

## Responses to review comments on bg-2016-54 by Yoon et al.

### Associate Editor

Dear authors

Having now read the revised version of your technical note, I conclude it should be accept for publication in BG, after some minor revision. I made my own review of your MS and I suggested some changes on several points that need clarification before publication. Looking forward reading a revised version of your paper.

With best regards, Gwenaël Abril

- **Response:** We appreciate your positive comments and valuable suggestions. We have revised our manuscript incorporating all your comments and suggestions, as detailed below. Thank you very much for your time and effort!

L55 eddy covariance measurements also include the paper by Polsenaere et al (2013)  
Polsenaere P., Deborde J., Detandt G., Vidal L.O., Pérez M.A.P. and Abril G. (2013) Thermal enhancement of gas transfer velocity of CO<sub>2</sub> in an Amazon floodplain lake revealed by Eddy Covariance. *Geophysical Research Letters* 40, 1734–1740, doi:10.1002/grl.50291.

- **Response:** The paper has been cited in Line 55.

L191 what was the motivation for choosing a different water flow in each equilibrator type? Later in the discussion, water flow must be considered as an important parameter that affects response time.

- **Response:** Different optimal water flow rates were determined in preceding laboratory tests to enable fast equilibration without causing chamber overflow, as newly described in Lines 190–192. The potential effect on response time has also been mentioned in Lines - .

L217 please specify which CO<sub>2</sub> concentration was selected to span the LICOR, and which ones were used for linearity check

- **Response:** More descriptions of the CO<sub>2</sub> analyzer QC are provided in Lines 219–221.

*The IRGA used for the two equilibrators (LI820) was spanned with a pure N<sub>2</sub> gas (>99.9%) and a CO<sub>2</sub> standard gas at 10,000 ppm. Linearity check was performed with two additional CO<sub>2</sub> standard gases (500 and 5,000 ppm).*

L328 change “good agreement” to “excellent agreement” (R>0.99)

- **Response:** The change has been made in Line 331.

L335-336 please consider that faster equilibration in the spray-type compared to the marble-type can be due to differences in water flow (2.5 L min<sup>-1</sup> versus 1.5 L min<sup>-1</sup>)

- **Response:** Following your suggestion, a new sentence has been added in Lines 340–341.

*The small difference in response time between the equilibrators might have resulted from different operational conditions including the difference in water flow (2.5 and 1.5 L min<sup>-1</sup> for the spray- and marble-type equilibrators, respectively).*

L345 to L353, avoid repetition on the fact that passive equilibration is slower

- **Response:** The redundant sentences have been rewritten to avoid repetition in Lines 351-354.

*The longer response time of the membrane-enclosed sensor can be explained by the fact that passive equilibration occurs without any physical process to facilitate equilibration underwater (Santos et al., 2012). Moreover, the diffusion-type IRGA of the membrane-enclosed sensor generally exhibited longer response times compared with those of the flow-through IRGAs of the equilibrators systems.*

L378 Frankignoulle et al. have compared equilibrator data with  $p\text{CO}_2$  calculated from pH and alkalinity, and not headspace equilibration.

- **Response:** The citation has been replaced by Abril et al. (2006) in Line 382.

L381 what does “(approximately 12:00) refer to ? please clarify

- **Response:** It has been clarified as follows (Lines 384-386).

*However, after 12 o'clock the measurements deviated substantially as the boat entered the river segments where the inflow from a highly polluted tributary enriched in  $p\text{CO}_2$  elevated the  $p\text{CO}_2$  of the main stem above the upper detection limits of the two different sensors (~10,000 and 7,000 ppm)*

L382 provide the value of upper detection limits of the sensors.

- **Response:** The change has been made in Line 386.

L420 change “could have amplified” by “apparently amplified”

- **Response:** The change has been made in Line 424.

L437 and throughout the MS: change “spot” to “discrete”

- **Response:** The term “spot” was replaced by “discrete” throughout the MS.

L446 simplify: “Other mechanical antifouling techniques (e.g., brushing and wiping) could be applied to the membrane-enclosed sensor system; nevertheless, the copper-mesh screen could be superior for long-term  $p\text{CO}_2$  monitoring programs that require easy deployment, minimal maintenance, and low energy demand. “ to something like “Other mechanical antifouling techniques (e.g., brushing and wiping) could be applied to the membrane-enclosed sensor system, but would consume more energy”

- **Response:** The change has been made in Lines 450-451.

L468 & L492 “spot measurements/sampling” > “discrete measurements/sampling”

- **Response:** The change has been made.

L498 remove the last sentence “Our technical recommendations and caveats can form a solid empirical basis for further studies that is required to improve the performance and maintenance of gas equilibration systems during continuous  $p\text{CO}_2$  monitoring in a wide range of inland waters.” Let’s let the scientific community involved in  $p\text{CO}_2$  measurements decide for that in the future.

- **Response:** The change has been made.

# Technical note: Assessing gas equilibration systems for continuous $p\text{CO}_2$ measurements in inland waters

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**Abstract.** High-frequency continuous measurements of the partial pressure of  $\text{CO}_2$  ( $p\text{CO}_2$ ) are crucial to constraining the spatiotemporal dynamics of  $\text{CO}_2$  emissions from inland water systems. However, direct measurements of  $p\text{CO}_2$  are scarce, and no systematic comparisons have been conducted on the suitability of the widely used measurement systems for continuous underway or long-term deployment in various field conditions. We compared spray- and marble-type equilibrators and a membrane-enclosed  $\text{CO}_2$  sensor to assess their suitability to continuous long-term or underway  $p\text{CO}_2$  measurements in an urbanized river system in Korea. Both equilibrators had a shorter response time compared with the membrane-enclosed sensor, and could capture large spatial variations of  $p\text{CO}_2$  during a transect study along a highly urbanized river reach. The membrane-enclosed sensor based on passive equilibration provided comparable underway measurements along the river sections where  $p\text{CO}_2$  varied within the sensor detection range. When deployed in a eutrophic river site, the membrane-enclosed sensor was able to detect large diel variations in  $p\text{CO}_2$ . However, biofouling on the membrane could reduce the accuracy of the measurement during long deployments exceeding several days. The overall results suggest that the fast response of the equilibrator systems facilitates capturing large spatial variations in  $p\text{CO}_2$  during short underway measurements. However, the attendant technical challenges of these systems, such as clogging and desiccant maintenance, have to be addressed carefully to enable their long-term deployment. The membrane-enclosed sensor would be suitable as an alternative tool for long-term continuous measurements, if membrane biofouling could be overcome by appropriate anti-fouling measures such as copper-mesh coverings.

## 25 1 Introduction

Recent synthesis efforts have highlighted the importance of carbon dioxide ( $\text{CO}_2$ ) emissions from inland waters in the global carbon cycle (Cole et al., 2007; Battin et al., 2009; Butman and Raymond, 2011; Raymond et al., 2013; Borges et al., 2015). Various methods have been employed over the years to measure the partial pressure of  $\text{CO}_2$  ( $p\text{CO}_2$ ) in a wide range of aquatic systems (Takahashi 1961; Keeling et al., 1965; Park et al., 1969; Smethie et al., 1985; Kling et al., 1992). Recent studies on ocean  $p\text{CO}_2$ , such as the International Ocean Carbon Coordination Project and the Surface Ocean  $\text{CO}_2$  Atlas

(Feely et al., 1998; Dickson et al., 2007; Pierrot et al., 2009; Pfeil et al., 2013) have stimulated technical advances, including the development of automated equilibration systems and standardized measurement protocols. Compared with the relatively narrow  $p\text{CO}_2$  ranges in the oceans ( $\sim 100\text{--}700 \mu\text{atm}$ ) (Valsala and Maksyutov, 2010), the  $p\text{CO}_2$  in inland waters ranges from values  $< 100$  to  $> 10,000 \mu\text{atm}$  (Abril et al., 2015). Moreover, the range of temporal and spatial variations in freshwater  $p\text{CO}_2$  is much wider than those in the oceans because of the substantial variations in environmental conditions, complex C transformation, and emission processes, as well as anthropogenic disturbances (Cole et al., 2007). For instance, the temporal dynamics of phytoplankton metabolisms could cause large diurnal fluctuations of  $p\text{CO}_2$  (Nimick et al., 2011). Moreover, turbulence enhances the  $\text{CO}_2$  emissions from rapidly flowing waters, which can result in steep downstream gradients of  $p\text{CO}_2$  from the upstream sources (Dawson et al., 2001; Abril et al., 2014). Furthermore, the contribution from labile organic matter of anthropogenic origin can enhance the emission of  $\text{CO}_2$  from urbanized inland waters (Frankignoulle et al., 1998; Zhai et al., 2005; Griffith and Raymond, 2011). In view of these unique conditions, specific to inland waters, vigorous field tests have to be conducted before new methods can be deployed for continuous underway or long-term measurements of  $p\text{CO}_2$  in inland water systems.

The  $\text{CO}_2$  emission rate can be determined either by directly measuring the transfer of  $\text{CO}_2$  across the water–air interface, or by estimating the flux based on (1) differences in the  $p\text{CO}_2$  between the water and air, and (2) the gas-transfer velocity. Floating chambers have been used often to measure the amount of  $\text{CO}_2$  released from a fixed area of the water surface during a relatively short measurement period (Podgrajsek et al., 2014; Lorke et al., 2015). However, the attendant technical challenges include the difficulty of deploying the floating chamber stably over often turbulent water surfaces and the disrupted natural turbulence inside the floating chamber that could result in overestimations of the  $\text{CO}_2$  flux (Vachon et al., 2010), especially when the chamber is anchored at a fixed spot (Lorke et al., 2015). Recently, Lorke et al. (2015) have proposed improved designs for floating chambers that minimize the bias of the gas-transfer velocity, including a freely drifting chamber on running water, or an anchored chamber with a close contact over the water surface. However, validation and further technical improvements are needed before these proposed chamber systems could be applied in practice. Eddy-covariance flux measurements can be used as an alternative method for direct flux measurement; however, this technique has been applied only in a small number of aquatic systems (Huotari et al., 2011; [Polsenaere et al., 2013](#); Podgrajsek et al., 2014). The indirect measurement approach based on  $p\text{CO}_2$  has been used more widely compared with the direct flux measurement method. Moreover, the performance reliability of this method has been evaluated across a wide range of aquatic systems, where the gas-transfer velocity can be estimated with supplementary environmental data (Raymond et al., 2012). The water–air difference in  $p\text{CO}_2$  is determined from the  $p\text{CO}_2$  measurements in the water and air and subsequently incorporated into an air–water gas-transfer model (Liss and Slaster, 1974; Deacon, 1977; Wanninkhof, 1992; Raymond and Cole, 2001; Wanninkhof et al., 2009). In addition, the  $p\text{CO}_2$  can be estimated from two of the three variables in the carbonate equilibrium model, namely, pH, alkalinity, and dissolved inorganic C (DIC) (Lewis et al., 1998; Dickson et al., 2007). As the calculated  $p\text{CO}_2$  data can be obtained easily from existing water quality databases, these data have been used widely in estimating the  $\text{CO}_2$  emissions from local to global inland water systems (e.g., Li et al., 2013; Lauerwald et al., 2013; Raymond et al., 2013).

65 However, Abril et al. (2015) have recently warned that the calculated  $p\text{CO}_2$  in acidic, organic-rich inland waters could be overestimated by 50 to 300 %, relative to direct  $p\text{CO}_2$  measurements. Such overestimation is ascribed to the combined effect of an unaccounted contribution of organic acids to alkalinity and the limited buffering capacity of the carbonate system in these waters.

70 Various methods have been developed successfully for continuous  $p\text{CO}_2$  monitoring in order to address the large spatiotemporal variability in  $p\text{CO}_2$  across a wide range of inland water systems (Frankignoulle et al., 2001; Johnson et al., 2010; Crawford et al., 2015). In addition, a small number of sensor-based studies have been successful in resolving large temporal variations of  $p\text{CO}_2$  in inland water systems (Johnson et al., 2010; Huotari et al., 2013; Bastviken et al., 2015). Usually, these monitoring techniques were tested in headwater watersheds; however, they have not been applied yet to the long-term monitoring of  $p\text{CO}_2$  in larger river systems, where human impact, such as high loads of organic pollutants is severe. Equilibrators have been deployed successfully for continuous underway  $p\text{CO}_2$  measurements in large rivers and estuaries (Frankignoulle et al., 1998; Griffith and Raymond, 2011; Bianchi et al., 2013; Abril et al., 2014). However, these efforts have been focused on the spatial variability of  $p\text{CO}_2$  rather than on integrating both spatial and temporal variations to provide accurate estimates of  $\text{CO}_2$  emission. Moreover, the individual systems developed for continuous  $p\text{CO}_2$  measurements have not been compared of consistent measurement accuracy over long-term deployments. Therefore, this study aims (1) to compare the accuracy and maintenance requirements of three widely used gas equilibration systems for field application in a series of laboratory and field cross-validation tests, and (2) to provide recommendations to address the technical problems and maintenance requirements that could hamper continuous long-term or underway measurements of  $p\text{CO}_2$  in inland waters. The three systems we compared are a spray-type equilibrator, a marble-type equilibrator, and a membrane-enclosed  $\text{CO}_2$  sensor.

