LIMNOLOGY
and
OCEANOGRAPHY: METHODS

Limnol. Oceanogr.: Methods 12, 2014, 729–741

A new device to follow temporal variations of oxygen demand in deltaic sediments: the LSCE benthic station

Flora Toussaint[1], Christophe Rabouille[1], Cécile Cathalot[1], Bruno Bombled[1], Abdel Abchiche[2], Oualid Aouji[2], Gilles Buchholtz[2], Aurélien Clemençon[2], Nicolas Geyskens[2], Michel Répécaud[3], Ivane Pairaud[4], Romaric Verney[5] and Nadine Tisnérat-Laborde[1]*

[1]Laboratoire des sciences du climat et de L'environnement UMR 8212, CEA-CNRS -UVSQ Av de la Terrasse, 91190 Gif-sur-Yvette, France

[2]Division of the Institut National des Sciences de L'Univers (DT-INSU, CNRS, France), 1 place A. Briand, 92195 Meudon, France

[3]Ifremer, LDCM, F-29280 Plouzané, France

[4]Ifremer, LER PAC, F-83507, La Seyne sur Mer, France

[5]Ifremer, DYNECO PHYSED, F-29280 Plouzané, France

Abstract

A new benthic station equipped with oxygen microelectrodes and environmental sensors was developed by Laboratoire des Sciences du Climat et de L'Environnement (LSCE) and Division Technique of the Institut National des Sciences de L'Univers (DT-INSU) to perform in situ time series monitoring of sediment oxygen demand, linked to the mineralization of organic matter. The time series typically cover periods of 2-3 months, with a base frequency of 1 set of oxygen profiles per day. The profiling head assessed the lateral heterogeneity of the sediment oxygen demand at the beginning of the time series over a 0.8-m long rectangle to discriminate spatial and temporal variability. A continuous recalibration is performed using a moored oxygen optode anchored to the benthic station together with a set of environmental sensors. These sensors (turbidity, temperature, salinity, and oxygen) can trigger a high-frequency profiling mode to investigate the fate of particulate organic matter delivered during floods, resuspension, and deposition events. Deployments of the benthic station were performed in the Rhone River subaqueous delta (Mediterranean Sea). We show that "stable" periods (when neither floods nor storms occur) were characterized by a stable oxygen demand. In the case of resuspension events, an increase of the sediment oxygen demand by a factor of 2-3 with a relaxation time of 1 day was observed, indicating that the new benthic station can adequately capture the impact of resuspension events on the oxygen demand in deltaic sediments.

Estuaries and deltas where riverine particulate matter accumulates are major interfaces between the continents and the ocean and are thus particularly important in the global carbon cycle (Cai 2011; Regnier et al. 2013). Bianchi and Allison (2009) showed that the deposition of organic matter (OM) in deltaic sediment is a critical component of carbon sequestration and exchange within the global ocean. The fate of riverine inputs of OM in coastal/deltaic sediments is poorly constrained: the contribution of mineralization versus burial processes is one of the drivers that determine the balance between CO_2 sources and sinks in coastal seas (Borges 2005; Cai 2011). Furthermore, several studies have shown that estuaries are characterized by high water-to-air CO_2 fluxes (Hedges et al. 1997; Cai 2011), but uncertainties concerning the intensity of these fluxes still remain. It is hence critical to better constrain the fate of OM in these areas.

In estuaries, a large part of the high variability in OM inputs is associated with river flow (Moreira-Turcq et al. 2013), and in particular, with particle delivery during flood events. In the NW Mediterranean Sea, river floods can bring, in only a few days, more than 80% of the total annual particulate inputs to the coastal ocean and deltaic areas (Antonelli et al. 2008), which may change the balance between mineralization and burial. In addition, as a consequence of global climate change, several models have predicted a shift in the frequency and intensity of high-magnitude storms (Leckebusch et al. 2006; Pinto et al. 2007; MerMex Group 2011), which can change the intensity of sec-

*Corresponding author: E-mail: christophe.rabouille@lsce.ipsl.fr

Acknowledgments

Full text appears at the end of the article.

DOI 10.4319/lom.2014.12.729

ondary transport by resuspension. Until now, estimations of benthic O_2 demand in deltaic sediment have been based on discrete measurements of oxygen fluxes at the sediment-water interface during cruises, rarely including flood conditions (Cathalot et al. 2010). Due to the complexity and temporal and spatial variability of these systems, it seems difficult to interpolate between such discrete measurements, leading to serious uncertainties about the current estimates of organic matter recycling in deltaic sediments.

One approach for estimating the benthic mineralization of OM is the use of diffusive oxygen uptake (DOU) rates at the sediment-water interface using oxygen microprofiling (Jorgensen and Revsbech 1985). To follow the oxygen demand in these highly variable deltaic depo-centers, we developed a benthic station able to collect in situ time series of oxygen microprofiles, which contains a 2D microprofiler similar in design to the one developed by Glud et al. (2009). Other benthic platforms designed for time series oxygen flux measurements have relied on the use of benthic chambers on ROVER type vehicles in the deep sea (Smith et al. 1997, Sherman and Smith 2009) or the use of eddy covariance (Berg et al. 2003). Eddy covariance (EC) could represent a good counterpart measurement for long-term monitoring of sediment oxygen uptake. Indeed, EC measurements are noninvasive, rather large scale, and allow total flux measurements in environmental settings where microsensors cannot be applied: cohesive (Berg et al. 2009) and sandy (Berg et al. 2013) sediments, hard bottom substrates (Glud et al. 2010), and coral reefs (Long et al. 2013). However, current deployments of EC found in the literature mostly involve daily timescales, except one set of data that was recently collected at the Venus observatory over a 4-month period (Sanders et al. 2014). The EC technique is indeed poorly adapted to study the dynamics of benthic activity in high variability environments (Holtappels et al. 2013; Attard et al. 2014) as current intensity and direction are critical parameters for this technique.

Our benthic station thus offers a suitable alternative to study transient events affecting benthic mineralization rates (e.g., flood, resuspension) and the associated relaxation processes. This instrument is a combination of the 2D microprofiler and an array of environmental sensors (oxygen, temperature, pressure, turbidity, and salinity) connected to an Aanderaa RCM9 logger, which enables the detection of environmental changes occurring during flood or storm events. These changes can trigger a high-temporal-resolution mode with an increased frequency of profiling in sediment, thus allowing measurements over several months, including extreme events in sensitive coastal areas. Furthermore, the benthic station provides oxygen porewater profiles in addition to diffusive oxygen uptakes, which can be helpful in understanding the biogeochemical dynamics in the sediment by the use of diagenetic models.

The aims of this paper are to 1) present the general concept of this new instrument and each of its components, 2) validate and discuss the technique by showing results from a deployment in the Rhône River subaqueous delta, and 3) assess the spatial variability and temporal evolution of this area of seafloor during and after resuspension events.

Materials and procedures

Frame, composition, and power of the benthic station

The benthic station is an autonomous tripodal frame made of aluminum and stainless steel with dimensions of 1.96 m × 1.90 m × 1.30 m. This frame was designed to minimize the interference between the benthic station and the current near the seabed to keep the erosion-deposition processes undisturbed. The legs were elongated, the frame was opened, and most of the volume occupied by measurement gears was placed at least 50 cm above the seafloor. The benthic station can perform oxygen microprofiles in the sediment along an 88-cm long axis (Fig. 1; Fig. 2). The benthic station frame is protected against corrosion by an aluminum anode. This station is constituted by a control unit developed by the Engineering Division of the Institut National des Sciences de L'Univers (DT-INSU, CNRS, France), a moving rack carrying 1 resistivity electrode, 7 in situ oxygen microsensors and their amplifiers (Unisense) mounted on a wagon. The movements of the oxygen electrodes are operated by 2 motors (Unisense/Faulhaber) along 2 horizontal and vertical axes. The vertical motor is able to move the electrodes over and in the sediment with a precision of 12.5 μm. A horizontal motor can move the wagon horizontally to assess spatial heterogeneity of DOU and avoid the disturbance linked to previous profiles and electrode penetration. Between each profiling, the wagon moves laterally by 12 cm. When it reaches the end of the measurement space, it is shifted by 1 cm and moves in the other direction by 12 cm. With this procedure, the station is able to perform 85 sets of profiles without hitting the same position.

Two pressure-compensated batteries (Sea battery™ Power Module, 24 V and 40 amp hour, manufactured by Deep Sea Power & Light) operate the benthic station for a period of 3 months (maximum autonomy). Power consumption in the benthic station was optimized by turning elements on only when necessary.

Control unit

The control unit developed by the DT-INSU in relation with LSCE contains the electronics and the computer program that link all constituents of the benthic station (Fig. 3).

