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Turbidity events observed *in situ* along the Congo submarine channel

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Abstract:

As part of the multidisciplinary programme BIOZAIRE devoted to studying deep-sea benthic ecosystems in the Gulf of Guinea, particulate input and its relationship with near-bottom hydrodynamics were monitored using long-term moorings from 2000 to early 2005. Particular attention was given to material input through the Congo (ex-Zaïre) submarine channel that extends 760 km from the Congo River mouth to the abyssal plain (>5100 m) near 6°S. Due to its direct connection to the Congo River, the Congo canyon and channel system are characterised by particularly active recent sediment transport. During this first *in situ* long-term monitoring along the channel, an energetic turbidity event was observed in January 2004 at three locations along the channel from 3420 to 4790 m in depth. This event tilted and displaced the moorings installed at 3420 m (site ZR′) and 4070 m (site ZD′), and resulted in high sediment deposition at all three mooring sites. The event moved at an average velocity of 3.5 m s^{-1} along the numerous channel meanders between 3420 and 4070 m, then at 0.7 m s^{-1} between 4070 m and the end of the channel at 4790 m. The particle cloud rose above the top of the valley at 4070 m (site ZD′), but not at 3420 m (site ZR′) where the channel was too deep. Lastly, the mooring line broke at site ZD′ in October 2004 probably due to a strong event like that of 2001 previously described by Khripounoff et al. [Khripounoff, A., Vangriesheim, A., Babonneau, N., Crassous, P., Dennielou, B., Savoye, B., 2003. Direct observation of intense turbidity activity in the Zaire submarine valley at 4000 m water depth. Marine Geology (194), 151–158]. Between these strong events, several peaks of high turbidity and particle flux occurred, but without noticeable current increases. These events were probably due to local sliding of sediment accumulated on the walls or terraces on the side of the channel. The area near 4000 m depth and the lobe appear to be the main depocentres of particulate input rich in organic matter derived from the Congo River.

Keywords: Gulf of Guinea; Zaïre; Congo canyon; Deep current; Turbidity current; Suspended sediment transport

1. Introduction

Submarine canyons are known to be preferential conduits for the transfer of material from the continent to the deep ocean. The majority of canyons start at the shelf break, whereas only a few incise the shelf and directly connect to a river mouth, such as the Congo canyon (ex-Zaïre canyon), the Monterey canyon or the Var canyon. In general, the finer grained material settles in the upper and the middle canyon. This material is sometimes resuspended by focused internal waves or enhanced low-frequency currents and driven to the deep ocean by flushing events linked to meteorological forcing conditions. In canyons directly connected to shore, these activities are particularly intense when river floods trigger high-energy turbidity currents that transport material far down the canyon.

Direct observation of current and/or particle transport events in canyons have been reported. In a British Columbia fjord connected to two rivers, Prior *et al.* (1987) detected three turbidity events in one year that reached the distal exit of the system at 40 to 50 km at approximately 600 m depth. Studies of the Eel canyon off California (Puig *et al.*, 2003) and canyons in the Gulf of Lions in the western Mediterranean Sea (Canals *et al.*, 2006; Palanques *et al.*, 2006) all demonstrated cascading events from the nearby shelf. The Baltimore canyon off the US East Coast (Gardner, 1989), the Nazaré canyon off Portugal (De Stigter *et al.*, 2007) and the Cap Breton canyon off France (Mulder *et al.*, 2001) are also subject to particle transport events, but of lower magnitude or to a lesser offshore extent. The Monterey canyon off California is a geological structure comparable to the Congo canyon, directly connected to a river and extending long offshore, with a fan at more than 3000 m depth. Its activity has been monitored using long-term measurements of temperature, salinity, light transmission and, occasionally, current speeds. Johnson *et al.* (2001) reported four events in 12 years (1988-2001) and other strong events were described by Xu *et al.* (2002, 2004) and Paull *et al.* (2003) from the same canyon. Events, detected from temperature changes, turbidity peaks or current speed peaks (reaching approximately 190 cm s^{-1} at 1000 m depth) were related to river floods or meteorological events. Some moorings were displaced or buried. The velocity of the front of a turbidity event was found to be between 1.7 and 2.8 m s^{-1}. The Var canyon is also directly connected to the Var river and indirect evidence of turbidity events has been reported by Migeon *et al.* (2001).

Recently, an extreme turbidity event in the Congo submarine channel was reported (Khripounoff *et al.*, 2003). This event occurred in March 2001 at 4000 m depth at the beginning of the BIOZAIRE programme. This was the first time that a turbidity current had been observed *in situ* at such a great depth. During the event, a current speed of more than 120 cm s^{-1} was measured 150 m above the channel floor, and coarse sand and plant debris were collected in a sediment trap at 40 m above the bottom. The turbidity current clearly spilled over the edges of the channel as demonstrated by the high quantity of turbiditic material found in a sediment trap moored 13 km south of the channel axis.