## 85 **2 Gas equilibration systems used for continuous $p\text{CO}_2$ measurements in inland waters**

Numerous gas equilibration methods have been used to measure the  $p\text{CO}_2$  in inland waters. Gases dissolved in water need to be equilibrated between the liquid and an artificially created *headspace*, after which the gas concentration in the headspace air can be analyzed with a gas analyzer (Swinerton et al., 1962). Equilibration methods can be grouped into three categories, namely, *manual headspace equilibration*, *equilibrators*, and *membrane-based equilibration* (Table 1, and Figs 1). In addition, these equilibration methods can be classified based on combinations of *manual* vs. *automatic* system operations and *active* vs. *passive* equilibration mechanisms. The system operations include water sampling and circulation, water–air equilibration, and air flow circulation. Active equilibration differs from passive equilibration in that gas transfer across the water–air interface is facilitated by an external supply of energy. Gas analysis is usually conducted by a gas chromatograph (GC) or an infrared gas analyzer (IRGA). Additional to such methods, an isotope ratio mass spectrometer (IRMS) or a cavity-enhanced absorption spectrometer can be used to analyze methane ( $\text{CH}_4$ ) or the stable C isotopes of  $\text{CO}_2$  and  $\text{CH}_4$  as well (Friedrichs et al., 2010; Maher et al., 2013; Gonzalez-Valencia et al., 2014; Webb et al., 2016). Manual headspace equilibration, by

shaking a collected water sample in a closed bottle or syringe, has long been used as a standard method for measuring  $p\text{CO}_2$  in inland waters (Kling et al., 1992; Hope et al., 1995; Raymond and Cole, 2001). Here, we focus on automated gas equilibration systems that can be used for continuous underway or long-term measurements of  $p\text{CO}_2$  in inland waters.

100 Various automated equilibrator systems have been used for both *discrete* and continuous measurements of  $p\text{CO}_2$  in inland waters and oceans (Takahashi, 1961; Keeling et al., 1965; Park et al., 1969; Feely et al., 1998; Frankignoule et al., 2001). The spray- and marble-type equilibrators are the two most widely used such systems (Fig. 1; Table 1). The equilibrator automates the manual shaking used in the headspace equilibration method by using a spray, nozzle, or showerhead (as termed in different papers) and marbles that increase the water–air interface for gas exchange. In the spray-type equilibrator, 105 the pumped water is sprayed from a nozzle and the  $p\text{CO}_2$  in the droplets is subsequently equilibrated with the headspace air within the chamber of the equilibrator (Takahashi, 1961). Spray-type equilibrators have been used as a standard method in oceanic  $p\text{CO}_2$  monitoring studies since their introduction in the late 1950s (Takahashi, 1961; Keeling et al., 1965; Feely et al., 1998; Dickson et al., 2007; Pierrot et al., 2009), with several commercial versions being currently available (e.g., GO8050, General Oceanics, USA). Spray-type equilibrators have been used in diverse inland water systems (Raymond and Hopkinson, 110 2003; Zhai et al., 2005; Maher et al., 2013; Crawford et al., 2015; Joesoef et al., 2015). The marble-type equilibrators were developed to address the monitoring conditions specific to inland waters, such as high loads of sediments and organic matter (Frankignouille et al., 2001; Abril et al., 2006). In the marble-type equilibrator, the pumped water flows over the surface of the marbles, which increase the air–water interface and reduce the volume of headspace air, enabling gas exchange between the flowing water and the headspace air (Frankignouille et al., 2001; Abril et al., 2006). The equilibrated air continuously 115 circulates in a closed loop linking the equilibrator headspace to a gas analyzer, usually an IRGA, or a cavity-enhanced absorption spectrometer (Friedrichs et al., 2010; Gonzalez-Valencia et al., 2014; Webb et al., 2016). These *automatic* and *active* equilibration systems integrate water sampling, equilibration, and gas analysis in a loop by using water or air pumps powered by external sources (Table 1). This implies that factors such as power supply and maintenance could limit the application of these equilibrator systems to continuous monitoring of  $p\text{CO}_2$  in certain inland water systems. For instance, 120 long-term observation at a remote site could be hampered by maintaining power supply for a sustained period. In addition, the components of such an equilibrator system, namely, water pumps, tubing, nozzles, and marbles could become clogged up by small particles and large debris when the system is deployed for long-term monitoring in turbid or eutrophic waters (Santos et al., 2012).

A membrane-based equilibration system can be established when a diffusion-type IRGA  $\text{CO}_2$  sensor, enclosed in a water- 125 impermeable but gas-permeable membrane, is placed directly in water (Figs. 1, S1; Table 1; Johnson et al., 2010). Gas equilibration occurs between the inside (headspace over the sensor) and the outside (water) of the membrane. The  $\text{CO}_2$  concentration in the equilibrated air inside the membrane is detected by the sensor and the data can be stored by a connected data logger. A number of commercial membrane-enclosed sensor systems are available (e.g., eosGP, Eosense Inc., Canada; Mini-Pro  $\text{CO}_2$ , Pro-Oceanus Systems Inc., Canada). Some of the  $\text{CO}_2$  sensors used in these commercial systems can detect a 130 wide range of  $\text{CO}_2$ , covering the usual range of  $p\text{CO}_2$  found in inland waters. This *automatic* but *passive* equilibration system

does not require extra energy for equilibration or for water and air pumping, therefore, this system has a significant advantage over other equilibrator systems with higher energy demands. This relatively compact “all-in-one” system (from equilibration to detection), together with the relatively low cost, facilitates easy field deployment that can be replicated at multiple locations. In addition, a wide range of applicability allows a cross-comparison of C transfer across various watershed compartments, including sediments, soils, and dead wood (Johnson et al., 2010; Leith et al., 2015; Troxler et al., 2015). The potential problems of the membrane-enclosed sensor system, including long response time and biofouling, have not been adequately investigated yet. More time is usually required for equilibration by passive diffusion, with the typical response times ranging from several to dozens of minutes (Santos et al., 2012; Webb et al., 2016). Longer response times could hamper the detection of large spatial or temporal variations of  $p\text{CO}_2$ . Moreover, biofouling on the membrane surface can result in over- or underestimation of the  $p\text{CO}_2$  over long-term deployment. However, previous studies have not reported any significant effects of biofouling during long-term deployment in headwater streams with relatively low ranges of  $p\text{CO}_2$  (Johnson et al., 2010; Crawford et al., 2013; Peter et al., 2014; Leith et al., 2015). No investigation has been conducted on whether the membrane-enclosed sensor could be used for continuous underway measurements of  $p\text{CO}_2$  in large rivers and estuaries

Other membrane-based and hybrid equilibration systems, such as membrane contactors, have been used as alternative membrane-based equilibration methods and these systems are available commercially for industrial applications (e.g., Liqui-Cel<sup>®</sup>). The membrane contactors allow *automatic* and *active* measurement of  $p\text{CO}_2$  when coupled with an automated  $\text{CO}_2$  analyzer system (Hales et al., 2004; Santos et al., 2012). Such membrane contactors have been used in various inland waters, including boreal (Teodoru et al., 2011) and tropical waters (Abril et al., 2015; Teodoru et al., 2015). However, the potential clogging and biofouling problems remain unresolved, hampering the long-term deployment of these systems in eutrophic waters. Bastviken et al. (2015) have presented a hybrid system that combines floating chambers and low-cost  $\text{CO}_2$  sensor modules to detect changes in the  $\text{CO}_2$  concentration in the chamber headspace. The use of low-cost detectors enables replicated monitoring at multiple sites, which is essential to detecting the spatiotemporal variations of  $p\text{CO}_2$ .

Abril et al. (2015) have found general agreement in the measurements obtained from the manual headspace-equilibration method and the marble-type and contactor equilibrators over a wide range of  $p\text{CO}_2$  (0–15,000  $\mu\text{atm}$ ) and other water chemical properties in various inland waters, ranging from temperate to tropical systems. An earlier comparison had established good agreement between a marble-type equilibrator and the manual headspace equilibration method (Abril et al., 2006). Johnson et al. (2010) have established moderate agreement between a membrane-enclosed sensor and a manual headspace equilibration relevant to the  $p\text{CO}_2$  in four boreal inland waters. Santos et al. (2012) have compared various systems, such as a spray-type, a marble-type, three membrane contactor equilibrators (Liqui-Cel), and a passive polypropylene membrane system (ACCUREL<sup>®</sup> PP, Membrana GmbH, Germany) with the aim of establishing a system for coupled  $^{222}\text{Rn}$  and  $p\text{CO}_2$  measurements in the groundwater discharged into coastal waters. Although all the systems produced similar results for  $p\text{CO}_2$  in the laboratory tests with a groundwater sample ( $\sim 12,000 \mu\text{atm}$ ), the response times of these equilibration methods differed markedly. The polypropylene membrane exhibited a particularly long response time (82 min)

165 compared with those of the other systems, which ranged from 4–18 min. Empirical evidence to support the agreement between the membrane-enclosed sensor and the other equilibration systems is still insufficient. In sum, the response time and biofouling of the equilibration systems, together with other maintenance requirements such as power supply and consumable replacement, need to be assessed in various field conditions to enable the successful deployment of such systems in continuous underway or long-term measurements of  $p\text{CO}_2$ .

## 170 **3 Materials and methods**

### **3.1 Equilibration systems**

To assess the applicability of the three selected equilibration systems to continuous  $p\text{CO}_2$  measurements in inland waters, we compared their performance with each other and validated their performance against that of the manual headspace equilibration (Kling et al., 1992; Hope et al., 1995). Manual headspace equilibration was conducted using a polypropylene  
175 syringe (60 ml; HSW Norm-Ject Luer Lock Tip; Henke-Sass Wolf GmbH, Germany) to collect a 30 ml water sample and a 30 ml sample of the ambient air. The syringe was shaken manually for 2 min, after which a subsample of the equilibrated air was collected in a 50 ml gas-tight syringe (Swastik Enterprise, Gujarat, India). The gas sample and an additional 30 ml sample of ambient air were injected directly into a GC (7890A, Agilent, USA), fitted with a Supelco Hayesep Q 12 ft. 1/8 inch column during the laboratory tests. In the field tests, the gas sample collected in the syringe was transferred to a pre-  
180 evacuated vial for gas analysis in the laboratory, usually within three days. The  $p\text{CO}_2$  was calculated from the  $\text{CO}_2$  concentrations of the equilibrated air and ambient air samples, water temperature, and barometric pressure, based on Henry's law (Hudson, 2004).

The spray-type equilibrator included a spray nozzle (GG 3/8 - SS 15, Spraying System Co., USA) in an acrylic tube (inner diameter 40 mm, outer diameter 48 mm, and height 200 mm), based on the designs commonly used in previous studies  
185 (Figs. 1, S1; Table S1; Keeling et al., 1965; Feely et al., 1998; Raymond and Hopkinson, 2003). A marble-type equilibrator, smaller than those used in previous studies (Frankignoulle et al., 2001; Abril et al., 2006), was designed, based on laboratory tests to enhance the portability of the device without compromising the measurement accuracy. The device consisted of an acrylic tube (inner diameter 40 mm, outer diameter 48 mm, and height 300 mm) filled with glass marbles (diameter 10 mm) (Figs. 1, S1; Table S1). Water was continuously pumped into both equilibrators with a bilge pump (Tsunami T800, Attwood  
190 Co., USA) at  $\sim 2.5 \text{ L min}^{-1}$  for the spray-type equilibrator and at  $\sim 1.5 \text{ L min}^{-1}$  for the marble-type equilibrator. [Different optimal water flow rates were determined in preceding laboratory tests to enable fast equilibration without causing chamber overflow.](#) A diaphragm pump was used to circulate the equilibrated air through an air filter and a desiccant (Drierite) column between the equilibrator chamber and an IRGA (LI820, Li-Cor, USA) at  $700 \text{ ml min}^{-1}$ . The collected data were logged every second in a laptop computer. Potential changes in the water temperature inside the equilibrator chamber were checked during  
195 field deployments by comparing the in-stream water temperature with that of the chamber outflow in various weather conditions. The temperature differences between the river water and the equilibrator outflow water were usually within



0.3°C. The differences in barometric pressure between the inside and outside of the equilibrator chamber were lower than 5  $\mu$ atm when the chamber vent was closed. The vent was closed during all the measurements after preliminary laboratory tests had confirmed that the small increase in the barometric pressure would not affect the accuracy of the  $p\text{CO}_2$  measurement. The small initial pressure build-up immediately after turning on the water pump was relieved during ventilation for a few seconds through a vent channel that was established by using a three-way cock on the air-flow circuit. In addition, the integral pressure compensation function of the IRGA (LI820) we used was able to reduce any potential risk of inaccurate  $\text{CO}_2$  analysis being induced by pressure changes.

