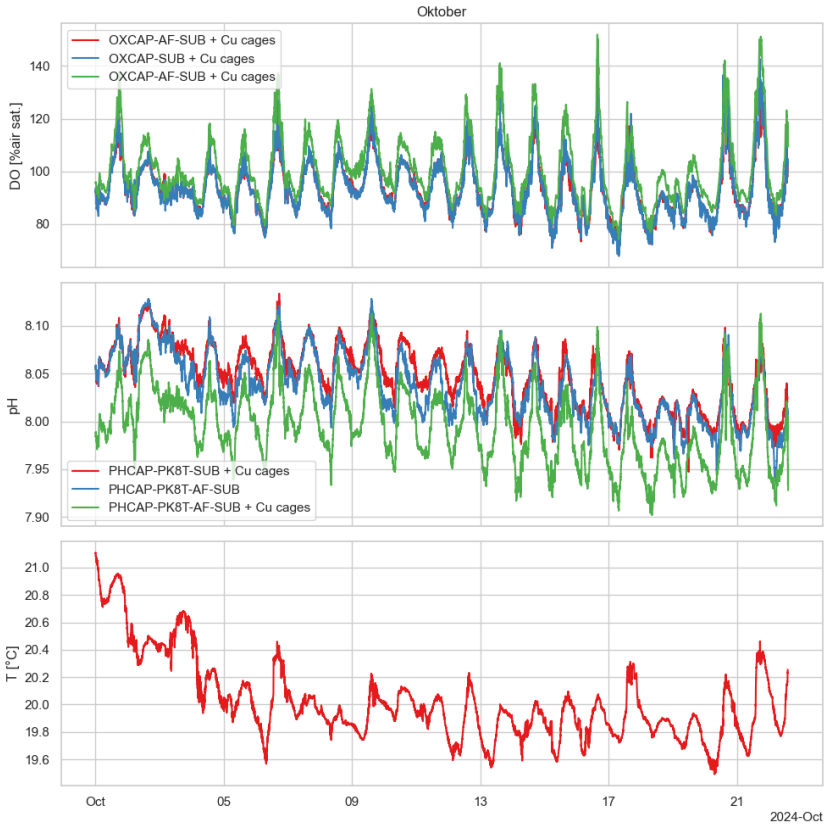

Fig. 16 Time series data of pH, DO (%air sat.) and temperature (°C) in October 2024 in Rovinj.

In Fig. 17 the sensor with antifouling layer and copper mesh and the sensor without antifouling protection are compared for the first 3 months of the deployment. Both graphs show the pH without drift correction, with prospective drift correction and with interpolated drift correction.

The sensor without antifouling protection shows a drift of about 0.3 pH over 3 months, while the sensor with protection drifts by 0.15 pH. The interpolated drift correction of the sensor with protection is similar to the prospective drift correction. This means that the sensor drift is equal to the sensor drift under lab conditions.

For the pH diagram of the sensor without protection, there is a pronounced difference (0.25 pH) visible between the interpolated and the prospective drift correction. This difference is caused by biofouling. The marine organisms populating the sensor surface damage the sensor causing sensor drift.

In conclusion, the sensor with antifouling layer and copper mesh is effectively protected from biofouling.