All measurements are logged in the memory of the benthic station. The benthic station is also connected to the instrumented buoy "Mesurho" managed by IFREMER via a Subconn micro 5-contact cable (MacArtney Inc.). The Mesurho buoy also contains other instruments that track several environmental parameters (waves, weather conditions, current, turbidity, oxygen, pressure, fluorescence, temperature, and salinity). The frequency for data logging is 30 min, and the data transmission by General Packet Radio Service (GPRS) is currently fixed at once every 4 hours, allowing a reduced set of

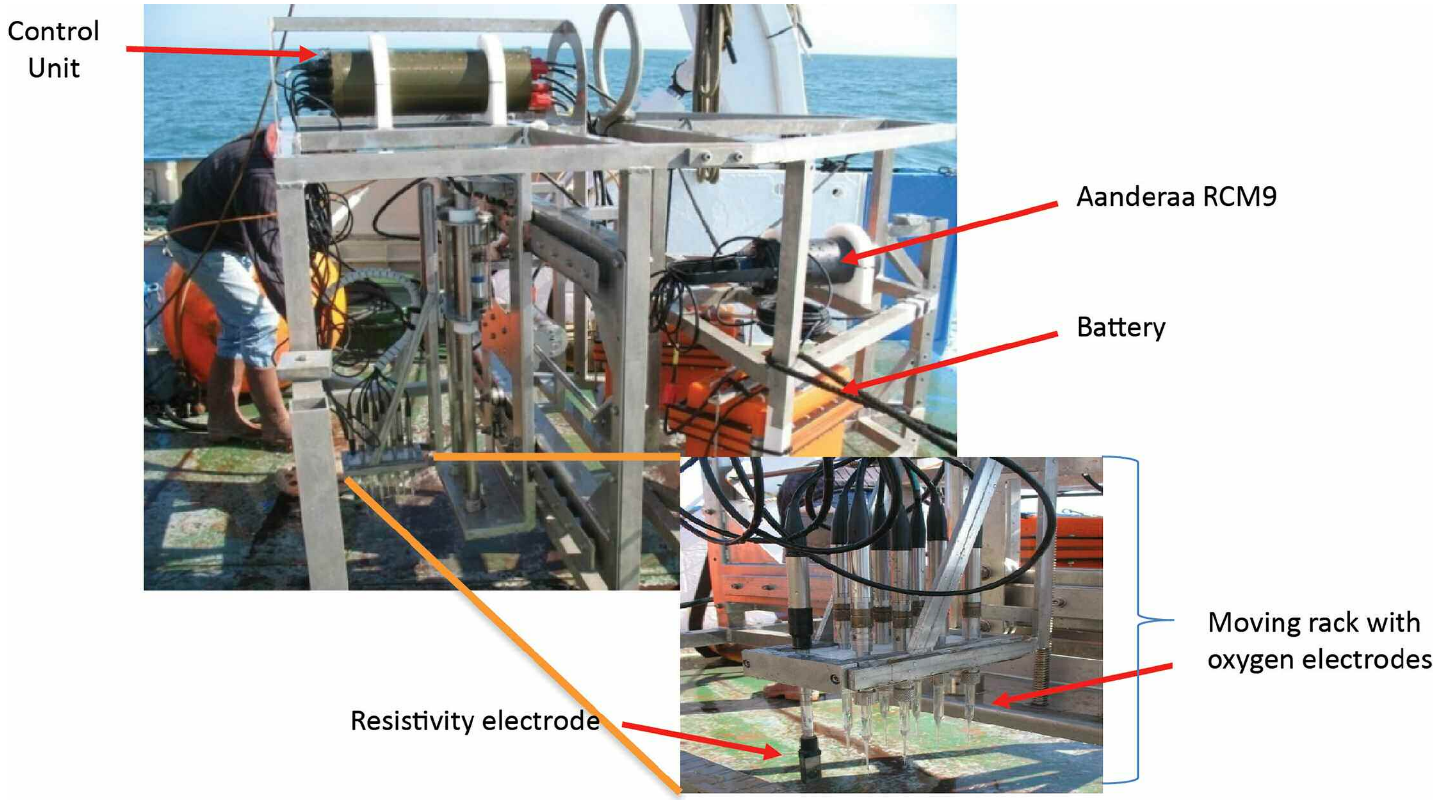

Fig. 1. Picture of benthic station and zoomed view of rack carrying oxygen and resistivity electrodes.

data from the benthic station to be sent to the Coriolis database at IFREMER Brest where it is stored and qualified.

Electrodes (Unisense) resistivity electrode

A resistivity electrode (Unisense), described by Andrews and Bennett (1981), is used to detect the position of the sediment-water interface as previously used in Smith et al. (1997) and Glud et al. (2009). The resistivity electrode is composed of four thin parallel wires buried in a matrix of epoxy, with their thin end in electrical contact with seawater. This electrode is positioned 2 cm ahead of the oxygen microelectrodes. During the initial descent, the actual measurement of the resistivity electrode is compared with the electrode signal in seawater. The sediment-water interface is reached when the difference between the two signals (actual resistivity – seawater resistivity) is larger than a chosen threshold. The downward movement of the profiler is stopped, and the measurement of oxygen microprofiles begins.

Oxygen microelectrodes

When the benthic station is inactive, the seven electrodes are at their highest position and the moving rack is in contact with magnetic switches (Unisense). When not profiling, they are shielded in a mesh cage, which protects them against small physical shocks, which can be potentially damaging. The microelectrodes are Clark microsensors containing a built-in reference and an internal guard cathode (Revsbech 1989). These microsensors have a tip outer diameter of 100 µm, a stirring sensitivity of < 1% and a 90% response time of 10 s, and the current drift is less than 5% per hour. The step resolution of oxygen measurements is 200 µm and the total distance is 4 cm. The total duration of profiling operation is around 1h30mn including sediment-water interface detection, oxygen profiling and upward movement to the reference position. The effective time for an individual profile is 5 mn (around 20 steps from the oxic water to the anoxic zone) and the time for a complete set of 7 profiles is around 30 mn because of different electrode penetrations in the irregular sediment. To calibrate the oxygen microsensor, we used a linear calibration between the bottom water oxygen content measured by the oxygen optode on the RCM9 (Aanderaa optode) at the beginning of each profile and the anoxic zone of the sediment. Classically, the location of the sediment-water interface was assigned as a break in the oxygen concentration gradient. The observed change of slope is due to the decreased diffusion coefficient in the sediment compared with the diffusive boundary layer (Jorgensen and Revsbech 1985; Revsbech 1989).