The membrane-enclosed sensor system consisted of a  $\text{CO}_2$  transmitter, containing a CARBOCAP<sup>®</sup> sensor (GMP222; GMT222, Vaisala, Finland) and a data logger (CR10X; CR1000, Campbell Scientific Inc., USA), as has been described in detail by Johnson et al. (2010). The sensor probe was enclosed in polytetrafluoroethylene (PTFE) membrane tubing (200-07, International Polymer Engineering, USA) (Figs. 1, S1; Table S1). The open end of the membrane tubing was sealed with a rubberizing compound (Plasti Dip, Plasti Dip International, USA). The membrane-enclosed sensor was placed directly underwater at the desired depth. When necessary, the membrane-enclosed sensor was covered by metal housing to protect the membrane from underwater obstacles such as large floating debris. Power and electric signals were delivered through a cable between the underwater sensor, the transmitter, and the data logger stored in a console box on the ground. Three  $\text{CO}_2$  sensors, a data logger, and two batteries (12 V 7 AH, Rocket, Korea; 12 V 100 AH, ATLASBX, Korea) were placed in two portable, custom-made plastic containers. Since the  $\text{CO}_2$  sensor does not integrate any compensation function for variations in temperature and barometric pressure, the outputs of the sensor were corrected by separately collected data on temperature and barometric pressure (Johnson et al., 2010).

All the  $\text{CO}_2$  analyzers and sensors were calibrated in the laboratory, using  $\text{CO}_2$  gases of known concentrations (0, 500, 5,000, and 10,000 ppm) immediately before each laboratory or field test. When the  $\text{CO}_2$  sensors were deployed over several weeks, they were checked for measurement accuracy during the maintenance intervals of 1–3 months and, if required, were recalibrated against the same set of standards. The IRGA used for the two equilibrators (LI820) was spanned with a pure  $\text{N}_2$  gas (>99.9%) and a  $\text{CO}_2$  standard gas at ~10,000 ppm. Linearity check was performed with two additional  $\text{CO}_2$  standard gases (500 and 5,000 ppm). During discrete and underway measurements, measurements of air temperature and barometric pressure were recorded by a portable data logger (Watchdog 1650 Micro Station, Spectrum Technologies Inc., USA) that included an integral air temperature/humidity sensor and an external barometric pressure sensor. For long-term deployment tests, additional air temperature/humidity and water temperature measurements were recorded in a Campbell data logger. The water temperature was measured with a portable pH meter (Orion 5-Star Portable, Thermo Scientific, USA) or a multi-parameter water quality sonde (6820 V2, YSI Inc., USA).

### 3.2 Laboratory tests

The response time and measurement accuracy of the three equilibration systems were compared by using tap and distilled water that were continuously flowing into a 6 L container that was exposed to the ambient air to maintain a constant  $p\text{CO}_2$ .

230 Both equilibrators and the membrane-enclosed sensor were first placed in a tap water container ( $p\text{CO}_2$ :  $\sim 2,500 \mu\text{atm}$ ) and subsequently moved to a distilled water container ( $\sim 600 \mu\text{atm}$ ) to determine the response times. The response time ( $t_{95}$ ) was determined as the time required to reach the 95 % level of the final stabilized  $p\text{CO}_2$  values that exhibited variations smaller than 1 % of the coefficients of variation (CV) for 2 min. In addition, the response time can be assessed by calculating the time constant ( $\tau$ ) of the exponential or e-folding curve fitting of varying  $p\text{CO}_2$  values during high-to-low equilibration  
235 (Johnson, 1999). As the various response patterns observed for the membrane-enclosed sensor could not be fitted by the ideal exponential decay curve, we present only  $t_{95}$  results.

### 3.3 Field tests of the spray-type equilibrator and the membrane-enclosed sensor

In May 2015, we compared the measurement accuracy and response times of the spray-type equilibrators and the membrane-enclosed sensor at 12 sites. These sites, ranged from forested headwater streams ( $38^\circ 15' \text{ N}$ ,  $128^\circ 7' \text{ E}$ , 582 m.a.s.l. through  
240 stream and river locations, blocked by dams or weirs, to the tidal reach along the Metropolitan Seoul ( $37^\circ 41' \text{ N}$ ,  $126^\circ 39' \text{ E}$ , 1 m.a.s.l.) of the Han River in South Korea. Additional measurements, using the manual headspace equilibration method and the membrane-enclosed sensor, were performed at 6 of the 12 sites every month from July 2014 to July 2015, in order to obtain more response time data under various field conditions. To compare simultaneously the performance of the three equilibration systems, another field campaign was conducted in May 2016 in a tributary watershed and along the tidal reach  
245 of the Han River. The 14 survey sites ranged from a forested headwater stream ( $37^\circ 48' \text{ N}$   $127^\circ 1' \text{ E}$ , 148 m.a.s.l.) through the urbanized stream locations (Joongnang Stream) to the tidal reach of the Han River. The Han River is intensively dammed, with more than ten large dams and several old and newly built weirs. The predominant flow condition of each site was determined as either standing or flowing water, based on the distance from the closest up- or downstream dam or weir, and the specific flow conditions during the field study. The level of  $p\text{CO}_2$  and other environmental conditions at the sites were  
250 heterogeneous enough to allow a cross-validation test. For example, the ranges of the dissolved oxygen (DO), pH, and dissolved organic carbon (DOC) were 3.5–11.6  $\text{mg L}^{-1}$ , 6.8–9.0 and 1.0–5.1  $\text{mg C L}^{-1}$  in the 2015 field campaign, and 6.5–10.7  $\text{mg L}^{-1}$ , 5.3–7.4, and 1.0–5.0  $\text{mg C L}^{-1}$  in the 2016 campaign, respectively.

The water  $p\text{CO}_2$  at a depth of 20 cm was determined by using simultaneously the manual headspace equilibration, membrane-enclosed sensor, and spray-type equilibrator systems. The membrane-enclosed sensor was placed directly at 20  
255 cm below the surface. A peristaltic pump (Masterflex E/S portable sampler, Cole-Parmer Instrument Co., USA) was used to collect water into a sampling bottle for the manual headspace equilibration measurement, while a bilge pump was used for the spray- or marble-type equilibrator. The same measurement procedures and instrumental set-ups as in the laboratory tests were used for all three equilibration systems.

### 3.4 Continuous underway measurements of $p\text{CO}_2$

260 To test the applicability of the three equilibration systems to continuous underway measurements of  $p\text{CO}_2$ , a boating expedition was undertaken on 11 May 2015 along the tidal reach of the Han River, which receives varying loads of organic

matter and CO<sub>2</sub> via its tributaries (37°31' N, 127°1' E, 7 m.a.s.l.). The surveyed river reach is influenced strongly by the inflow from several urban streams, including Tan Stream and Joongnang Stream, draining from the Seoul metropolitan area. We assumed that the significant spatial variations in *p*CO<sub>2</sub> and other water quality components along the confluence with the urban streams would create ideal conditions for cross validation of the three equilibration systems. Prior tests had showed that three equilibration systems would perform well at moderate boat speeds around 10 km h<sup>-1</sup>. During underway measurements, the speed was maintained at ~10 km h<sup>-1</sup> over the distance of ~30 km. This speed is consistent with the usual boat speed range used for other continuous underway measurements (Abril et al., 2014; Crawford et al., 2015). The boat was stopped for ~10 min at each of the nine discrete-sampling locations to collect water samples and to measure *p*CO<sub>2</sub> by using the manual headspace-equilibration method.

The water *p*CO<sub>2</sub> at 20 cm below the surface was continuously measured at intervals of 1 or 5 s with the three equilibration systems. One membrane-enclosed sensor, together with a bilge pump delivering the collected water into the spray- and marble-type equilibrators, and another on-board membrane-enclosed sensor were attached to a pole and placed 20 cm below the water surface on one side of the boat. Two flow-through IRGAs (LI-820, Licor, USA; GMP343, Vaisala, Finland) were coupled with the spray- and marble-type equilibrators, respectively. A portable multi-parameter pH meter (Orion 5-Star Portable, Thermo Scientific, USA) was used to measure simultaneously the water temperature, pH, electrical conductivity, and dissolved oxygen in the continuously collected water on-board. The air temperature and barometric pressure were recorded in a micro-logger (Watchdog 1650 Micro Station, Spectrum Technologies Inc., USA). The two membrane-enclosed sensors (one placed in the river water and the other immersed in the pumped water on-board) had upper detection limits of 10,000 and 7,000 ppm, respectively.

### 3.5 Continuous long-term measurements of *p*CO<sub>2</sub>

Several laboratory and field tests were conducted to examine the application potential of the three equilibration systems to continuous long-term monitoring in the tidal reach of the Han River. The spray-type equilibrator was selected for use, as the preliminary tests had shown that it was easier to maintain the power supply and air-flow dehydration with this type of equilibrator than with the marble-type. The long-term measurement stability of the spray-type equilibrator was tested in comparison with that of the membrane-enclosed sensor in a series of unmanned field deployments. However, the significant power consumption from the pumping and the gradual clogging of the nozzle resulted in repeated failures of the system. The resulting *p*CO<sub>2</sub> data exhibited abnormal patterns 2–3 d after the start of the monitoring. Therefore, we focus here on the long-term performance and the relevant antifouling measures of the membrane-enclosed sensor.

As part of the long-term monitoring project, a membrane-enclosed sensor (“bulk membrane” sensor) was deployed at a depth of 20 cm below the surface, along an uninhabited island on the downstream reach of the Han River, near the city center of Seoul (37°32' N, 126°55' E, 5 m.a.s.l.). The deployment period lasted one year, starting in July 2014. To examine the effectiveness of the copper-mesh screening, intended to reduce biofouling on the membrane surface, another membrane-enclosed sensor, covered with copper mesh (“membrane+Cu” sensor), was deployed at the same site for 43 d from 31 May

295 to 12 July 2015. The bulk membrane and membrane+Cu sensors were attached to a buoy, ~3 m off a dock constructed along the island shore. Two automobile batteries (12 V 100 AH) were placed in a series on the island to power the sensors, together with the CO<sub>2</sub> transmitter and a data logger. The two parallel batteries supplied power for two weeks to two in-stream sensors and an additional sensor used for the concurrent measurement of the air  $p\text{CO}_2$  1 m above the water surface. During routine biweekly maintenance visits, the membrane surface was cleaned with a soft cloth and brushes and  
300 subsequently rinsed with deionized water, after which the copper-mesh screen was replaced. In addition to CO<sub>2</sub>, the pH, DO, water temperature, conductivity, and turbidity were monitored by using a multi-parameter water quality sonde (6820 V2, YSI Inc., USA). The accuracy of the pH probe was regularly verified on site with pH buffers and concurrent pH measurements, using a portable pH meter (Orion 5-Star, Thermo Scientific, USA). All the collected data were logged at 10 min intervals.