As part of the multidisciplinary programme BIOZAIRE lead by the French Research Institute for the Exploitation of the Sea (Ifremer) (Sibuet and Vangriesheim, this volume) that was devoted to comparing the different benthic ecosystems of the Gabon-Angola margin, it was important to explore the impact of turbidity events occurring in the Congo submarine channel on benthic fauna. The Congo submarine channel was the longest channel that had not yet been monitored. After the 2001 event (Khripounoff *et al.*, 2003), Ifremer deployed other moorings in and near the channel at depths ranging from 3400 m to 4800 m, which were maintained from late 2001 to early 2005 during the BIOZAIRE programme. Results from these moorings are reported and discussed here.

2. Regional setting

2.1. Hydrology and circulation in the Gulf of Guinea

In the 1970s, several cruises were carried out by the Netherlands Institute for Sea Research (NIOZ) and the French Institute of Scientific Research for Cooperative Development (ORSTOM, now called the French Research Institute for Development IRD) to study the hydrographics of the Gulf of Guinea in relation to the Congo River outflow (Van Bennekom and Berger, 1984). The deep layers of the Gulf were then examined in more detail based on more intensive hydrographic sections across the basin (Arhan *et al.*, 1998, Warren and Speer, 1991 and Arhan *et al.*, 2003). More recently, IRD carried out the EQUALANT cruises in 1999 and 2000 and then Ifremer conducted two hydrographic sections in 2003 above the Congo submarine fan as part of the BIOZAIRE programme. Results of these sections are in Vangriesheim *et al.* (this volume) with reference to the previous cruises.
The circulation in this area is complicated: the eastward-flowing equatorial currents encounter the north-south oriented coast and converge with the northward-flowing Benguela Current (Stramma and England, 1999). The surface water circulation of the region is driven by the dominant trade winds and the monsoon regime. It includes the westward-flowing South Equatorial Current and its countercurrents as well as the cyclonic Angola Gyre, centred near 13°S, 5°E. The eastern branch of the Angola gyre is the Angola Current which flows southward along the African coast, fed by the Gabon-Congo Undercurrent near 6°S. In some places, winds and currents favour upwelling such as that of the Benguela Current in the south and the seasonal upwelling around the equator and off the Congo-Angola coast from July to September (Picaut, 1983). The intermediate and deep circulation is driven by the thermohaline circulation. Between 500 m and 1200 m lies the Antarctic Intermediate Water, characterised by an oxygen maximum and a salinity minimum. At a deeper level, the North Atlantic Deep Water (NADW) enters the Gulf of Guinea basin from the west, passing the Mid-Atlantic Ridge near the equator and near 20-25°S, and then flows to the south in the Angola Gyre. Below 2000 m, the NADW progressively mixes with Antarctic Bottom Water (AABW), which is formed in the Antarctic region but enters the eastern basin of the Gulf of Guinea from the north via the Romanche Fracture Zone, with only limited passage through the Walvis Ridge. Due to the location of the Congo submarine fan near 6°S, residual currents in the deep layers are expected to have eastward and/or southward components in the study area.
An original feature in the deep Gulf of Guinea is the oxygen and nutrient concentration anomalies near the bottom at approximately 4000 m which have been observed along the Gulf of Guinea margin (Van Bennekom and Berger, 1984; Warren and Speer, 1991; Van Bennekom, 1996; Arhan *et al.*, 1998; Oudot *et al.*, 1998). The origin of these anomalies has not been fully determined, except that they appear linked with the degradation of organic particulate matter possibly supplied by turbidity currents. The coincidence between the anomaly core and the high energy of the turbidity events observed at this depth (Khripounoff *et al.*, 2003) suggests that these events play an important role in the near-bottom environment at approximately 4000 m in this area and create novel conditions for benthic fauna at this depth. These anomalies are further described and discussed in Braga *et al.* (2004) and in Vangriesheim *et al.* (this volume).

2.2. The Congo canyon and channel system

The Congo submarine canyon was discovered in 1886 aboard the British cable ship *Buccaneer* (Buchanan, 1888). The Congo canyon/channel system starts at the mouth of the Congo River, located near 6°S on the Atlantic coast of equatorial Africa (between