To calculate the diffusive oxygen uptake, we used Fick's first law of diffusion

$$DOU = -\Phi D_s \left.\frac{dO_2}{dz}\right|_{z=0}$$

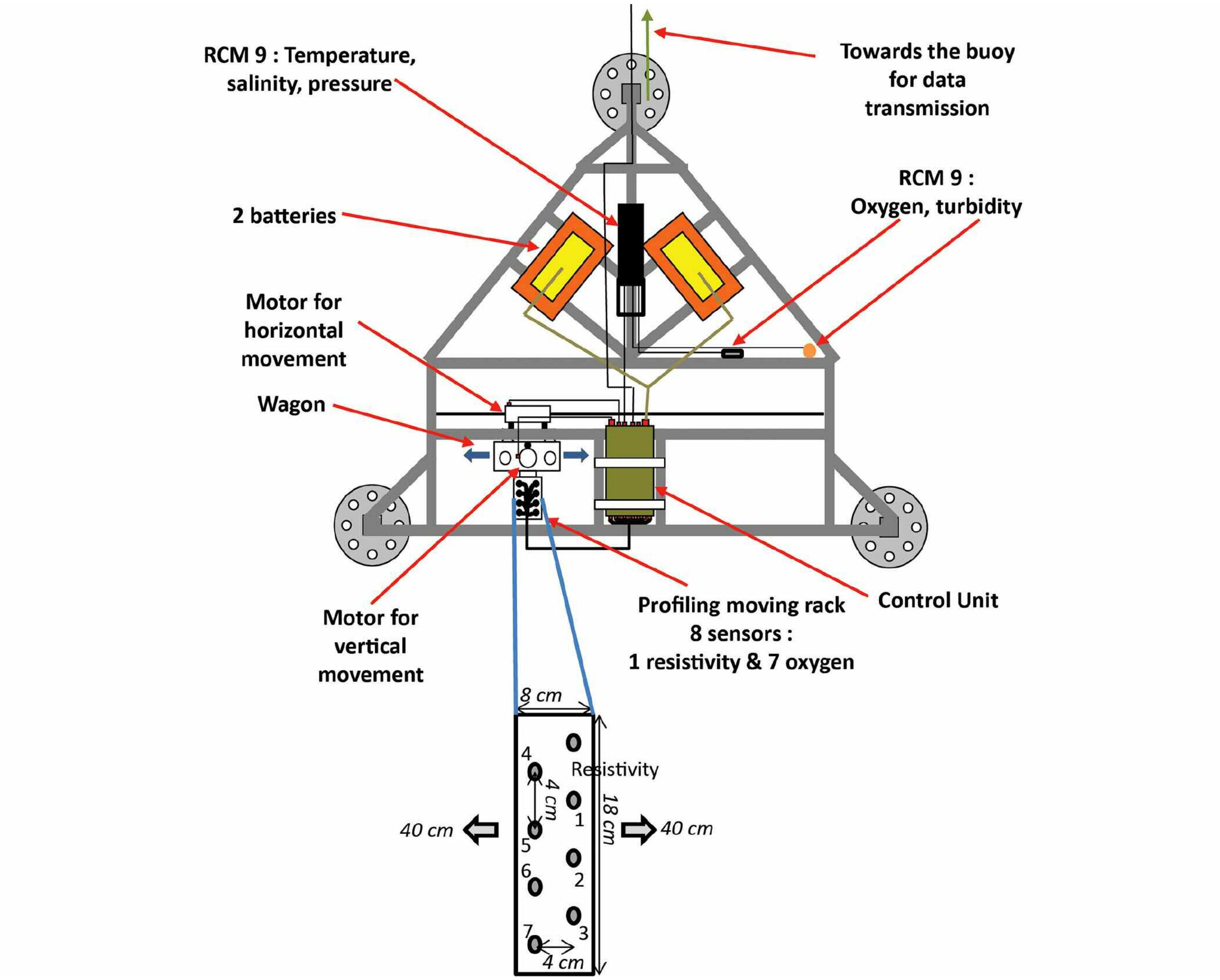

Fig. 2. Design of benthic station and zoomed view of profiling moving rack that carries 7 oxygen and 1 resistivity electrodes.

where Φ is the porosity at the sediment-water interface, D_s is the O_2 diffusion coefficient and $\left.\frac{dO_2}{dz}\right|_{z=0}$ is the oxygen gradient just below the sediment-water interface (400 µm). Ds was estimated as $Ds = D_0^{O2}/(1 + 3[1 - \Phi])$ (Iversen and Jorgensen 1993). D_0^{O2} is the molecular diffusion coefficient of O_2 ($cm^2\ s^{-1}$) at in situ temperature and salinity (Broecker and Peng 1974).

The oxygen penetration depth was determined from the O_2 profile and corresponds to the depth where the oxygen concentration was less than 1 µmol l^{-1}.

After deployment, each profile is analyzed to determine its validity, and electrode readings are discarded if they present the following features: a deformed oxygen profile at the sediment-water interface (generally linked with bioturbation) or an inability to locate the interface because the profile was entirely measured in water or in the sediment.

Aanderaa RCM9 sensors

The Aanderaa RCM9 LW is positioned at 1 m above the sediment on the benthic station frame. It is equipped with four probes to monitor variations in environmental parameters: turbidity, oxygen, salinity, and temperature. The frequency of data acquisition is one set of readings every 20 min. The oxygen optode (ref. 3830) has a range from 0–500 µM and an accuracy of <8 µM or 5%.

At the start of the deployment, the oxygen probe is calibrated against the bottom water oxygen content sampled near the benthic station with divers and estimated by Winkler titration (Grasshoff et al. 1983). Turbidity sensor 3712 measures scattered light with a range of 0 to 500 NTU and an accuracy of 2%. Calibration of the turbidity sensor is performed using the concentration of suspended matter in bottom water. To do so, bottom water was sampled using a Niskin bottle and filtered with GF-F filters, and the turbidity content was deter-

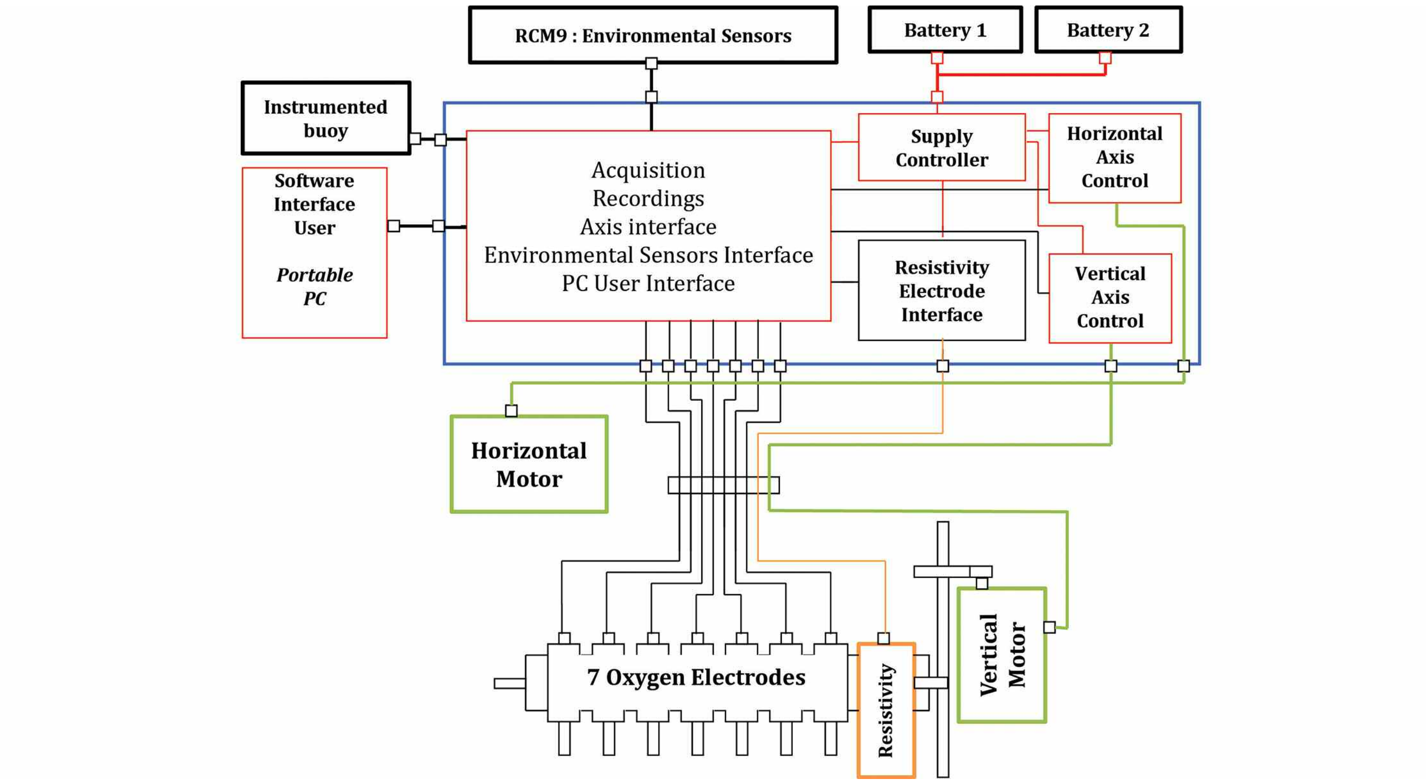

Fig. 3. Functional diagram of benthic station. The blue rectangle corresponds to the control unit.

mined by weighing the dry suspended material retained on the filters.

Functioning of benthic station

At the start of the deployment, an initial set of 56 oxygen microprofiles is completed throughout the whole measurement area, i.e., along the entire horizontal axis at 8 different positions. These 56 profiles allow the estimation of the initial DOU spatial variability. In low turbidity conditions, defined as a turbidity level below 30 NTU (see hereafter), the benthic station performs one profiling per day. During flood or storm events, when the turbidity level exceeds this specific threshold, the station is triggered to high-frequency mode. The threshold was determined after several months of studies in this area and fixed to 30 NTU (Fig. 4). The high-frequency mode consists in an increase of the profiling frequency after the triggering signal has been recorded three times, i.e., 1 h: profiles are performed immediately and with a chosen waiting time after measurements equal to 1 h, 2 h, 4 h, and 8 h, before returning to the low-frequency mode (with 1 profile per day).

Assessment

Study site

The LSCE benthic station was deployed in the marine part of the Rhone River delta (Lansard et al. 2009). With a catchment area of 97,800 km^2 and a mean water discharge of 1 700 m^3 s^{-1}, the Rhône River is the main source of freshwater, sediments, and OM to the Gulf of Lions (Sempéré et al. 2000; Pont et al. 2002; MerMex Group 2011). The flood threshold is established at 3000 m^3 s^{-1} (Pont et al. 2002), and the Rhône River is characterized by rapid floods mostly occurring during autumn and winter. The annual POC delivery is 19.2 ± 6 10^4 tC y^{-1} (Sempéré et al. 2000). Up to 80% of the particle inputs occur during flood periods (Antonelli et al. 2008; Ollivier et al. 2010). The Rhône River delta (Fig. 5) is a sedimentation system, with net sediment accumulation rates close to 35 cm y^{-1} on the upper prodelta (Charmasson et al. 1998). Previous studies have shown that the prodelta is characterized by strong spatial (Lansard et al. 2008, 2009) and temporal (Cathalot et al. 2010) variations of OM input and that floods have an effect on mineralization in prodelta sediment (Cathalot et al. 2010).