### 305 3.5 Data analysis

We assessed the agreement of the  $p\text{CO}_2$  measurements among the equilibration systems by linear regression analysis and by examining the CV values across the monitoring sites, after the normal distribution of data had been confirmed by the Shapiro–Wilk test. We used the  $t$ -test to compare the differences in response time ( $t_{95}$ ) between the equilibration systems. The relationships between the response time and  $\Delta p\text{CO}_2$  (defined as the difference between the initial and the stabilized final  
310  $p\text{CO}_2$  during deployment) were established for the flowing and standing water types. For the continuous long-term measurements, the relative difference of  $p\text{CO}_2$  was calculated from the natural log-transformed ratio between the values of the membrane sensor and the membrane+Cu sensor. The pH– $p\text{CO}_2$  relationships were described by locally weighted scatterplot smoothing (LOESS; Cleveland and Devlin, 1988) to examine the viability of the  $p\text{CO}_2$  measurements arising from the biofouling in the time series data. The analysis was based on the assumption that robust pH– $p\text{CO}_2$  relationships  
315 could be expected from the carbonate equilibrium model if there were no artifact effects such as sensor biofouling. The temporal changes in the pH– $p\text{CO}_2$  relationships were examined to assess the biofouling-induced deviations from the robust pH– $p\text{CO}_2$  relationship. All statistical analyses, including the descriptive statistics,  $t$ -test, regression analyses, and LOESS, were conducted on the R software environment for statistical computing and graphics (R Development Core Team, 2011).

## 4 Results and discussion

### 320 4.1 Cross validation of system performance

A series of laboratory tests established good agreements in the measurement accuracy of the three compared equilibration systems, as demonstrated by the correspondence among the three systems at a given  $p\text{CO}_2$  (Fig. 2). The CV of the measurements of the three equilibration systems was 3.0 % for the tap water and 6.2 % for the deionized water. The response time test indicated the fast response of the spray- and marble-type equilibrators ( $t_{95}$ : ~ 1 min 45 s for both the low-to-high

325 and the high-to-low equilibrations) in comparison with the slow response of the membrane-enclosed sensor, which exhibited different values of  $t_{95}$ : 16 min 30 s and 19 min for the low-to-high and high-to-low transitions, respectively (Fig. 2).

In addition, the short-term continuous measurements of  $p\text{CO}_2$  for 30–60 min at various field sites showed general agreement between the three equilibration systems and the manual headspace equilibration measurements over a wide range of  $p\text{CO}_2$ , from 152 to 10,150  $\mu\text{atm}$  (Fig. 3). The measurement results of the three equilibration systems and the manual equilibration  
330 method showed strongly positive pairwise relationships, with all the comparisons indicating  $R^2 > 0.99$  and slope ( $\beta$ ) within 0.97–1.02 (Fig. 3). The excellent agreement found between the compared methods is consistent with the results of other studies that have demonstrated the accuracy of the equilibrators (Abril et al., 2006; Santos et al., 2012; Abril et al., 2015), or the membrane-enclosed sensor (Johnson et al., 2010), although these previous comparisons were conducted separately for each equilibration system.

335 Consistent with the results of the laboratory test, the spray- and marble-type equilibrators exhibited response times that were shorter than those of the membrane-enclosed sensor during the field tests ( $t$ -test:  $P < 0.001$ ; Fig. 4). Both equilibrators usually reached the level of  $p\text{CO}_2$  equilibration within a few minutes (Fig. 4a); whereas the membrane-enclosed sensor required a longer time to reach the same  $p\text{CO}_2$  level (Fig. 4b). The mean  $t_{95}$  was 1 min 45 s for the spray-type equilibrator and 2 min 5 s for the marble-type equilibrator, without showing noticeable differences between the standing and flowing  
340 waters. The small difference in response time between the equilibrators might have resulted from different operational conditions including the difference in water flow (2.5 and 1.5  $\text{L min}^{-1}$  for the spray- and marble-type equilibrator, respectively). The response time of the spray-type equilibrator was shorter than the response times reported by another study (8 min; Santos et al., 2012), but were similar to the response times of the marble-type equilibrators reported by other studies (2–3 min; Frankignoulle et al., 2001; Abril et al., 2014). The differences in the response time of the spray-type equilibrators  
345 could be ascribed to various factors, including the different levels of  $p\text{CO}_2$  (~100–10,000  $\mu\text{atm}$  in this study vs. > 10,000  $\mu\text{atm}$  in the study by Santos et al., 2012), the equilibrator size (251 vs. 1963  $\text{cm}^3$ ), the length of the air circuit, and the performance of the spray nozzle. The mean  $t_{95}$  for the membrane-enclosed sensor was 6 min 58 s and 14 min 49 s for flowing and standing waters, respectively. This result suggests that whereas the response time is mainly controlled by the difference in  $p\text{CO}_2$  between the air and water, different degrees of turbulence in different water-flow conditions could affect  
350 the gas diffusion velocity significantly, which could be described by the diffusion coefficient of Fick's laws. The longer response time of the membrane-enclosed sensor can be explained by the fact that passive equilibration occurs without any physical process to facilitate equilibration underwater (Santos et al., 2012). Moreover, the diffusion-type IRGA of the membrane-enclosed sensor generally exhibited longer response times compared with those of the flow-through IRGAs of the equilibrator systems. In addition, the gas diffusivity across the water–membrane interface could differ from the diffusivity  
355 between the water–air interfaces within the equilibrator chambers. Since water turbulence could enhance the equilibration efficiency of the membrane-enclosed sensor, the deployment time in flowing water could be shortened compared with the longer time required for deployment in standing water.

The response time increased logarithmically for both equilibration systems with  $\Delta p\text{CO}_2$  (Fig. 4; note a log scale for the x-axis). The response time increased with increasing  $\Delta p\text{CO}_2$  (i.e., high water  $p\text{CO}_2$ ), with steeper increases being observed for the membrane-enclosed sensor, particularly in standing water. The slope of the relationship was in the descending order: the membrane-enclosed sensor in standing water (7.7), the membrane-enclosed sensor in flowing water (0.8), the marble-type equilibrator (0.6), and the spray-type equilibrator (0.5). There was no clear difference in the response time of both equilibrators across a wide range of  $\Delta p\text{CO}_2$ . Only small portions of the variations in the response time observed for the membrane-enclosed sensor were accounted for by  $\Delta p\text{CO}_2$  in flowing water ( $R^2 = 0.18$ ;  $P < 0.05$ ). The relationship between  $\Delta p\text{CO}_2$  and the response time measured in flowing water was not statistically significant ( $R^2 = 0.04$ ;  $P = 0.29$ ), suggesting that the water flow and other in-stream processes could have additional effects on the response time. The temperature could also affect response time, although regression analysis did not indicate any significant relationship between the temperature and response time, probably because of the relatively narrow range of temperature variations among the sampling sites. The results suggest that the deployment time of the membrane-enclosed sensor for short-term (< 1 h) deployments, as part of multi-site **discrete** monitoring, should be carefully determined, based on the water-flow conditions and expected range of  $p\text{CO}_2$  levels. It is crucial that sufficient time be allowed for underwater deployment to ensure the accurate measurement of  $p\text{CO}_2$  with the membrane-enclosed sensor. Therefore, we suggest a minimum deployment time of 10 min for flowing water and 30 min for standing water, which would cover a range of  $t_{95}$  that was determined in various flow conditions (Fig. 4). Where the long response time poses an obstacle to multiple **discrete** measurements in a wide range of locations within a limited space of time, employing the equilibrators could be a quicker alternative with the same level of measurement accuracy.

#### 4.2 Continuous underway measurements

The continuous underway measurements of the two equilibrators and the two membrane-enclosed sensors were generally in good agreement, namely, within 10 % CV, except for the river sections for which drastic changes in  $p\text{CO}_2$  were observed (Fig. 5). The two equilibrators produced almost the same results across the monitored reach. This comparison corroborates the accuracy of the previously obtained underway  $p\text{CO}_2$  measurements, which have compared separately the performance of each of the equilibrator types with those of the manual headspace equilibration measurements (Abril et al., 2006; Griffith and Raymond, 2011; Abril et al., 2014). The  $p\text{CO}_2$  measurements of the membrane-enclosed sensors generally corresponded well to those of the equilibrator and headspace equilibration measurements. However, after 12 o'clock the measurements deviated substantially as the boat entered the river segments where the inflow from a highly polluted tributary enriched in  $p\text{CO}_2$  elevated the  $p\text{CO}_2$  of the main stem above the upper detection limits of the two different sensors (~10,000 and 7,000 ppm) (Fig. 5). The sensor measurements also deviated noticeably from the measurements obtained with the spray- and marble-type equilibrators for the period from 12:20 to 12:35, during which the  $p\text{CO}_2$  changed abruptly. In contrast with the long response times observed for **discrete** measurements at the 26 sites (Fig. 4), the membrane-enclosed sensors exhibited good agreements with the other results across most of the river sections where  $p\text{CO}_2$  changed relatively gradually (Fig. 5). The increased

turbulence from the movement of the boat could have enhanced the equilibration of the membrane-enclosed sensor. In addition, there was little difference in the  $p\text{CO}_2$  values measured by the in-stream sensor and another sensor immersed in the pumped water on-board the vessel. The relatively high flow rate of the water pump ( $1.5\text{--}2.5\text{ L min}^{-1}$ ) could have generated sufficient mixing for rapid equilibration.

395 The test results suggest that both the spray- and marble-type equilibrators can be used for underway measurements along waterways with significant spatial variations of  $p\text{CO}_2$ . However, it remains unclear how long the measurement accuracy could be maintained during an extended cruise along high- $\text{CO}_2$  waterways, without maintenance of the replaceable items, including nozzles, marbles, and desiccants. Bakker et al. (1996) reported on frequent blockages of their showerhead equilibrator with particulate materials derived from algal blooms in Dutch coastal waters. Long deployments of the spray-  
400 type equilibrator in eutrophic freshwaters could also result in similar clogging problems. Despite the increasing use of membrane-enclosed sensors for long-term continuous  $p\text{CO}_2$  measurements in freshwater systems (Johnson et al., 2010; Huotari et al., 2013; Peter et al., 2014; Leith et al., 2015), previous studies have rarely examined the spatial variations in  $p\text{CO}_2$  across a wide range of environmental conditions. Our transect results demonstrate that the membrane-enclosed sensor could provide reliable continuous underway measurements in the inland water systems that show large spatial variations of  
405  $p\text{CO}_2$  such as the monitored river reach. Proper calibration of the sensor for a high range of  $p\text{CO}_2$  should be done before the sensor is deployed in the high- $\text{CO}_2$  water. As the in-stream and on-board sensors produced almost the same measurement results, we suggest that the on-board measurements with pumped water could be used as a safer method for concurrent measurements of  $p\text{CO}_2$  and other water quality components. On-board measurements could be a way to avoid damage by unknown underwater obstacles such as large floating debris.

#### 410 **4.3 Continuous long-term measurements**

The  $p\text{CO}_2$  measurements from the membrane-enclosed sensors with and without the copper-mesh screen started to diverge substantially 3–5 d after the biweekly maintenance (Figs 6, S2a). During the later phases of the biweekly monitoring intervals, the  $p\text{CO}_2$  measurements from the sensor without the copper mesh screen (bulk membrane sensor) exhibited larger diurnal fluctuations than those from the sensor protected with the copper-mesh screen (membrane+Cu sensor). When the  
415 daily averages were compared to reduce the diurnal fluctuations, the  $p\text{CO}_2$  measurements of the bulk membrane sensor were higher than those of the membrane+Cu sensor. Furthermore, these differences increased with time from the day that maintenance was done. The relative differences in the daily mean  $p\text{CO}_2$  between the two sensors remained within 10 % for 5, 2, and 7 d after the routine maintenance on the 153th, 169th, and 182th day of the year, respectively. During the monitoring period, extraordinary algal blooms occurred that were ascribed to a combination of factors, such as severe drought, warm  
420 temperatures, and high loads of nutrients discharged from water treatment facilities and the polluted tributaries draining the Seoul metropolitan area. The chlorophyll-a concentration increased from  $21.1\text{ mg m}^{-3}$  on 2 June to  $46.7\text{ mg m}^{-3}$  on 2 July (Water Information System of Korea; <http://water.nier.go.kr>). The bulk membrane sensor could have been more prone to biofouling by planktonic and associated bacterial communities than the membrane+Cu sensor was. Enhanced production or

consumption of CO<sub>2</sub> around the sensor membrane **apparently amplified** the diurnal fluctuations of *p*CO<sub>2</sub>, leading to  
425 considerable divergence between the two sensor measurements with increasing time after maintenance.