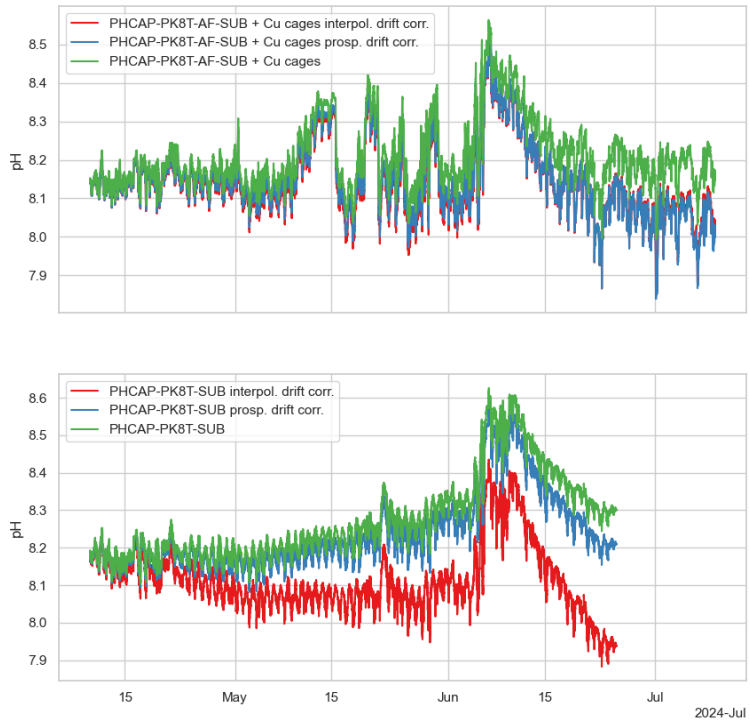

Fig. 17 Comparison of pH drift compensation between the sensor with antifouling coating and Cu mesh and the standard sensor, Rovinj.

4 CONCLUSION

Both deployments provided valuable insights into the performance, reliability, and durability of **PyroScience AquapHOx©** loggers in dynamic coastal environments. Overall, all tested sensors performed well under challenging conditions in both Kiel and Rovinj, though some drift was observed throughout the deployment periods. As expected, newer sensors equipped with antifouling protection exhibited better performance, maintaining higher data accuracy and reducing the need for frequent maintenance compared to standard sensors without this feature. These findings highlight the improvement of our antifouling strategies in long-term oceanographic monitoring, particularly in nutrient-rich and biofouling-prone coastal and shallow environments. The coastal applications presented in this paper represent very challenging shallow water environments for environmental sensors, such as those used for monitoring pH and DO. In open ocean and deep-sea applications, both biofouling and potential drift effects are expected to be significantly lower.

In addition to these logger-based insights, PyroScience also offers **AquapHOx©** real-time data transmitters compatible with optical pH and oxygen sensors equipped with a novel antifouling layer. These transmitters enable remote monitoring with real-time data transmission. Unlike stand-alone loggers, however, the transmitters require an external data logger and battery for operation. PyroScience provides a pigtail interface cable to connect **AquapHOx©** transmitters to third-party systems.

ACKNOWLEDGEMENTS

We would like to thank Björn Buchholz for his assistance with the deployment facility on a floating pontoon at the GEOMAR Helmholtz Centre for Ocean Research (Kiel, Germany). Special thanks to Dr. Mario Esposito and Sayoni Bhattacharya for organizing the deployment frame and supporting us with the integration of our **AquapHOx**© devices on this pontoon facility. We would like to thank Dr. Maria Blažina for the continued support during our deployments in Rovinj.

REFERENCES

Delauney et al. 2010: Biofouling protection for marine environmental sensors, Ocean Sci., 6, 503–511, https://doi.org/10.5194/os-6-503-2010

Nehir et al. 2022: Field Application of Automated Spectrophotometric Analyzer for High-Resolution In Situ Monitoring of pH in Dynamic Estuarine and Coastal Waters, Front. Mar. Sci. 9:891876, https://doi.org/10.3389/fmars.2022.891876

Urbini et al. 2020: Temporal and Spatial Variability of the CO_2 System in a Riverine Influenced Area of the Mediterranean Sea, the Northern Adriatic, Front. Mar. Sci. 7:679, https://doi.org/10.3389/fmars.2020.00679

APPENDIX

Fig. 18 and 19 show photos of the surfaces of the pH and oxygen sensors without novel antifouling layer under a microscope, taken after deployment in Kiel Fjord, showing signs of biofouling. The lines visible on the **OXCAP-SUB** (Fig. 19) sensor are not cracks, but deposits of marine organisms.

Both **PHCAP-PK8T-AF-SUB** and **OXCAP-AF-SUB** sensors with antifouling coatings exhibited significantly less adhering organic matter on their surfaces (Fig. 20 and 21). The photos align well with the recorded data (Fig. 3-8) and demonstrate that the new antifouling coatings effectively mitigate biofouling on the sensor surface.