Benthic station deployments

The benthic station was deployed in the Rhône prodelta area and connected to the instrumented Mesurho buoy, which is located 20 m deep (43°19.2 N, 4°52 E) at 3 km beyond the river mouth (Fig. 5). The benthic station was positioned by divers at a distance less than 10 m south from the "Mesurho" buoy, to avoid trawling.

The benthic station was deployed twice in contrasting environmental conditions: low and stable daily flow conditions of the river in Sep 2011 and more variable flow conditions during April 2012. For each deployment, results from the benthic

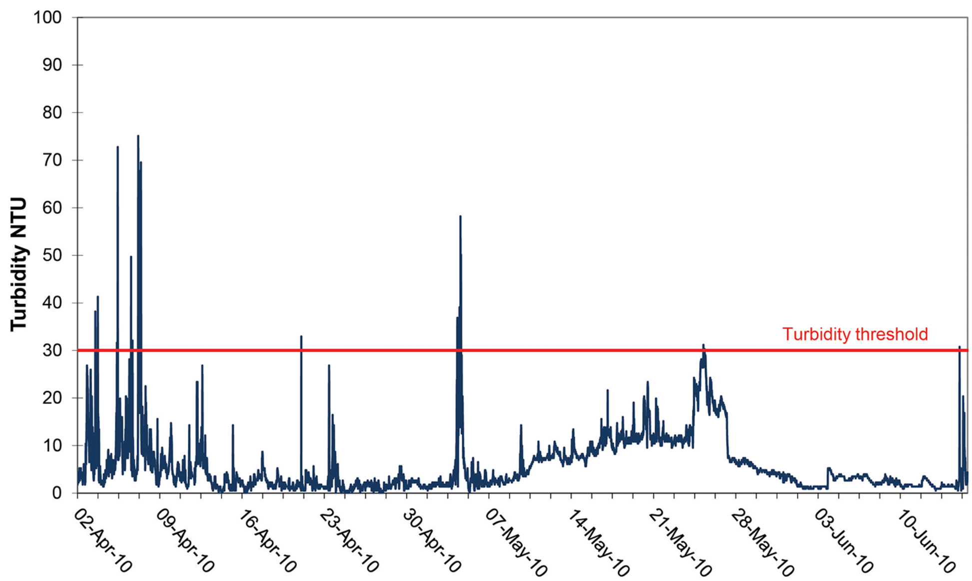

Fig. 4. Variation of turbidity between Access 1 and 2 (1 Apr 2012 to 24 Jun 2012) cruises determined with the turbidity RCM9 sensor, and definition of turbidity threshold.

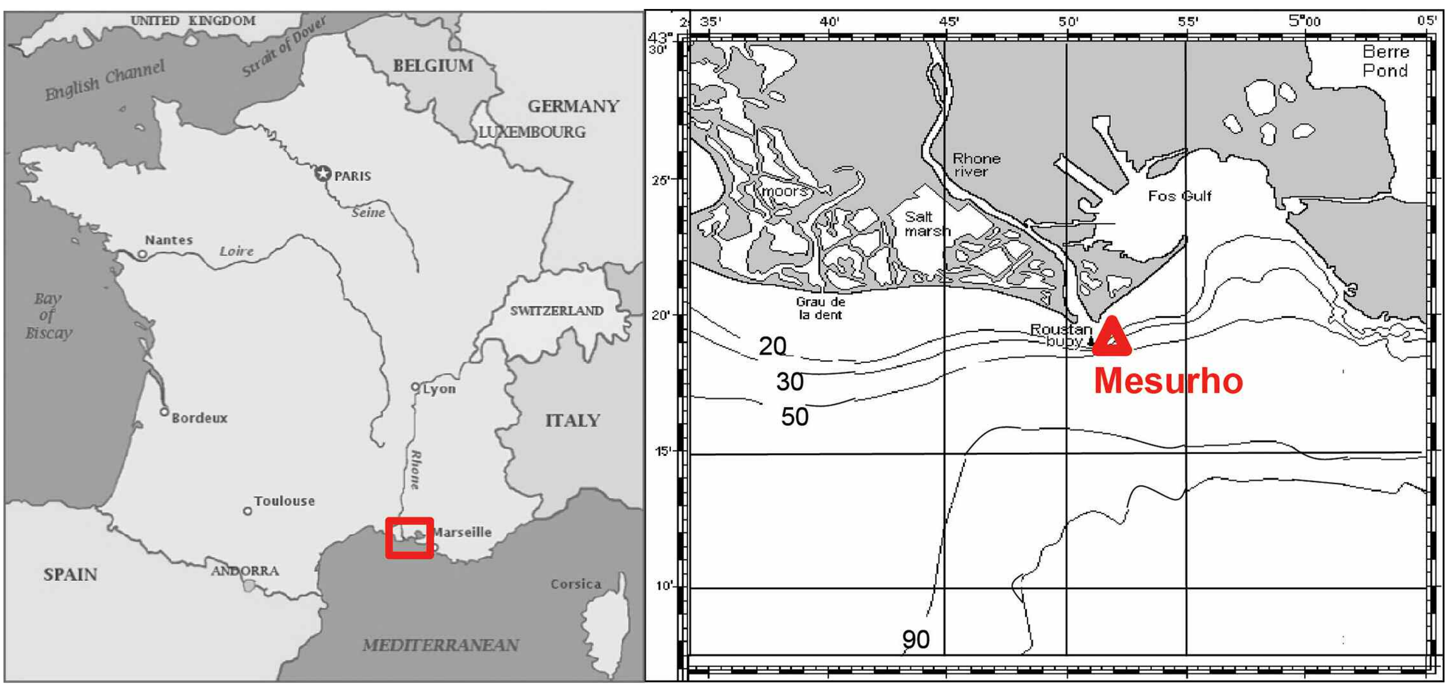

Fig. 5. Study area: the Rhone River delta. For display in figures, we fixed the spatial variability to 2σ of the measured value (i.e., ± 3.8 mmol O_2 m^{-2} d^{-1}, Fig. 7c) to cover 90% of the variability.

station were compared to data obtained with a well-tested instrument, a benthic microprofiler deployed simultaneously (Cathalot et al. 2010). A description and the principle of the benthic microprofiler can be found in Rabouille et al. (2003) and Dedieu et al. (2007).

Spatial and temporal variability during stable period

The initial set of profiles performed along the horizontal axis at the beginning of the time series allow the assessment of the spatial variability of the diffusive oxygen uptake for our measurement area. Fig. 6 shows a map of the spatial variability of DOU in sediment performed on 22 Sep 2011 with a variation of oxygen fluxes between 6.3 and 15.2 mmol O_2 m^{-2} d^{-1}. In total, 40 profiles were considered (Fig. 6). The average DOU of the 40 profiles was 9.2 ± 1.9 mmol O_2 m^{-2} d^{-1} (n = 40). Profiles were acquired during day and night during this initial mapping and show no statistical difference.

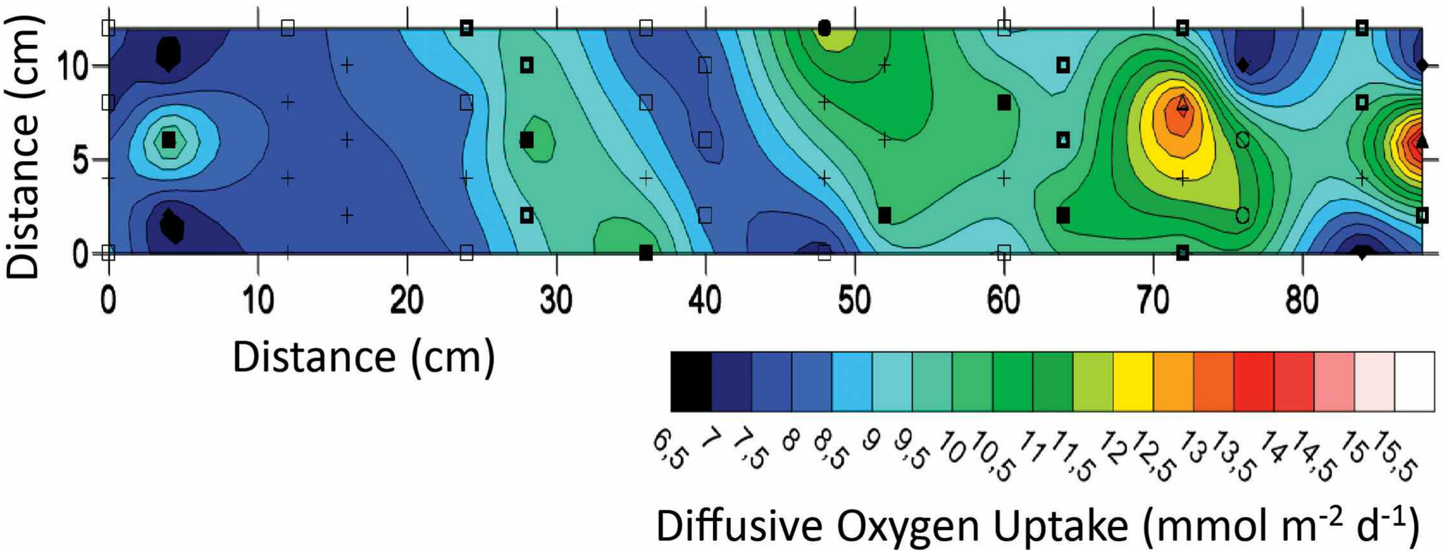

Fig. 6. Initial set of profiles showing spatial variability of DOU in sediment at the beginning of the Sep 2011 cruise, 21 and 22 Sep, in a 12 cm by 88 cm measurement area (crosses correspond to missing or excluded profiles and other symbols correspond to valid profiles with different DOUs). The "Surfer" software was used to compute the spatial interpolation of DOU using linear kriging.