The relationships between the pH and *p*CO<sub>2</sub> were used to examine the increasing biofouling effects with time after the  
maintenance day (Fig. 7). The pH–*p*CO<sub>2</sub> relationships for the bulk membrane sensor shifted upward with time after  
maintenance, whereas those for the membrane+Cu sensor remained consistent over time (Fig. 7a). If additional CO<sub>2</sub>  
molecules were produced or consumed by the biofilms formed on the membrane sensor, it could disturb the usual pH–*p*CO<sub>2</sub>  
430 relationship, which could be explained by the carbonate equilibrium model (Nimick et al., 2011). In addition, the  
relationships between the daily CVs of pH and *p*CO<sub>2</sub> were stronger for the membrane+Cu sensor ( $R^2 = 0.91$ ) than for the  
bulk membrane sensor ( $R^2 = 0.51$ ) (Fig. 7b). The consistent pH–*p*CO<sub>2</sub> relationships observed for the membrane+Cu sensor  
indicated the reliability of the measured *p*CO<sub>2</sub> values. However, validating the method would require concomitant *p*CO<sub>2</sub>  
measurements using other equilibration methods across a wide range of *p*CO<sub>2</sub>.

435 The test results suggest that the membrane-enclosed sensor could be vulnerable to biofouling in polluted waters similar to the  
studied site, which could amplify the diurnal fluctuations of *p*CO<sub>2</sub>. The ever-present problem of biofouling must be taken  
into account in the long-term deployment of any *p*CO<sub>2</sub> equilibration system. If appropriate antifouling measures are not  
undertaken, repeated maintenance visits at short intervals of 3–5 d could be required for such long-term deployments in  
eutrophic rivers with high levels of and large diurnal fluctuations in *p*CO<sub>2</sub>. Daily average *p*CO<sub>2</sub> values could be used as  
440 representative *p*CO<sub>2</sub> levels within a week from the maintenance day, but the uncertainty level cannot be determined without  
concomitant measurements using other **discrete** or continuous measurements that are not significantly influenced by  
biofouling. We recommend that the copper-mesh screen be used to minimize the biofouling effects as a cost- and energy-  
efficient measure. Antifouling techniques can be classified into various categories, including mechanical (e.g., wiper, brush,  
water jet, and ultrasonic sound) and biocidal (e.g., copper, chlorine, and UV) approaches (Delauney et al., 2010). Currently,  
445 wipers and copper-based materials are commonly applied to various water quality probes. For instance, the YSI company  
supplies antifouling kits for water quality sondes, including wipers, copper-mesh screens, copper-alloy guards, and copper  
tapes, given that these practices have been found effective in various inland and marine environments (YSI Incorporated,  
2010). Compared with other biocides, the relatively low toxicity of copper ensures effective application in aquatic  
environmental monitoring (Manov et al., 2004). Other mechanical antifouling techniques (e.g., brushing and wiping) could  
450 be applied to the membrane-enclosed sensor system, **but it should be noted that these additional measures would consume  
more energy**. Biofouling could be a negligible problem in oligotrophic waters. For instance, we deployed membrane-  
enclosed sensors without copper-mesh screening at a forest headstream for one week and at a reservoir for two weeks in  
June–July 2015, during the same season the antifouling test was being conducted. Following the 2-week deployment at the  
oligotrophic reservoir surface water, the membrane surface did not exhibit any visible sign of biofouling (Fig. S2) and the  
455 pH–*p*CO<sub>2</sub> relationship remained stable, showing no significant deviations as time progressed (Fig. S3).

Stable power supply is another important factor for successful long-term and continuous observation. A membrane-enclosed  
sensor consumes approximately 30 times less power than does a single-bilge pump for equilibrators. The two parallel



automobile batteries generally lasted two weeks, maintaining the power supply to the three membrane-enclosed sensors. Using an analog timer or relay system, the power of the membrane-enclosed sensor could be switched on and off at a pre-set interval. We estimate that the two automobile batteries (2×12 V 100 AH in series) could power one membrane-enclosed sensor for up to 3 or 6 months, assuming 30 min measurement operations at 2 or 4 h intervals. By measuring  $p\text{CO}_2$  at intervals of 2 or 4 h, enough data could be provided for daily average values, accounting for 92 or 85 % of daily  $p\text{CO}_2$  variations, respectively, as compared with high-frequency  $p\text{CO}_2$  measurements at 10 min intervals (Fig. 8). In inland waters, with low risk of biofouling, the membrane+Cu sensor could withstand an extended monitoring time up to several months, if the temporal resolution were set at hourly scales, considering the trade-off between the time resolution and the increasing power demand.

## 5 Conclusions

In the laboratory tests and field comparisons at sites encompassing headwater stream, lacustrine, riverine, and estuarine waters with a wide range of  $p\text{CO}_2$ , the  $p\text{CO}_2$  measurements of the three tested equilibration systems agreed well with each other and with the manual headspace equilibration measurements. Both the discrete measurements at 26 sites and the underway measurements along the tidal river reach demonstrated the rapid and accurate responses of the two equilibrator systems to large spatial variations in  $p\text{CO}_2$ . These results suggest that both equilibrators can perform well during short underway measurements of  $p\text{CO}_2$  in isolation, or in combination with cavity-enhanced spectrometric measurements of  $\delta^{13}\text{C}$  in  $\text{CO}_2$  and  $\text{CH}_4$ . However, further tests are required to determine how long the marbles and the nozzle could remain unaffected by biofouling or clogging during continuous deployments over several hours to days. To address potential clogging and blockage problems of the equilibrators, spare sets of the equilibrator chamber should be prepared during underway measurements. An automated switching between replicate equilibrator chambers at pre-fixed intervals could help to extend the monitoring duration. Although technical challenges, such as power supply and the limited capacity of the desiccant, prevented our equilibrator systems from performing properly during long-term deployment over several days, future studies could explore other types of  $\text{CO}_2$  sensors that consumed less power and were more moisture resistant.

The membrane-enclosed sensor exhibited longer response times compared with those of the equilibrators, especially at slow water flow, which is a disadvantage for observing rapid and/or large  $p\text{CO}_2$  variations. Nevertheless, this sensor captured the spatial variations of  $p\text{CO}_2$  reasonably well within its upper detection limit during the underway measurements along the highly urbanized river reach. This result demonstrates the applicability of the membrane-enclosed sensor for underway  $p\text{CO}_2$  measurements, particularly in inland water systems where the spatial variability of  $p\text{CO}_2$  is relatively small or gradual. The copper-mesh screening was found efficient for reducing the inaccuracy of the  $p\text{CO}_2$  measurements, attributed to the biofouling on the membrane surface, which results from extended deployment in eutrophic water. We suggest that the membrane-enclosed sensor would be suitable for long-term continuous measurements if the sensor had a proper detection range and could be protected by a biofouling-resistant covering.

490 Although studies on inland water  $p\text{CO}_2$  are advancing toward fine-resolution and broad-extent observation, no single approach was able to unveil fully the high spatiotemporal variability encountered in various inland water systems. As the multidisciplinary approach of macrosystems ecology calls for coordinated multiple approaches, in view of the spatiotemporal variability in complex systems (Levy et al., 2014), the results shown here indicate the limitations of the individual monitoring methods. Furthermore, our results suggest that a three-pronged approach should be established to studies on  $p\text{CO}_2$  in river systems with strong human influence, namely, coordinated monitoring, involving repeated **discrete** samplings at multiple sites, long-term monitoring in a few selected sites, and continuous underway measurements along river reaches that have highly variable levels of  $p\text{CO}_2$ . To better constrain both the natural and the anthropogenic factors that determine spatiotemporal dynamics of  $\text{CO}_2$  in diverse inland water systems, equilibration systems need to resolve the high temporal and spatial variability of  $p\text{CO}_2$ . Although the accuracy of the tested equilibration systems has been validated by our tests and other studies, their applicability to long-term deployment in difficult field conditions, such as limited power supply and biofouling, still requires further rigorous tests.

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### References

- 510 Abril, G., Richard, S., and Guérin, F.: In situ measurements of dissolved gases ( $\text{CO}_2$  and  $\text{CH}_4$ ) in a wide range of concentrations in a tropical reservoir using an equilibrator, *Sci. Total Environ.*, 354, 246–251, 2006. Abril, G., Martinez, J.-M., Artigas, L. F., Moreira-Turcq, P., Benedetti, M. F., Vidal, L., Meziane, T., Kim, J.-H., Bernardes, M. C., Savoye, N., Deborde, J., Souza, E. L., Alberic, P., Landim de Souza, M. F., and Roland, F.: Amazon River carbon dioxide outgassing fueled by wetlands, *Nature*, 505, 395–398, 2014.
- 515 Abril, G., Bouillon, S., Darchambeau, F., Teodoru, C. R., Marwick, T. R., Tamooh, F., Ochieng Omengo, F., Geeraert, N., Deirmendjian, L., Polsemaere, P., and Borges, A. V.: Technical Note: Large overestimation of  $p\text{CO}_2$  calculated from pH and alkalinity in acidic, organic-rich freshwaters, *Biogeosciences*, 12, 67–78, 2015. Bastviken, D., Sundgren, I., Natchimuthu, S., Reyier, H., and Gålfalk, M.: Technical Note: Cost-efficient approaches to measure carbon dioxide

- (CO<sub>2</sub>) fluxes and concentrations in terrestrial and aquatic environments using mini loggers, *Biogeosciences*, 12, 3849–3859, 2015.
- 520 Bakker D. C. E., De Baar H. J. W. and de Wilde H. P. J. Dissolved carbon dioxide in Dutch coastal waters. *Mar. Chem.*, 55, 247–263, 1996.
- Battin, T. J., Luysaert, S., Kaplan, L. A., Aufdenkampe, A. K., Richter, A., and Tranvik, L. J.: The boundless carbon cycle, *Nature Geosci.*, 2, 598–600, 2009.
- 525 Bianchi, T. S., Garcia-Tigreros, F., Yvon-Lewis, S. A., Shields, M., Mills, H. J., Butman, D., Osburn, C., Raymond, P., Shank, G. C., DiMarco, S. F., Walker, N., Reese, B. K., Mullins-Perry, R. Quigg, A., Aiken, G. R., and Grossman, E. L.: Enhanced transfer of terrestrially derived carbon to the atmosphere in a flooding event, *Geophys. Res. Lett.*, 40, 116–122, 2013.
- Borges, A. V., Darchambeau, F., Teodoru, C. R., Marwick, T. R., Tamooch, F., Geeraert, N., Omengo, F. O., Guerin, F., 530 Lambert, T., Morana, C., Okuku, E., and Bouillon, S.: Globally significant greenhouse-gas emissions from African inland waters, *Nature Geosci.*, 8, 637–642, 2015.
- Butman, D. and Raymond, P.A.: Significant efflux of carbon dioxide from streams and rivers in the United States, *Nature Geosci.*, 4, 839–842, 2011.
- Cleveland, W. S., and Devlin, S. J.: Locally weighted regression: An approach to regression analysis by local fitting, *J. Amer. 535 Statist. Assoc.*, 83, 596–610, 1988.
- Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., Duarte, C. M., Kortelainen, P., Downing, J. A., Middelburg, J. J., and Melack, J.: Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget, *Ecosystems*, 10, 172–185, 2007.
- Crawford, J. T., Striegl, R. G., Wickland, K. P., Dornblaser, M. M., and Stanley, E. H.: Emissions of carbon dioxide and 540 methane from a headwater stream network of interior Alaska, *J. Geophys. Res. Biogeosci.*, 118, 482–494, 2013.
- Crawford, J. T., Loken, L. C., Casson, N. J., Smith, C., Stone, A. G., and Winslow, L. A.: High-speed limnology: Using advanced sensors to investigate spatial variability in biogeochemistry and hydrology, *Environ. Sci. Technol.*, 49, 442–450, 2015.
- Dawson, J. J. C., Bakewell, C., and Billett, M. F.: Is in-stream processing an important control on spatial changes in carbon fluxes in headwater catchments?, *Sci. Total Environ.*, 265, 153–167, 2001.
- 545 Deacon, E. L.: Gas transfer to and across an air-water interface, *Tellus*, 29, 363–374, 1977.
- Delauney, L., Compère, C., and Lehaitre, M.: Biofouling protection for marine environmental sensors, *Ocean Sci.*, 6, 503–511, 2010.
- Dickson, A. G., Sabine, C. L., and Christian, J. R. (Eds.): Guide to best practices for ocean CO<sub>2</sub> measurements, PICES Special Publication 3, Carbon Dioxide Information Analysis Center, Oak Ridge, USA, 2007.
- 550 Feely, R. A., Wanninkhof, R., Milburn, H. B., Cosca, C. E., Stapp, M., and Murphy, P.: A new automated underway system for making high precision *p*CO<sub>2</sub> measurements onboard research ships, *Analytica Chimica Acta*, 377, 185–191, 1998.