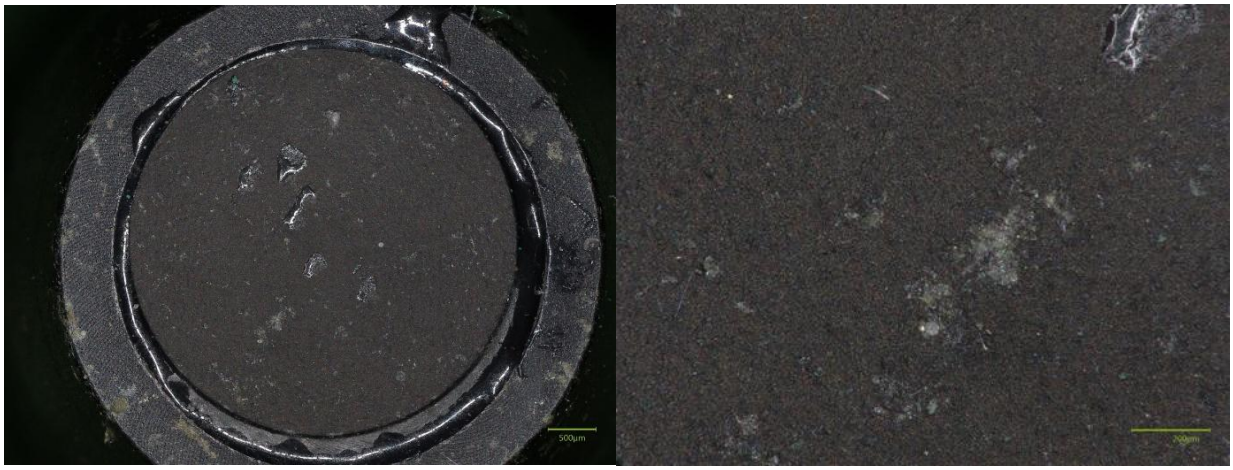

*Fig. 18 Microscope photo of the **PHCAP-PK8T-SUB** sensor surface taken after the deployment in Kiel.*

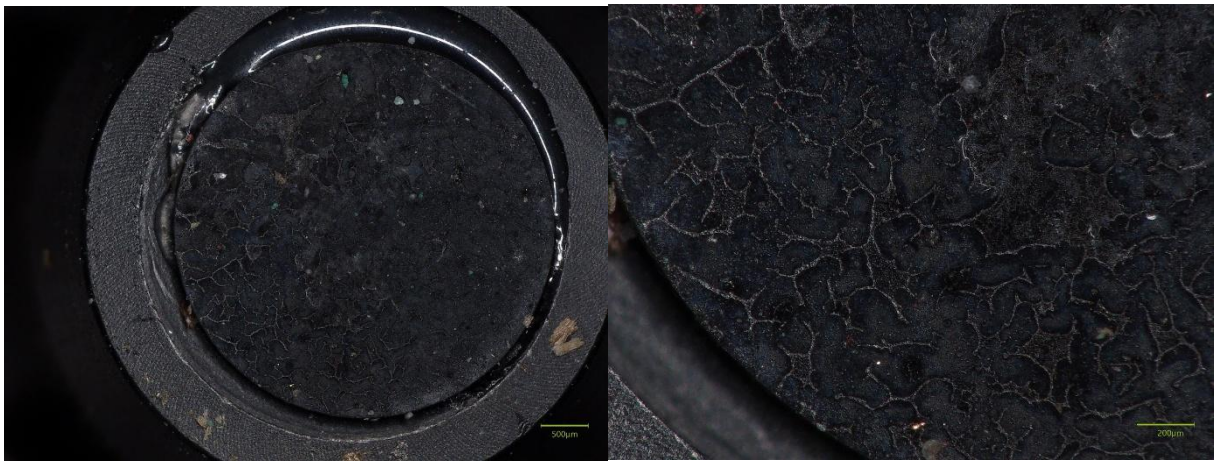

*Fig. 19 Microscope photo of the **OXCAP-SUB** sensor surface taken after the deployment in Kiel.*