Fluxes obtained with the autonomous benthic lander deployed at the same time nearby show DOU rates around 7.9 ± 1.2 mmol O_2 m^{-2} d^{-1} (n = 4), which are statistically equal to rates from the benthic station (Mann-Whitney test, P value < 0.05). The DOU rates observed during this deployment correspond to the lower range for this area located at the river mouth (2 km) in a deposition zone. Indeed, the Rhône River prodelta sediment shows an annual DOU variability between 8 and 17 mmol O_2 m^{-2} d^{-1} (Lansard et al. 2008; Cathalot et al. 2010).

Before starting to investigate the temporal evolution of the oxygen in the sediment, we assessed the stability of the measuring system during a low river discharge period with calm weather. During the Sep 2011 deployment, the mean Rhône River flow was 800 m^3 s^{-1}, which is below the annual average flow rate of 1700 m^3 s^{-1} (Pont et al. 1997): the flow rate was very stable and the turbidity level was low (Fig. 7a and 7b). During the initial mapping, the diffusive oxygen uptake was fairly constant (Fig. 6), except for the spot at position 72 cm, which displayed substantially higher DOU. During the time series, all DOU values fell within 2σ of the average O_2 flux with an average of 10.6 mmol O_2 m^{-2} d^{-1} (±0.7 mmol O_2 m^{-2} d^{-1}; Fig. 7c), except one DOU value measured on 25 Sep 2011: the value rose to 18.6 ± 4.7 mmol O_2 m^{-2} d^{-1}. This high value was measured at position 70 cm coinciding with position 72 cm where the DOU was substantially higher during the initial mapping: the DOU at these two positions showed no statistical differences (Mann-Whitney test, P = 0.006). This stability of the DOU during the time series also shows that the disturbance induced by the holes created by electrode penetration in the sediment is limited and does not affect the oxygen microprofiles. In addition, the shift between electrode profiles of 1 cm is in agreement with the spacing chosen by Glud et al. (2009) of 0.7 cm in the Sagami Bay.

The spatial distribution of in situ O_2 profiles obtained in September displays a rather limited range of variation with the existence of "hot spots" separated by decimetric distances (Fig. 6). The small-scale variation is linked to the benthic fauna and OM distribution in the sediment which is known to occur with a characteristic distance of a few centimeters in coastal shelf sediment (Rabouille et al. 2003; Glud et al. 2005, 2009). In the Rhone subaqueous delta, we observed a larger scale of heterogeneity (over decimeters), which could be related to the local topography of the sediment and the deposition pattern of organic particles in this deltaic environment. The centimeter-scale variability, if present, is not accessible with our horizontal resolution (minimum of 4 cm between electrodes).

Monitoring DOU during resuspension events and its relaxation

The benthic station was deployed between March and May 2012. The Rhône river daily flow increased steadily from 700 to 2400 $m^3.s^{-1}$, below the flood threshold (Fig. 8a) linked to alpine snow melt. From 26 Mar to 10 Apr, environmental conditions remained constant with a small wave height and low bottom water turbidity (<10 NTU). During this period, the position of the sediment-water interface oscillated within ± 0.5 cm (1σ) with no visible trend (Fig. 8c). Three turbidity events recorded on this graph are linked to higher waves (Fig. 8b and 8d) on 10 April 26 April and 20 May. During these events, wave height reached 2.5 m (wave period of 7 s) and turbidity 60 to 250 NTU. At the same time, the DOU increased over 1 h to 25–35 mmol O_2 m^{-2} d^{-1} for the different events observed (Fig. 8e). These periods of large waves lasted from one to 5 days, and after they ceased, turbidity and DOU

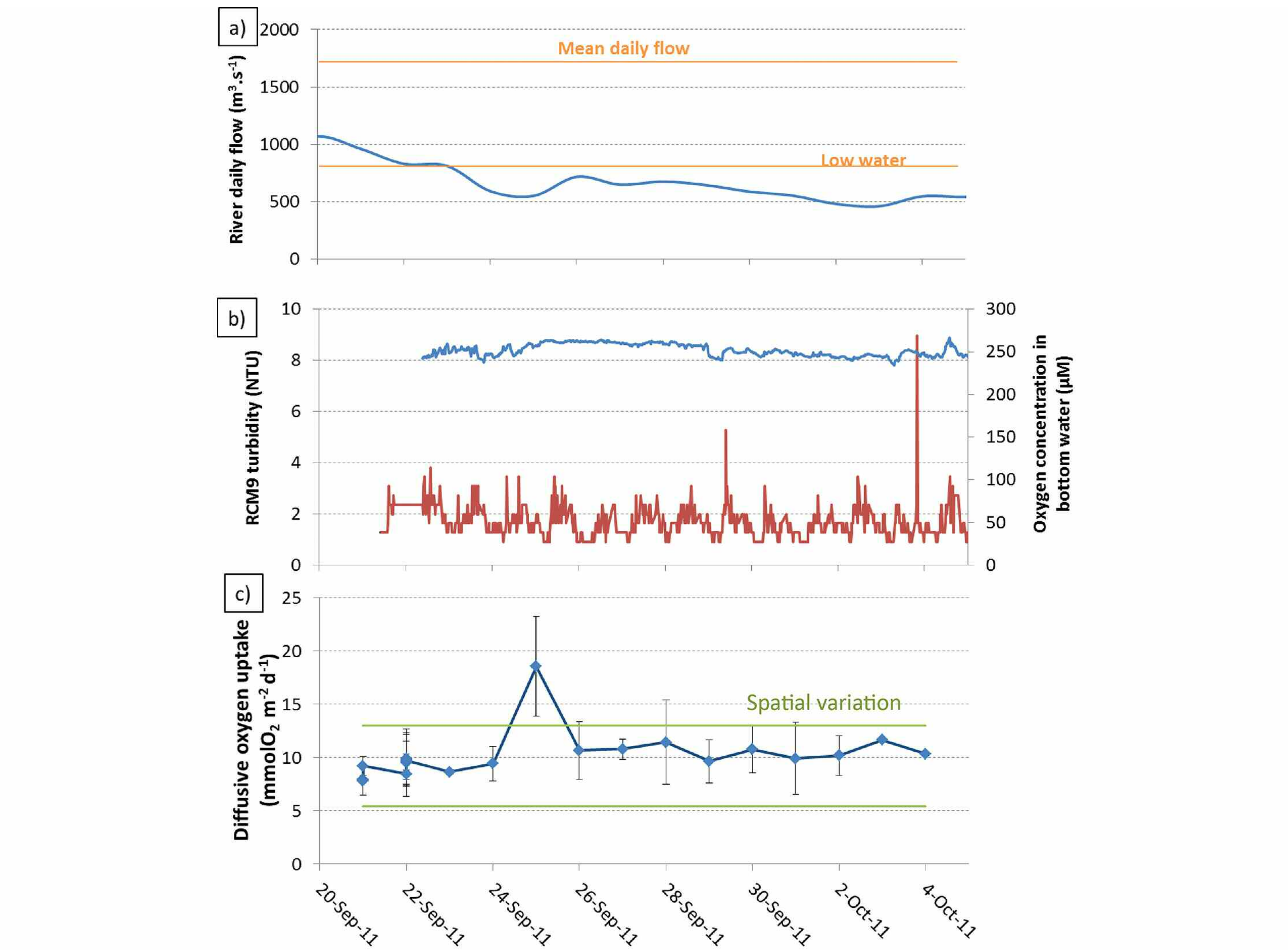

Fig. 7. a) Rhône River daily flow (m^3 s^{-1}), b) turbidity in red and oxygen concentration in bottom water in blue, and c) diffusive oxygen uptake (mmol O_2 m^{-2} d^{-1}) during autumn deployment. Error bars correspond to the dispersion between electrodes in one set of profiles (*n* = 3–7), and green lines show the spatial variability of 2σ based on the whole dataset (*n* = 40).

returned to their initial state. Two of these events, on 26 Apr and 20 May, were accompanied by a measurable erosion of the sediment-water interface (down to 2 cm), indicating a loss of material from the sediment linked with resuspension.