- Frankignoulle, M., Abril, G., Borges, A., Bourge, I., Canon, C., Delille, B., Libert, E., and Théate, J.-M.: Carbon dioxide emission from European estuaries. *Science*, 282: 434–436, 1998.
- 555 Frankignoulle, M., Borges, A., and Biondo, R.: A new design of equilibrator to monitor carbon dioxide in highly dynamic and turbid environments, *Water Res.*, 35, 1344–1347, 2001.
- Friedrichs, G., Bock, J., Temps, F., Fietzek, P., Körtzinger, A., and Wallace, D. W. R.: Toward continuous monitoring of seawater  $^{13}\text{CO}_2/^{12}\text{CO}_2$  isotope ratio and  $p\text{CO}_2$ : Performance of cavity ringdown spectroscopy and gas matrix effects, *Limnol. Oceanogr. Methods*, 8, 539–551, 2010.
- 560 Gonzalez-Valencia, R., Magana-Rodriguez, F., Gerardo-Nieto, O., Sepulveda-Jauregui, A., Martinez-Cruz, K., Walter Anthony, K., Baer, D., and Thalasso, F.: In situ measurement of dissolved methane and carbon dioxide in freshwater ecosystems by off-axis integrated cavity output spectroscopy, *Environ. Sci. Technol.*, 48, 11421–11428, 2014.
- Griffith, D. R., and Raymond, P. A.: Multiple-source heterotrophy fueled by aged organic carbon in an urbanized estuary, *Mar. Chem.*, 124, 14–22, 2011.
- 565 Hales, B., Chipman, D., and Takahashi, T.: High-frequency measurement of partial pressure and total concentration of carbon dioxide in seawater using microporous hydrophobic membrane contactors, *Limnol. Oceanogr. Methods*, 2, 356–364, 2004.
- Hope, D., Dawson, J. J. C., Cresser, M. S., and Billett, M. F.: A method for measuring free  $\text{CO}_2$  in upland streamwater using headspace analysis, *J. Hydrol.*, 166, 1–14, 1995.
- Hudson, F.: Sample preparation and calculations for dissolved gas analysis in water samples using GC headspace equilibration technique, RSKSOP-175, Revision No. 2, U.S. Environmental Protection Agency, USA, 2004.
- 570 Huotari, J., Ojala, A., Peltomaa, E., Nordbo, A., Launiainen, S., Pumpanen, J., Rasilo, T., Hari, P., and Vesala, T.: Long-term direct  $\text{CO}_2$  flux measurements over a boreal lake: Five years of eddy covariance data, *Geophys. Res. Lett.*, 38, L18401, 2011.
- 575 Huotari, J., Haapanala, S., Pumpanen, J., Vesala, T., and Ojala, A.: Efficient gas exchange between a boreal river and the atmosphere, *Geophys. Res. Lett.*, 40, 5683–5686, 2013.
- Joesoef, A., Huang, W. J., Gao, Y., and Cai, W. J.: Air–water fluxes and sources of carbon dioxide in the Delaware Estuary: spatial and seasonal variability, *Biogeosciences*, 12, 6085–6101, 2015.
- Johnson, J. E.: Evaluation of a seawater equilibrator for shipboard analysis of dissolved oceanic trace gases, *Anal. Chim. Acta.*, 395, 119–132, 1999.
- 580 Johnson, M. S., Billett, M. F., Dinsmore, K. J., Wallin, M., Dyson, K. E., and Jassal, R. S.: Direct and continuous measurement of dissolved carbon dioxide in freshwater aquatic systems – method and applications, *Ecohydrology*, 3, 68–78, 2010.
- Keeling, C. D., Rakestraw, N. W., and Waterman, L. S.: Carbon dioxide in surface waters of the Pacific Ocean: 1. Measurements of the distribution, *J. Geophys. Res.*, 70, 6087–6097, 1965.
- 585 Kling, G., Kipphut, G., and Miller, M.: The flux of  $\text{CO}_2$  and  $\text{CH}_4$  from lakes and rivers in arctic Alaska, *Hydrobiologia*, 1992.

- Lauerwald, R., Hartmann, J., Moosdorf, N., Kempe, S., and Raymond, P. A.: What controls the spatial patterns of the riverine carbonate system? – A case study for North America, *Chem. Geol.*, 337-338, 114–127, 2013.
- Leith, F. I., Dinsmore, K. J., Wallin, M. B., Billett, M. F., Heal, K. V., Laudon, H., Öquist, M. G., and Bishop, K.: Carbon dioxide transport across the hillslope–riparian–stream continuum in a boreal headwater catchment, *Biogeosciences*, 12, 1881–1892, 2015.
- 590 Levy, O., Ball, B. A., Bond-Lamberty, B., Cheruvilil, K. S., Finley, A. O., Lottig, N. R., Punyasena, S. W., Xiao, J., Zhou, J., Buckley, L. B., Filstrup, C. T., Keitt, T. H., Kellner, J. R., Knapp, A. K., Richardson, A. D., Tcheng, D., Toomey, M., Vargas, R., Voordeckers, J. W., Wagner, T., and Williams, J. W.: Approaches to advance scientific understanding of macrosystems ecology, *Front. Ecol. Environ.*, 12, 15–23, 2014.
- 595 Lewis, E., Wallace, D., and Allison, L. J.: Program developed for CO<sub>2</sub> system calculations, Carbon Dioxide Information Analysis Center, Lockheed Martin Energy Research Corporation for the US Department of Energy: Tennessee, USA, 1998.
- Li, S., Lu, X. X., and Bush, R. T.: CO<sub>2</sub> partial pressure and CO<sub>2</sub> emission in the Lower Mekong River, *J. Hydrol.*, 504, 40–56, 2013.
- 600 Liss, P. S., and Slater, P. G.: Flux of gases across the air-sea interface, *Nature*, 247, 181–184, 1974.
- Lorke, A., Bodmer, P., Noss, C., Alshboul, Z., Koschorreck, M., Somlai-Haase, C., Bastviken, D., Flury, S., McGinnis, D. F., Maeck, A., Müller, D., and Premke, K.: Technical Note: Drifting versus anchored flux chambers for measuring greenhouse gas emissions from running waters, *Biogeosciences*, 12, 7013–7024, 2015.
- Maher, D. T., Santos, I. R., Leuven, J. R. F. W., Oakes, J. M., Erler, D. V., Carvalho, M. C., and Eyre, B. D.: Novel use of cavity ring-down spectrometry to investigate aquatic carbon cycling from microbial to ecosystem scales. *Environ. Sci. Technol.*, 47, 12938–12945, 2013.
- 605 Manov, D. V., Chang, G. C., and Dickey, T. D.: Methods for reducing biofouling of moored optical sensors, *J. Atmos. Oceanic Tech.*, 21, 958–968, 2004.
- Nimick, D. A., Gammons, C. H., and Parker, S. R.: Diel biogeochemical processes and their effect on the aqueous chemistry of streams: A review, *Chem. Geol.*, 283, 3–17, 2011.
- 610 Park, P. K., Gordon, L. I., Hager, S. W., and Cissell, M. C.: Carbon dioxide partial pressure in the Columbia River, *Science*, 166, 867–868, 1969.
- Peter, H., Singer, G. A., Preiler, C., Chiffard, P., Steniczka, G., and Battin, T. J.: Scales and drivers of temporal *p*CO<sub>2</sub> dynamics in an alpine stream, *J. Geophys. Res. Biogeosci.*, 119, 1078–1091, 2014.
- 615 Pfeil, B., Olsen, A., Bakker, D. C. E., Hankin, S., Koyuk, H., Kozyr, A., Malczyk, J., Manke, A., Metzl, N., Sabine, C. L., Akl, J., Alin, S. R., Bates, N., Bellerby, R. G. J., Borges, A., Boutin, J., Brown, P. J., Cai, W. J., Chavez, F. P., Chen, A., Cosca, C., Fassbender, A. J., Feely, R. A., González-Dávila, M., Goyet, C., Hales, B., Hardman-Mountford, N., Heinze, C., Hood, M., Hoppema, M., Hunt, C. W., Hydes, D., Ishii, M., Johannessen, T., Jones, S. D., Key, R. M., Körtzinger, A., Landschützer, P., Lauvset, S. K., Lefèvre, N., Lenton, A., Lourantou, A., Merlivat, L., Midorikawa, T., Mintrop, L.,

- 620 Miyazaki, C., Murata, A., Nakadate, A., Nakano, Y., Nakaoka, S., Nojiri, Y., Omar, A. M., Padin, X. A., Park, G. H., Paterson, K., Perez, F. F., Pierrot, D., Poisson, A., Ríos, A. F., Santana-Casiano, J. M., Salisbury, J., Sarma, V. V. S. S., Schlitzer, R., Schneider, B., Schuster, U., Sieger, R., Skjelvan, I., Steinhoff, T., Suzuki, T., Takahashi, T., Tedesco, K., Telszewski, M., Thomas, H., Tilbrook, B., Tjiputra, J., Vandemark, D., Veness, T., Wanninkhof, R., Watson, A. J., Weiss, R., Wong, C. S., and Yoshikawa-Inoue, H.: A uniform, quality controlled Surface Ocean CO<sub>2</sub> Atlas (SOCAT),  
625 Earth Syst. Sci. Data, 5, 125–143, 2013.
- Pierrot, D., Neill, C., Sullivan, K., Castle, R., Wanninkhof, R., Lüger, H., Johannessen, T., Olsen, A., Feely, R. A., and Cosca, C. E.: Recommendations for autonomous underway *p*CO<sub>2</sub> measuring systems and data-reduction routines, Deep-sea Res. PT II, 56, 512–522, 2009.
- Podgrajsek, E., Sahlée, E., Bastviken, D., Holst, J., Lindroth, A., Tranvik, L., and Rutgersson, A.: Comparison of floating  
630 chamber and eddy covariance measurements of lake greenhouse gas fluxes, Biogeosciences, 11, 4225–4233, 2014.
- Polsenaere, P., Deborde, J., Detandt, G., Vidal, L. O., Pérez, M. A. P., Marieu, V., and Abril, G.: Thermal enhancement of gas transfer velocity of CO<sub>2</sub> in an Amazon floodplain lake revealed by eddy covariance measurements, Geophys. Res. Lett., 40, 1734–1740, 2013.
- R Development Core Team: R: A language and environment for statistical computing; R Foundation for Statistical  
635 Computing: Vienna, Austria, 2011, available at: <http://www.r-project.org>.
- Raymond, P. A., and Cole, J. J.: Gas exchange in rivers and estuaries: Choosing a gas transfer velocity, Estuaries, 24, 312–317, 2001.
- Raymond, P. A., and Hopkinson, C. S.: Ecosystem modulation of dissolved carbon age in a temperate marsh-dominated estuary, Ecosystems, 6, 694–705, 2003.
- 640 Raymond, P. A., Zappa, C. J., Butman, D., Bott, T. L., Potter, J., Mulholland, P., Laursen, A. E., McDowell, W. H., and Newbold, D.: Scaling the gas transfer velocity and hydraulic geometry in streams and small rivers, Limnol. Oceanogr. Fluids Environ., 2, 41–53, 2012.
- Raymond, P. A., Hartmann, J., Lauerwald, R., Sobek, S., McDonald, C., Hoover, M., Butman, D., Striegl, R., Mayorga, E., Humborg, C., Kortelainen, P., Durr, H., Meybeck, M., Ciais, P., and Guth, P.: Global carbon dioxide emissions from  
645 inland waters, Nature, 503, 355–359, 2013.
- Santos, I. R., Maher, D. T., and Eyre, B. D.: Coupling automated radon and carbon dioxide measurements in coastal waters, Environ. Sci. Technol., 46, 7685–7691, 2012.
- Smethie, W. M., Takahashi, T., Chipman, D. W., and Ledwell, J. R.: Gas exchange and CO<sub>2</sub> flux in the tropical Atlantic Ocean determined from <sup>222</sup>Rn and *p*CO<sub>2</sub> measurements, J. Geophys. Res. Oceans, 90, 7005–7022, 1985.
- Swinerton, J. W., Cheek, C. H., and Linnenbom, V. J.: Determination of dissolved gases in aqueous solutions by gas  
650 chromatography. Anal. Chem., 34, 483–485, 1962.
- Takahashi, T.: Carbon dioxide in the atmosphere and in Atlantic Ocean water, J. Geophys. Res., 66, 477–494, 1961.
- Teodoru, C., Prairie, Y., and del Giorgio, P.: Spatial heterogeneity of surface CO<sub>2</sub> fluxes in a newly created Eastmain-1 reservoir in northern Quebec, Canada, Ecosystems, 14, 28–46, 2011.