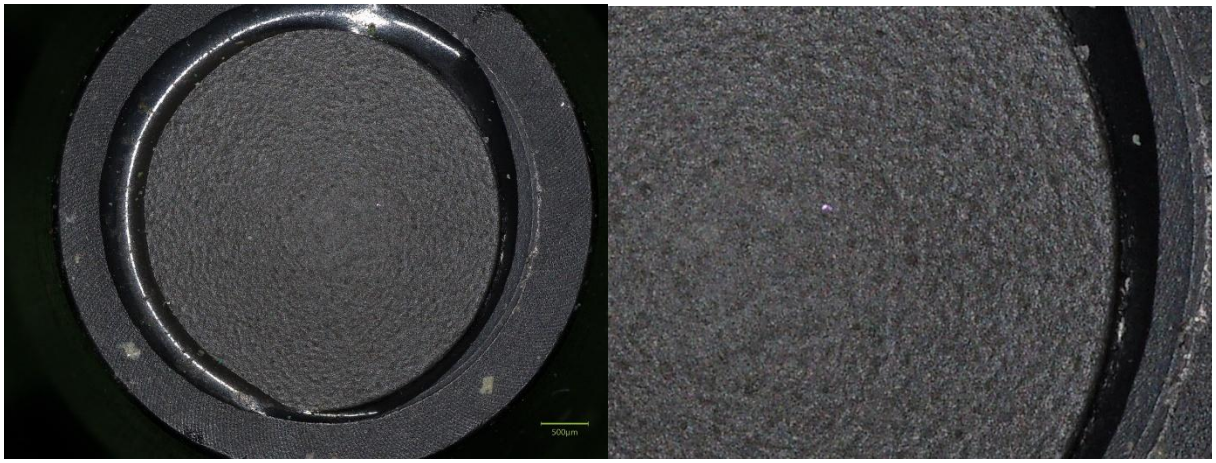

*Fig. 20 Microscope photo of the **PHCAP-PK8T-AF-SUB** sensor surface taken after the deployment in Kiel.*

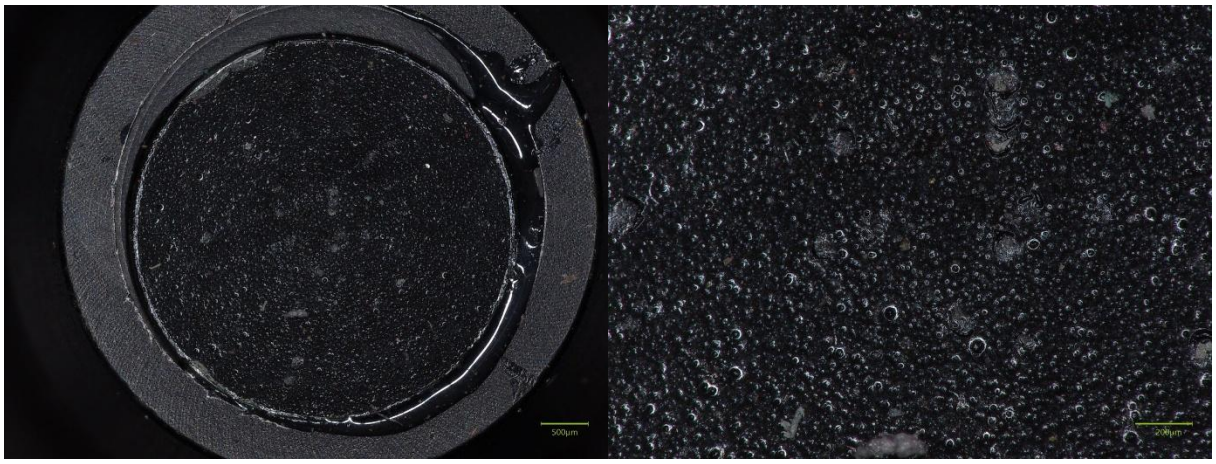

*Fig. 21 Microscope photo of the **OXCAP-AF-SUB** sensor surface taken after the deployment in Kiel.*

CONTACT

PyroScience GmbH
Kackertstraße 11
52072 Aachen
Deutschland

Tel.: +49 (0)241 5183 2210
Fax: +49 (0)241 5183 2299
info@pyroscience.com
www.pyroscience.com