Fig. 9 shows the evolution of sediment oxygen profiles during the first turbidity event on 10 April 2012. One set of profiles was performed at 7h00 (low frequency) on the 9 and 10 April and during the resuspension event (Fig. 8). The benthic station switched to the high-frequency mode on the 10 April at 20h20 with more frequent profiling to better monitor the system response and its subsequent relaxation. The first two profiles of Fig. 9, which were measured before the resuspension event, show a range of oxygen penetration depths (OPD) between 1.4 and 2.2 mm, i.e., within the natural spatial variability of OPD in these sediments (1.9 ± 0.5 mm). During the high frequency mode, a first set of profiles was performed 1 h after the detection of the event and then, profiles were separated by approximately 3, 7, 13, and 23 h corresponding to 20h20, 23h10, 3h00, 8h50, and 18h40, as one set of profiles requires 1h30 to be completed and the waiting time after profiles was increasing from 1h to 8h. OPD decreased rapidly after the resuspension event and reached 0.5 to 1 mm (Fig. 9), accompanied by the increase in DOU (Fig. 8). Finally, when profiling returned to a low frequency mode at 07h00 on 12 April 2012, the OPD was around 2 mm, close to the value recorded before the turbidity event.

During the initial set of profiles and the beginning of the time series in March-April 2012, the DOU remained constant with average values of 10.9 ± 2.6 mmol O_2 m^{-2} d^{-1} along with stable environmental parameters, which indicates stability in the sediment. During the three turbidity peaks of the March-May deployment, the oxygen demand increased quickly by a

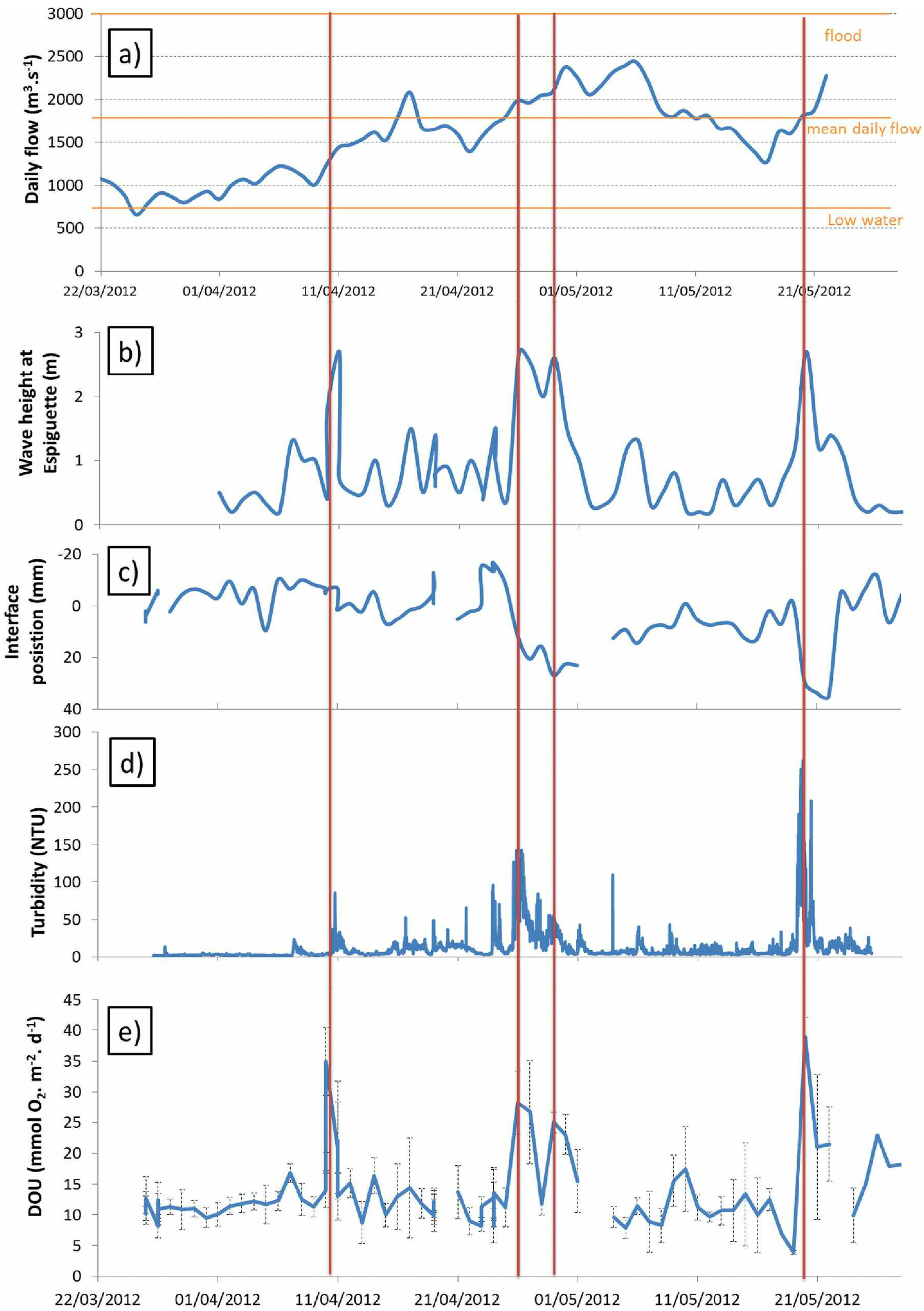

Fig. 8. a) Rhône river daily flow ($m^3\ s^{-1}$), b) wave height (m) at Espiguette (station located west of the Mesurho buoy; CANDHIS data), c) Sediment-water interface position (mm) determined with the resistivity electrode, d) turbidity contents in bottom waters (NTU), e) diffusive oxygen uptake rates in sediment (mmol $O_2\ m^{-2}\ d^{-1}$).

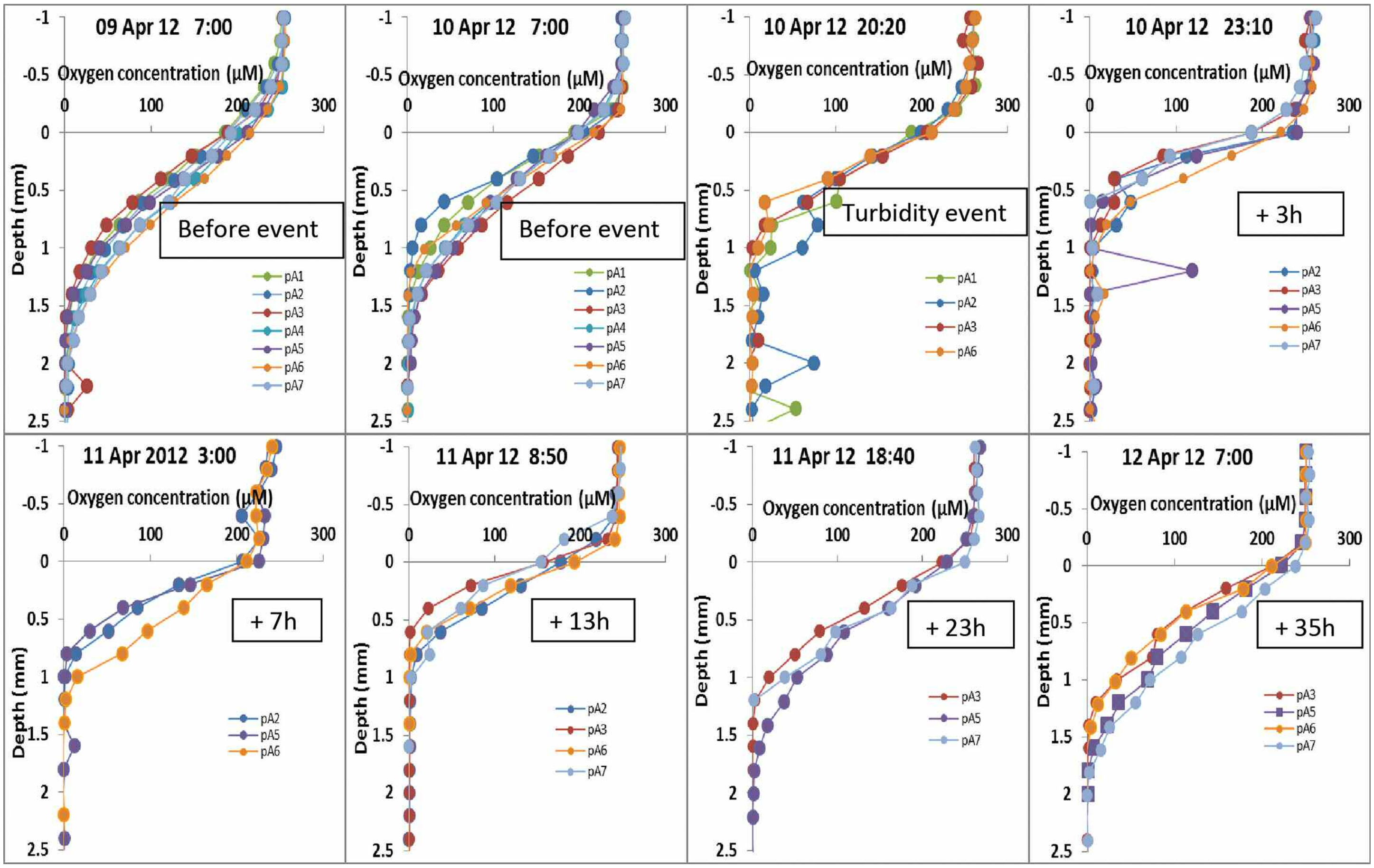

Fig. 9. Evolution of oxygen profiles after turbidity event with benthic station in low- and high-frequency profiling mode.