Angola and Democratic Republic of Congo). From there it extends 760 km westward to the abyssal plain (>5100 m), covering an estimated area of 300 000 km^2 (Babonneau, 2002). The direct connection between the river mouth and the abyssal plain via the canyon is a unique characteristic of the Congo system. It explains why the Congo submarine fan is one of the largest in the world and still affected by turbiditic sedimentation today (Savoye *et al.*, 2000). While documenting submarine cable breaks (estimated at approximately 60 per century) near the Congo canyon between 500 and 2300 m depth, Heezen *et al.* (1964) attributed the present-day activity to turbidity currents associated with river floods. The transport of great quantities of silt and sand through the canyon by intermittent turbidity currents has cut the channel deeply into the shelf and slope, produced pronounced meanders and formed a large submarine fan at the base of the continental slope. Recent activity on the fan has also been demonstrated by the presence of more than 10 m of Holocene fine-grained turbidites, as identified in cores recovered near the levee crest of the active channel (Van Weering and Van Iperen, 1984). According to Babonneau *et al.* (2002), the thalweg, at depths less than 3000 m—which includes the "canyon" (down to 1300 m) and the "upper-fan valley"(from 1300 m to 3000 m)—, is too deeply incised to allow sediment to spill over during turbidity events, except on the terraces inside the "upper-fan valley". At depths greater than 3000 m in the "channel-levee system", sediment spillover can occur when the thickness of turbidity currents (maximum estimated to 250-300 m) exceeds the depth of the channel. In what follows, we use the terms as defined by Babonneau *et al.* (2002) for the different parts of the canyon/channel system. More details on the geological setting of this area are given in Savoye *et al*. (this volume).

3. Materials and methods

The turbidity activity and influence of the Congo channel in the Gulf of Guinea were investigated using a series of moorings, successively installed from 2001 to 2005 during five cruises of the BIOZAIRE programme. Three mooring locations were chosen in the thalweg (sites ZR' at 3420 m, ZD' at approximately 4050 m and Lobe at 4790 m), and two were outside the channel (site ZD at approximately 3970 m and site Regab at 3150 m). In addition, two moorings were installed some distance away from the channel: one at 200 km away from the channel (site ZC, 4000 m depth) serving as a reference site and one on the upper slope (site ZA at 1300 m), the results of which are published elsewhere (Vangriesheim *et al*., 2005; Guiavarc'h, 2007; Guiavarc'h *et al.*, 2008). Figure 1 shows the location of all the moorings in the area with a detailed map of those installed in the Congo channel thalweg. The positions and depths of the moorings are listed in Table 1.
On each mooring deployed for this study (Figure 2), there were two sets of instruments, one near the bottom and the other at a shallower level. An RCM8 Aanderaa current meter was attached at 40 or 60 m above the bottom (m a.b.) depending on the mooring situation for the lower set, and a second one at 190 m a.b. (site ZD') or 410 m a.b. (sites ZC, ZD, ZR' and Lobe) for the upper set. A PPS5 or PPS3 Technicap sediment trap was attached 10 m below each of the current meters. At both depths, a TBD turbidimeter (NKE Instrumentation, France) was attached either on the sediment trap or on the current meter, except at site Lobe. At thalweg sites ZD' and ZR', channel depths were approximately 150 m and 250 m, respectively. The upper set of instruments installed at these sites was thus above the rim of the channel.
Figure 3 summarises the mooring periods and the intervals covered by the current data series.

Current speeds and directions recorded with the Aanderaa RCM8 current meters were vector-averaged over 1 h sampling intervals. Temperature and pressure were also measured each hour with a resolution of 0.007°C and 6 dbar, respectively. Throughout the entire experiment, current speed in "normal" conditions never exceeded 15 cm s^{-1}, the value conventionally taken as the upper limit for obtaining reliable flux data in sediment traps

(Heussner *et al.*, 1999). Moreover, current speeds generally ranged from 0 and 5 cm s^{-1} (i.e. 70 to 99% of the time, depending on the location) and only occasionally exceeded 10 cm s^{-1} at the ZC and Regab sites (Table 2). During “extreme” conditions, averaging may considerably underestimate sudden and instantaneous peak current speeds reached during the 1 h sampling interval. In addition, when the current meter is tilted, the vane does not align itself with the flow direction and the compass cannot work properly, causing the current direction data to be unreliable during extreme conditions. Due to some sensor failures, several data series are shorter than the complete duration of the moorings (Figure 3).
The TBD turbidimeters were autonomous devices developed by NKE Instrumentation, France, equipped with a Light Scattering Sensor built by WET Labs, USA. The sensors emit a forward red light beam and measure the optical intensity of the light backscattered from small suspended particles. The value recorded each half-hour is the mean of a burst of 16 measurements taken every 40 ms (in order to minimize the noise). Nevertheless, the signal recorded by an optical sensor is not smooth due to parasitic noise. Owing to difficulties in calibration, data are given in volts, thus allowing only qualitative assessment of turbidity fluctuations. Data series from different turbidimeters could not be quantitatively compared. The turbidimeters are designed to measure low turbidity as encountered in the deep ocean. In this turbidity range, the TBD turbidimeter gives a linear signal output, but it can reach its maximum value when turbidity exceeds the upper limit (saturation), as occurred during the extreme conditions. Pressure was also measured by the turbidimeters every half-hour.
Settling particles were collected with cone-shaped PPS5 or PPS3 Technicap traps with 24 or 12 sampling bottles. These traps have a sampling aperture of 1 or 0.05 m^2 covered with a honeycomb baffle with 10 cm deep cells, each 1 cm in diameter. The sampling interval was 15 or 30 days. Prior to deployment, the sampling bottles were filled with filtered sea water containing sodium borate-buffered formalin to give a final concentration of 3% in order to prevent *in situ* microbial decomposition (Lee *et al.*, 1992). On recovery, samples were stored in the dark at 4°C pending analysis.
The sinking particles collected with sediment traps were much larger (≥ 10µm) than small suspended particles (~ 1µm) which contribute the most to the backscattered light recorded by the turbidimeters. Moreover, the sediment trap provides information on particle flux while turbidity gives particle concentration. In extreme conditions, a tilted sediment trap does not properly collect particles.