- Teodoru, C. R., Nyoni, F. C., Borges, A. V., Darchambeau, F., Nyambe, I., and Bouillon, S.: Dynamics of greenhouse gases  
655 (CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O) along the Zambezi River and major tributaries, and their importance in the riverine carbon budget,  
Biogeosciences, 12, 2431–2453, 2015.
- Troxler, T. G., Barr, J. G., Fuentes, J. D., Engel, V., Anderson, G., Sanchez, C., Lagomasino, D., Price, R., and Davis, S. E.:  
Component-specific dynamics of riverine mangrove CO<sub>2</sub> efflux in the Florida Coastal Everglades, Agr. For. Meteorol.,  
213, 273–282, 2015.
- 660 Vachon, D., Prairie, Y. T., and Cole, J. J.: The relationship between near-surface turbulence and gas transfer velocity in  
freshwater systems and its implications for floating chamber measurements of gas exchange, Limnol. Oceanogr., 55,  
1723–1732, 2010.
- Valsala, V., and Maksyutov, S.: Simulation and assimilation of global ocean pCO<sub>2</sub> and air–sea CO<sub>2</sub> fluxes using ship  
observations of surface ocean pCO<sub>2</sub> in a simplified biogeochemical offline model, Tellus B, 62, 16640, 2010.
- 665 Wanninkhof, R.: Relationship between wind speed and gas exchange over the ocean, J. Geophys. Res. Oceans, 97, 7373–  
7382, 1992.
- Wanninkhof, R., Asher, W. E., Ho, D. T., Sweeney, C., and McGillis, W. R.: Advances in quantifying air-sea gas exchange  
and environmental forcing, Ann. Rev. Mar. Sci., 1, 213–244, 2009.
- Webb, J. R., Maher, D. T., and Santos, I. R.: Automated, in situ measurements of dissolved CO<sub>2</sub>, CH<sub>4</sub>, and δ<sup>13</sup>C values using  
670 cavity enhanced laser absorption spectrometry: Comparing response times of air-water equilibrators, Limnol. Oceanogr.  
Methods, 14, 323–337, 2016.
- YSI Incorporated: Using a copper-alloy based system for effective biofouling deterrence, A583 0410, YSI Incorporated,  
Yellow Springs, USA, 2010.
- Zhai, W., Dai, M., Cai, W.-J., Wang, Y., and Wang, Z.: High partial pressure of CO<sub>2</sub> and its maintaining mechanism in a  
675 subtropical estuary: the Pearl River estuary, China, Mar. Chem., 93, 21–32, 2005.

## Tables

**Table 1.** Summary of manual headspace equilibration and three gas equilibration systems

System	Principle	Equilibration method	Equilibration time (min)	References
Manual equilibration	Manual; active	Gas equilibration in the headspace over the water sample collected in a bottle or syringe by manual shaking	< 2	Kling et al., 1992; Hope et al., 1995
Spray-type equilibrator	Automatic; active	Enhanced gas equilibration by spraying gas-containing water droplets	1–12	Freely et al., 1998; Webb et al., 2016
Marble-type equilibrator	Automatic; active	Enhanced gas exchange over the large cumulative surface of marbles	1–13	Frankignoulle et al., 2001; Abril et al., 2006
Membrane-enclosed sensor	Automatic; passive	Diffusion-based “passive” equilibration between the inside and outside of the water-impermeable, gas-permeable membrane	> 10	Johnson et al., 2010



## 680 Figures

**Figure 1.** Schematic diagrams of four equilibration methods: (a) manual headspace equilibration; (b) marble-type equilibrator; (c) spray-type equilibrator; (d) membrane-enclosed sensor. Refer to Table 1 for descriptions of basic operation principles, and Figures S1 and S2 for pictures showing the three gas equilibration systems employed during field tests.

**Figure 2.** Laboratory cross-validation tests of three gas equilibration systems during (a) low-to-high and (b) high-to-low  
685 equilibration.

**Figure 3.** Comparison of  $p\text{CO}_2$  measurements of three gas equilibration systems (spray- and marble-type equilibrators and membrane-enclosed sensor) with the manual headspace equilibration at various inland waters, ranging from forested headwater streams to the estuary of the Han River.

**Figure 4.** Relationship between the response time ( $t_{100}$ ) and  $\Delta p\text{CO}_2$ , as the difference between the initial and the stabilized  
690 final  $p\text{CO}_2$  measurement, for the (a) spray-type equilibrator, (b) marble-type equilibrator, and (c) membrane-enclosed sensor. Note that the X-axis has a log scale. The solid and dashed lines indicate significant and insignificant relationships, respectively.

**Figure 5.** Continuous underway measurements of  $p\text{CO}_2$ , using a spray-type equilibrator, a marble-type equilibrator, and a  
695 membrane-enclosed sensor along the tidal reach of the Han River from 11 am to 3 pm, 11 May 2015. The inflow of urban streams containing high loads of organic matter, inorganic nutrients, and  $\text{CO}_2$  is indicated by brown arrows. The  $p\text{CO}_2$  measurements, using manual headspace equilibration (yellow circle) were performed on-board. Note that the membrane-enclosed sensors did not capture drastic increases in  $p\text{CO}_2$  after midday because of the upper detection limit of the sensors (7,000 or 10,000 ppm).

**Figure 6.** Continuous  $p\text{CO}_2$  measurements at a tidal reach of the Han River, using membrane-enclosed sensors without  
700 (“membrane” sensor) and with copper-mesh screening (“membrane+Cu” sensor), with (a) Original measurements (gray arrows indicate maintenance timing); (b) Relative differences between the log-transformed measurements by the two sensors; (c) The relationship between the daily means of  $p\text{CO}_2$  measurements by the two sensors.

**Figure 7.** (a) The relationship between pH and  $p\text{CO}_2$  during successive four-day monitoring periods following maintenance; (b) the relationship between coefficient of variations (CVs) of daily means of pH and  $p\text{CO}_2$ . Membrane-enclosed sensors  
705 without and with copper-mesh screening are indicated by “membrane” and “membrane+Cu”, respectively. Curves were fitted using LOESS (locally weighted scatterplot smoothing).

**Figure 8.** Temporal resolution effects on  $p\text{CO}_2$  measurements by a membrane-enclosed sensor with a copper-mesh covering. The data obtained from the copper-mesh-wrapped sensor in Figure 7 are presented by modifying temporal resolutions from 10 min to 4 h (a). The bottom panel shows the daily mean, minimum, and maximum  $p\text{CO}_2$  values normalized to the mean of  
710 the four calculations (b).

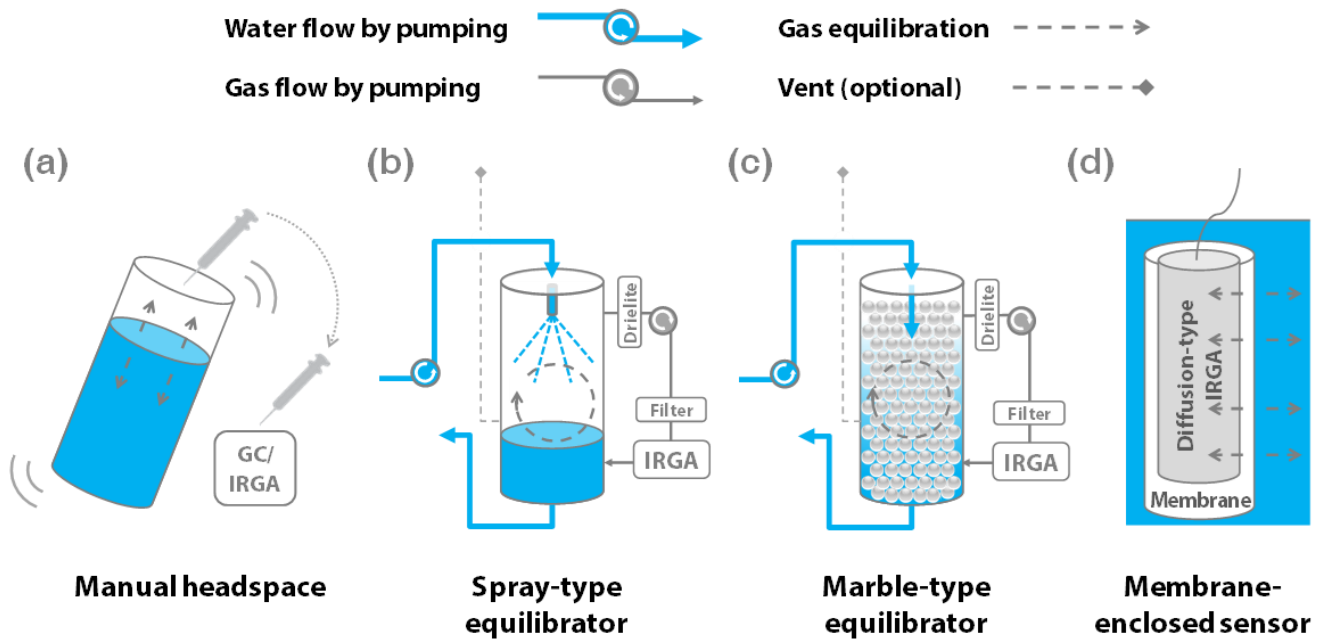
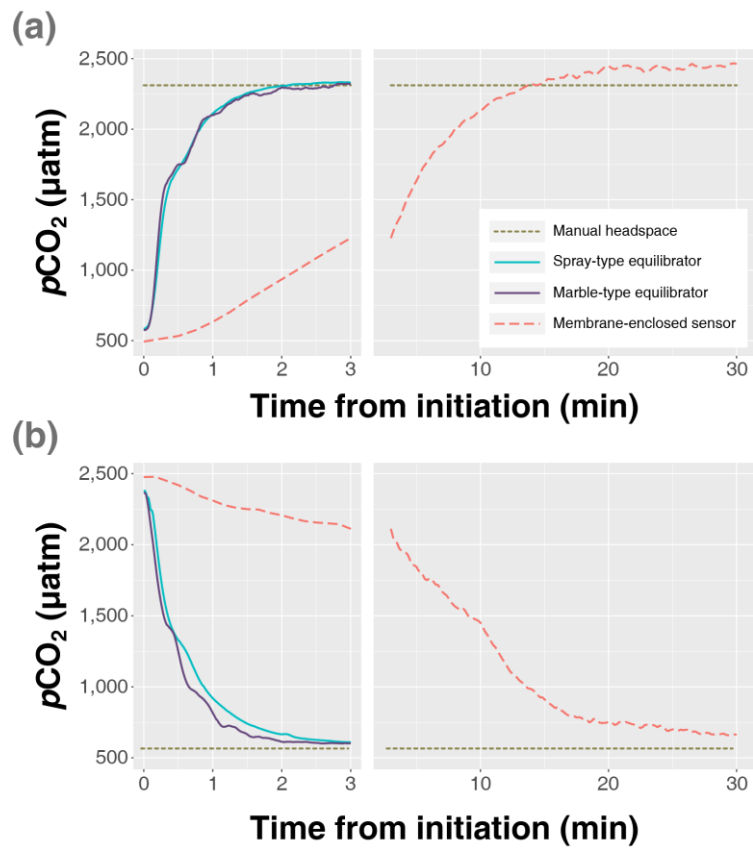


Figure 1.



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Figure 2.