factor of 2-3, accompanied by a decrease of oxygen penetration (Fig. 8 and 9). These rapid variations are correlated to resuspension events due to waves, as indicated by the sudden increase in wave height and turbidity (Fig. 8). In addition, Fig. 8c shows a downward displacement of the water-sediment interface when the wave height exceeds 2.5 m which indicates erosion of the sediment. Such a removal of surface sediment has also been shown at the nearby "La Balancelle" station located at 21 m depth east of the Rhone River mouth (Dufois et al. 2014) with erosion of up to 2 cm of sediment. Resuspension events linked to sediment erosion may have several effects on benthic mineralization activity: (1) a mechanical increase of DOU due to the re-diffusion of oxygen in uncovered sediment, (2) the re-oxidation of reduced elements that were buried deep in the sediment before the erosion event and are put in contact with oxygen (Pastor et al. 2011), or (3) the mineralization of old reactive carbon (Cathalot et al., 2014) that was previously buried and re-enters the oxic layer. Recent investigations using a numerical model for Louisiana shelf sediments (Harris et al. 2014) have shown that the re-oxidation of reduced compounds during sediment erosion events may be the primary cause of DOU peaks. With the high frequency measurements during the resuspension event of 10 April, the benthic station was able to follow the relaxation of DOU rates and oxygen profiles after the event. For such moderate events, a rapid relaxation of the system seems to prevail, with a return to the initial benthic mineralization activity in around 1 day (Fig. 9).

Discussion

In this discussion, we evaluate the three main goals of this paper as presented in the introduction: 1) present the new instrument, 2) validate the technique in the Rhône River delta, and 3) assess the temporal variation during a resuspension event. We have presented the general concepts and the realization of a benthic station deployed in a deltaic system to measure in situ time series of sediment oxygen profiles after environmental events. The first objective can be achieved by coupling a 2D profiler with environmental sensors which can switch the station from a low profiling frequency during calm periods (1 per day) to high profiling frequency during events (resuspension or flood).

The second aim was reached by collecting a dataset with the benthic station over 2 weeks in a calm period (Sep 2011) and by comparing the results of this deployment to data from an in situ microprofiler collected at the same station. All results, i.e., the in situ profiler DOU, the initial mapping of DOU by the benthic station, and the short time series show a good agreement, which indicates the ability of the benthic station in providing reliable DOUs.

And last, we recorded three resuspension events, which were surprisingly accompanied by large increases of DOU during the event (by a factor of 2-3). With the use of high frequency measurement, we were also able to record the relaxation of the system, which happened to be short, around 30 hours. We thus believe that the increase of DOU is related to the chemical oxidation of reduced compounds during the loss of 2-3 cm of sediment for each resuspension period. This sediment loss was also recorded by the benthic station.

Comments and recommendations

In the future, the benthic station will be used to monitor the impact of floods, which bring up to 80% of the annual sediment discharge for the Rhone River. This will help fill the lack of data concerning the effect of floods on benthic mineralization. This future task will be performed using the same design as the one shown in this paper.

The bentic station could be used in other environments, which display large temporal variations. Two examples can be given here: the dynamics of porewater oxygen in seasonally hypoxic regions, such as the Northern Gulf of Mexico (Rabalais et al. 2014), or the Thau lagoon (Dedieu et al. 2007), and the reduction of sediment oxic layers and related redox cycles in sediments affected by large phytoplankton bloom deposition (Barats et al. 2010). The study of oxygen dynamics in seasonally hypoxic area would require to use the oxygen sensor (Aanderaa optode) to trigger high-frequency measurement during the decrease of oxygen in the water column (instead of turbidity used in resuspension-flood studies). Other microelectrodes, such as sulfide, may be of interest for capturing the oxygen-sulfide dynamics in the sediment and porewater. In the case of diatom blooms, the record of oxygen profiles would be of great interest to understand the redox cycling within the sediment and the mobility of trace metals such as Mo. This metal recorded in molluscs shells such as scallops has been shown to correlate with phytoplankton blooms (Barats et al. 2010). As molluscs shells have started to be largely used for reconstructing high-resolution century-long records of coastal ocean biogeochemistry, it is important to understand the dynamics of trace metals and oxygen in the sediment. This particular application would require a fluorimeter to record the initiation of phytoplankton bloom settling to the sediment and trigger higher frequency measurements.

Acknowledgments

We wish to thank the captains and crews of the R. V. *Tethys II* for their help with sea work during the cruises. We would like to thank C. Ravel, N. Caillon, G. Monvoisin, and F. Zuberer, the divers, for their help during benthic station deployment. This work was supported by the French National Research Agency programme "Vulnérabilités: Milieux et Climat," under grant nr ANR-06-VULN-001 of the CHACCRA project, the French INSU-EC2CO program RiOMar.fr, the CEA, the MISTRALS/MERMEX-Rivers action (Marine Ecosystems Response in the Mediterranean EXperiment), and the international LOICZ project. We also thank the INSU Mi-Lourds programme and the Conseil Général 91 ASTRE programme for their help in funding the development of the benthic station. The station deployment is part of the Mesurho programme associating IFREMER, IRSN, CNRS, CETMEF, and Phares et Balises. FT was funded by a PhD grant from UVSQ. This is LSCE contribution 4407.

References

Andrews, D., and A. Bennett. 1981. Measurements of diffusivity near the sediment-water interface with a fine-scale resistivity probe. Geochim. Cosmochim. Acta 45:2169-2175 [doi:10.1016/0016-7037(81)90069-7].

Antonelli, C., F. Eyrolle, B. Rolland, M. Provansal, and F. Sabatier. 2008. Suspended sediment and Cs-137 fluxes during the exceptional December 2003 flood in the Rhone river, southeast France. Geomorphology 95:350-360 [doi:10.1016/j.geomorph.2007.06.007.].

Attard, K. M., R. N. Glud, D. McGinnis, and S. Rysgaard. 2014. Seasonal rates of benthic primary production in a Greenland fjord measured by aquatic eddy correlation. Limnol. Oceanogr. 59(5):1555-1569 [doi:10.4319/lo.2014.59.5.1555].

Barats, A., D. Amouroux, C. Peycheyran, L. Chauvaud, J. Thebault, and O. F. X. Donard. 2010. Spring molybdenum enrichment in scallop shells: a potential tracer of diatom productivity in temperate coastal environments (Brittany, NW France). Biogeosciences 7:233-245 [doi:10.5194/bg-7-233-2010].

Berg, P., H. Roy, F. Janssen, V. Meyer, B. B. Jorgensen, M. Huettel, and D. de Beer. 2003. Oxygen uptake by aquatic sediments measured with a novel non-invasive eddy-correlation technique. Mar. Ecol. Prog. Ser. 261:75-83 [doi:10.3354/meps261075].

———, R. N. Glud, A. Hume, H. Stahl, K. Oguri, V. Meyer, and H. Kitazato. 2009. Eddy correlation measurements of oxygen uptake in deep ocean sediments. Limnol. Oceanogr. Methods. 7:576-584 [doi:10.4319/lom.2009.7.576].

———, and others. 2013. Eddy correlation measurements of oxygen fluxes in permeable sediments exposed to varying current flow and light. Limnol. Oceanogr. 58:1329-1343.

Bianchi, T. S., and M. A. Allison. 2009. Large-river delta-front estuaries as natural "recorders" of global environmental change. Proc. Nat. Acad. Sci. U.S.A. 106(20):8085-8092 [doi:10.1073/pnas.0812878106].

Borges, A. V. 2005. Do we have enough pieces of the jigsaw to integrate CO_2 fluxes in the coastal ocean? Estuaries 28(1):3-

27 [doi:10.1007/BF02732750].

Broecker, W. S., and T. H. Peng. 1974. Gas exchange rates between air and sea. Tellus 26:21-35 [doi:10.1111/j.2153-3490.1974.tb01948.x].

Cai, W. -J. 2011. Estuarine and coastal ocean carbon paradox: CO_2 sinks or sites of terrestrial carbon incineration? Annu. Rev. Mar. Sci. 3:123-145 [doi:10.1146/annurev-marine-120709-142723].

Cathalot, C., and others. 2010. Temporal variability of carbon recycling in coastal sediments influenced by rivers: assessing the impact of flood inputs in the Rhone River prodelta. Biogeosciences 7:1187-1205 [doi:10.5194/bg-7-1187-2010].

———, and others. 2013. The fate of river organic carbon in coastal areas: a study in the Rhone River delta using multiple isotopic $\delta^{13}C$, $\Delta^{14}C$) and organic tracers. Geochim. Cosmochim. Acta 118:33-55 [doi:10.1016/j.gca.2013.05.001].

Charmasson, S., P. Bouisset, O. Radakovitch, A. S. Pruchon, and M. Arnaud. 1998. Long-core profiles of Cs-137, Cs-134, Co-60 and Pb-210 in sediment near the Rhone River (Northwestern Mediterranean Sea). Estuaries 21:367-378 [doi:10.2307/1352836].

Dedieu, K., and others. 2007. Benthic O2 distribution and dynamics in a Mediterranean lagoon (Thau, France): An in-situ microelectrode study. Est. Coast. Shelf Sci. 72:393-405 [doi:10.1016/j.ecss.2006.11.010].

Dufois, F., R. Verney, P. Le Hir, F. Dumas, and S. Charmasson. 2014. Impact of winter storms on sediment erosion in the Rhone River prodelta and fate of sediment in the Gulf of Lions (North Western Mediterranean Sea). Cont. Shelf Res. 72:57-72 [doi:10.1016/j.csr.2013.11.004].

———, F. Wenzhofer, A. Tengberg, M. Middelboe, K. Oguri, and H. Kitazato. 2005. Distribution of oxygen in surface sediments from central Sagami Bay, Japan: In situ measurements by microelectrodes and planar optodes. Deep-Sea Res. I 52(10):1974-1987 [doi:10.1016/j.dsr.2005.05.004].

———, H. Stahl, P. Berg, F. Wenzhoefer, K. Oguri, and H. Kitazato. 2009. In situ microscale variation in distribution and consumption of O_2: A case study from a deep ocean margin sediment (Sagami Bay, Japan). Limnol. Oceanogr. 54:1-12 [doi:10.4319/lo.2009.54.1.0001].

———, and others. 2010. Benthic O-2 exchange across hard-bottom substrates quantified by eddy correlation in a sub-Arctic fjord. Mar. Ecol. Progr. Ser. 417:1-12 [doi:10.3354/meps08795].

Grasshoff, K., M. Ehrhardt, and K. Kremling. 1983. Methods of seawater analysis. 419 pp.

Harris, C. K., K. Fennel, and R. Hetland. 2014. Effects of resuspension on sediment bed oxygen consumption: a numerical modeling study for the Louisiana shelf. Ocean Sciences Meeting 2014 Abstract, session #117 AGU/ASLO/TOS.

Hedges, J. I., R. G. Keil, and R. Benner. 1997. What happens to terrestrial organic matter in the ocean? Organic Geochem. 27:195-212 [doi:10.1016/S0146-6380(97)00066-1].

Holtappels, M., and others. 2013. Effects of transient bottom water currents and oxygen concentrations on benthic exchange rates as assessed by eddy correlation measurements. J. Geophys. Res. Oceans 118:1157-1169 [doi:10.1002/jgrc.20112].

Iversen, N., and B. B. Jorgensen. 1993. Diffusion coefficients of sulfate and methane in marine sediments—Influence of porosity. Geochim. Cosmochim. Acta 57(3):571-578 [doi:10.1016/0016-7037(93)90368-7].

Jorgensen, B. B., and N. P. Revsbech. 1985. Diffusive boundary-layers and the oxygen-uptake of sediments and detritus. Limnol. Oceanogr. 30:111-122 [doi:10.4319/lo.1985.30.1.0111].

Lansard, B., C. Rabouille, L. Denis, and C. Grenz. 2008. In situ oxygen uptake rates by coastal sediments under the influence of the Rhone River (NW Mediterranean Sea). Cont. Shelf Res. 28(12):1501-1510 [doi:10.1016/j.csr.2007.10.010].

———, ———, ———, and ———. 2009. Benthic remineralization at the land-ocean interface: A case study of the Rhone. Estuar. Coast. Shelf Sci. 81(4):544-554 [doi:10.1016/j.ecss.2008.11.025].

Leckebusch, G. C., B. Koffi, U. Ulbrich, J.G. Pinto, T. Spangel, and S. Zacharias. 2006. Analysis of frequency and intensity of winter storm events in Europe on synoptic and regional scales from a multi-model perspective. Clim. Res. 31:59-74 [doi:10.3354/cr031059].

Long, M. H., P. Berg, D. de Beer, and J. C. Zieman. 2013. In Situ coral reef oxygen metabolism: An eddy correlation study. PLOS One 8(3):e58581 [doi:10.1371/journal.pone.0058581].

MerMex Group. 2011. Marine ecosystems' responses to climatic and anthropogenic forcings in the Mediterranean. Progr. Oceanogr. 91:97-166 [doi:10.1016/j.pocean.2011.02.003].

Moreira-Turcq, P., and others. 2013 Seasonal variability in concentration, composition, age, and fluxes of particulate organic carbon exchanged between the floodplain and Amazon River. Global Biogeochem Cycl. 27(1):119-130 [doi:10.1002/gbc.20022].

Ollivier, P., O. Radakovitch, and B. Hamelin. 2011. Major and trace element partition and fluxes in the Rhône. Chem. Geol. 285:15-31 [doi:10.1016/j.chemgeo.2011.02.011].

Pastor, L., and others. 2011. Influence of the organic matter composition on benthic oxygen demand in the Rhone River prodelta (NW Mediterranean Sea). Cont. Shelf Res. 31:1008-1019 [doi:10.1016/j.csr.2011.03.007].

Pinto, J. G., U. Ulbrich, G. C. Leckebusch, T. Spangel, M. Reyers, and S. Zacharias. 2007. Changes in storm track and cyclone activity in three series ensemble experiments with the ECHAM5/MPI-OM1 GCM. Clim. Dynam. 29:195-210 [doi:10.1007/s00382-007-0230-4].

Pont, D. 1997. Les débits solides du Rhône à proximité de son embouchure: données récentes (1994–1995). Rev. Geogr. Lyon 72:23-33 [doi:10.3406/geoca.1997.4675].

———, J. P. Simonnet, and A. V. Walter. 2002. Medium-term changes in suspended sediment delivery to the ocean: Consequences of catchment heterogeneity and river management (Rhone River, France). Estuar. Coast. Shelf Sci. 54:1-18 [doi:10.1006/ecss.2001.0829].

Rabouille, C., L. Denis, K. Dedieu, G. Stora, B. Lansard, and C. Grenz. 2003. Oxygen demand in coastal marine sediments: Comparing in situ microelectrodes and laboratory core incubations. J. Exp. Mar. Biol. Ecol. 285:49-69 [doi:10.1016/S0022-0981(02)00519-1].

Rabalais, N. N., and others. 2014. Eutrophication-driven deoxygenation in the coastal ocean. Oceanography 27:172-183 [doi:10.5670/oceanog.2014.21].

Regnier, P., and others. 2013. Anthropogenic perturbation of the carbon fluxes from land to ocean. Nature Geosci. 6(8):597-607 [doi:10.1038/ngeo1830].

Revsbech, N. P. 1989. An oxygen microsensor with a guard cathode. Limnol. Oceanogr. 34:474-478 [doi:10.4319/lo.1989.34.2.0474].

Sanders, R. D., C. E. Reimers, A. Albright, R. Dewey, and P. Macoun. 2014. VENUS ocean observatory measurements of benthic oxygen and heat fluxes. Ocean Science Meeting abstract (ID 16639), Honolulu 2014.

Sempere, R., B. Charriere, F. Van Wambeke, and G. Cauwet. 2000. Carbon inputs of the Rhone River to the Mediterranean Sea: Biogeochemical implications. Glob. Biogeochem. Cycl. 14:669-681 [doi:10.1029/1999GB900069].

Sherman, A. D., and K. L. J. Smith. 2009. Deep-sea benthic boundary layer communities and food supply: A long-term monitoring strategy. Deep Sea Res. II 56:1754-1762 [doi:10.1016/j.dsr2.2009.05.020].

Smith, K. L. J., R. C. Glatts, R. J. Baldwin, S. E. Beaulieu, A. H. Uhlman, R. C. Horn, and C. E. Reimers. 1997. An autonomous, bottom transecting vehicle for making long time-series measurements of sediment community oxygen consumption to abyssal depths. Deep-Sea Res. 42:1601-1612.

Submitted 25 March 2014
Revised 24 September 2014
Accepted 13 October