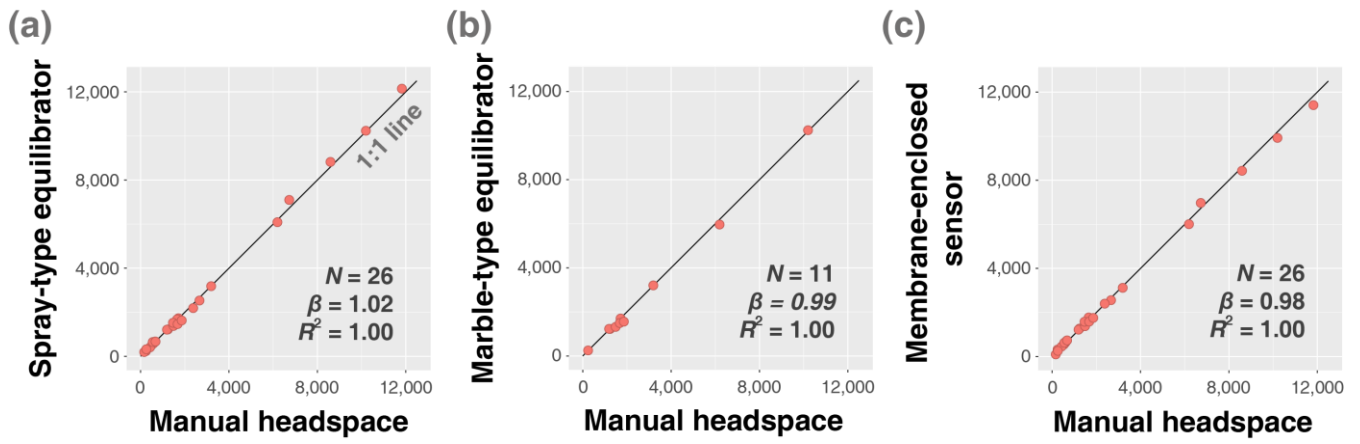


Figure 3.

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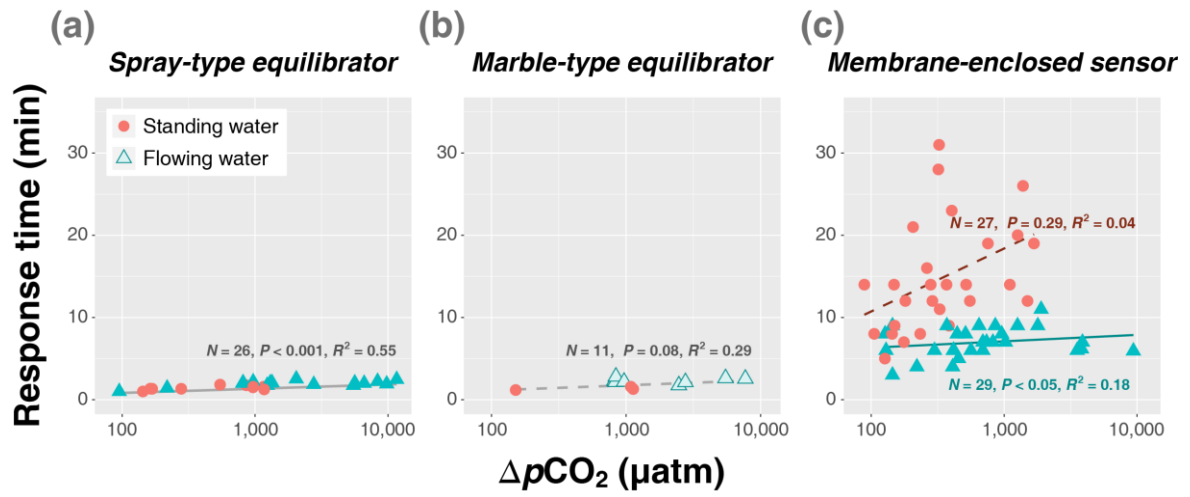
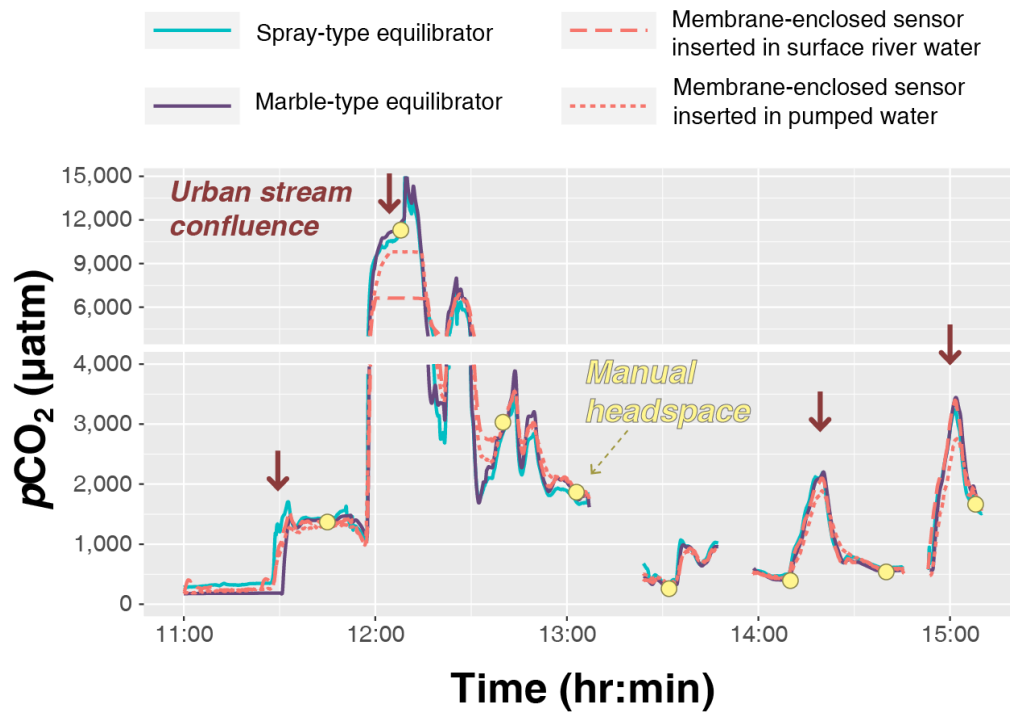


Figure 4.



725 Figure 5.

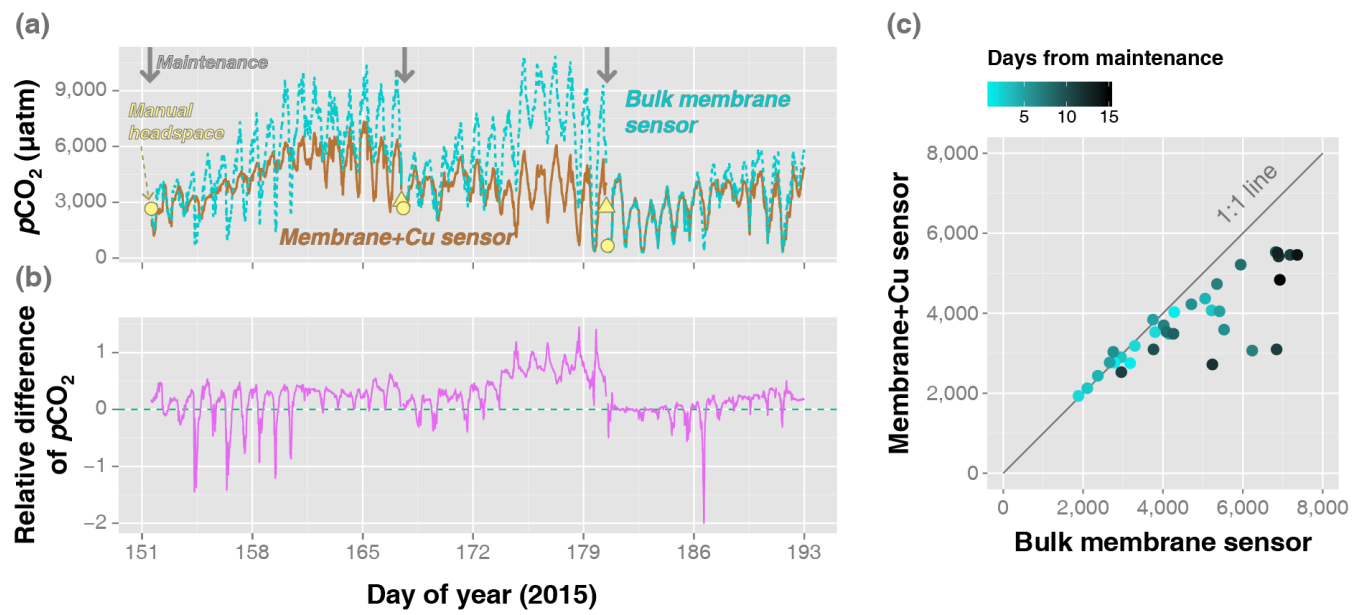
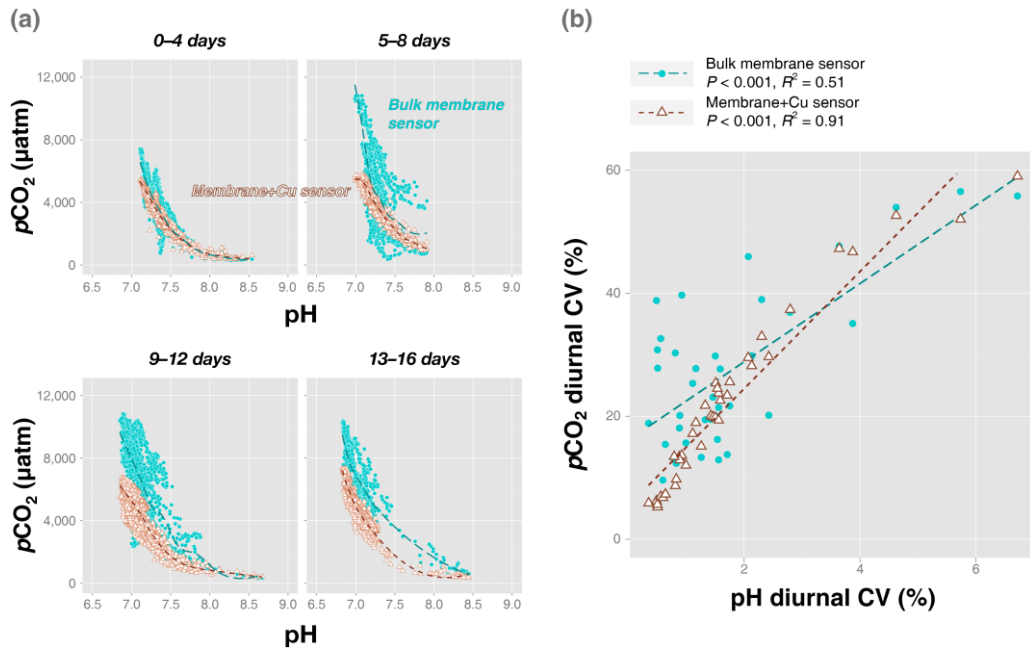


Figure 6.



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Figure 7.



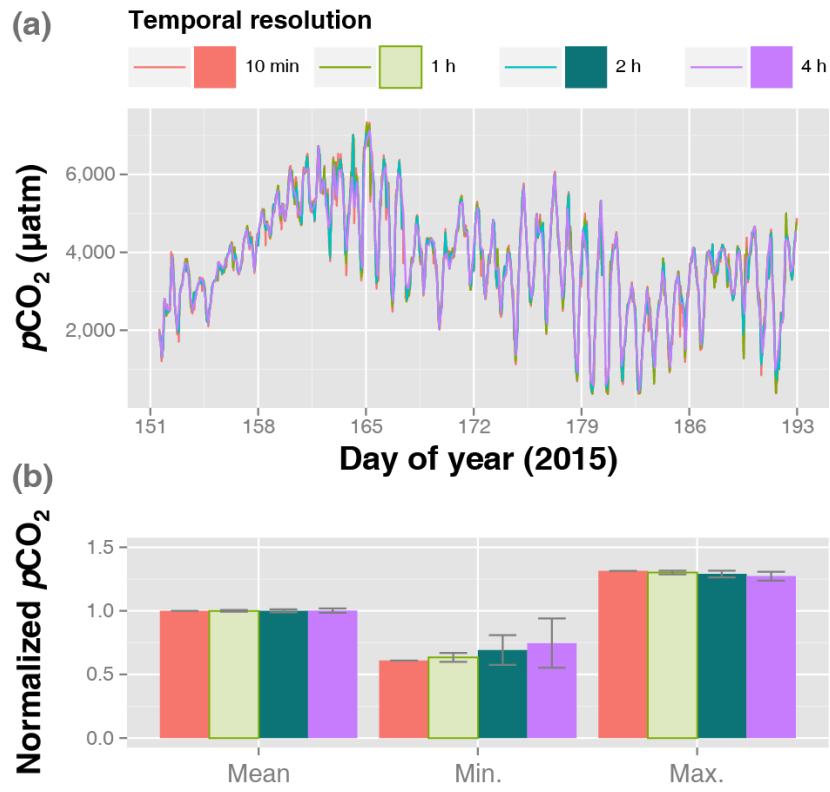


Figure 8.