4. Results

4.1. Currents and particle fluxes in the Gulf of Guinea

Table 2 shows the maximum and mean current speeds (scalar means) obtained during the successive legs at both levels on each mooring. To calculate these values, data obtained during extreme conditions were removed. Mean speeds generally ranged from 2 to 4 cm s^{-1} and maximum speeds rarely exceeded 10 cm s^{-1}.
Distinct oscillations of variable energy occurred at all locations. Figure 4 shows kinetic energy spectra of the longest data series at each site. At all sites, the energy spectra showed peaks at approximately 12.5 hr (semi-diurnal tide), at 4 to 5 days (inertial period) depending on latitude and at 15 days. These peaks were highest at site Regab and the lowest at site ZC.
Figure 5 displays the vector plots of the longest time series outside the channel and inside the channel. For these plots, the data were low-pass filtered with a cut-off period of 6 days to remove the semi-diurnal and inertial oscillations (periods of 4 to 5 days here) which would obscure the higher periods. Outside the channel, the current had no steady direction but oscillated at high periods. At site Regab, the oscillations followed a WNW-ESE direction. In the channel, at site ZD’, the current was mainly to the NE, which is up-channel. Due to the different oscillations and the low current speeds, the residual circulation was very slow (Figure 6). The residual currents were calculated by averaging the east and north

components over the whole time series (excluding the gaps) obtained at each mooring (durations are indicated in the caption of Figure 6).

The complete description of the particle fluxes measured in the Guinea basin is presented in Rabouille *et al.* (this volume). In short, average total mass fluxes at 400 m a.b. at sites ZC and ZD, calculated from the four-year dataset, were 67.2 and 80.7 mg m^{-2} d^{-1}, respectively. Close to the bottom (at 30 m a.b.), the total mass fluxes were higher than at 400 m a.b. (Figure 7). This increase can be related either to sediment resuspension from the seabed as at site ZC, or to sediment overspill from the channel, as at site ZD. For example, the particle overflow from an event that occurred in the channel in March 2001 (Khripounoff *et al.*, 2003) reached site ZD (Figure 7). During this period, the particle flux suddenly increased from 54 to 3300 mg m^{-2} d^{-1} in the sediment trap positioned at 30 m a.b but was not observed at 400 m a.b. No other sudden increases were recorded at site ZD during the experiment. Total mass fluxes showed little temporal variation at site ZC. A periodicity of 1 yr was observed, with maximum flux in June. At site Regab, the average total mass flux was 141.3 mg m^{-2} d^{-1} calculated from the four-month record.

4.2. Turbidity events in the Congo channel

In this section, we first examine the results from 2002-2003 when there was only one mooring in the channel thalweg at site ZD'. Then, the results of the three moorings simultaneously installed in 2004 at sites ZR', ZD' and Lobe are successively examined. For each site, we first describe currents (and pressure and temperature when relevant), then turbidity and particle fluxes at both measurement levels, first from the lower level (where events are more intense) and then from the upper level (Figures 8, 9, 10 and 11). The instantaneous current directions cannot be shown on these plots as they fluctuated too much due to the above-mentioned short-period oscillations. Their values during the events are given in the text.

Observations at site ZD' in 2002-2003

In 2002-2003, a mooring was installed in the channel axis at site ZD' (Table 1 and Figure 1) for two successive 1 yr periods (Figure 3). No energetic events were detected during either of these two legs. At 60 m a.b. (Figure 8, left, top), the current speed was low, with a mean of 2.5 cm s^{-1} and a maximum of 7.7 cm s^{-1}. Pressure (recorded by the tubidimeter) was stable over the recording period (except the change from 2002 to 2003 related to somewhat deeper re-deployment of the mooring on 01 February 2003), indicating that the moorings in the water column were stable and undisturbed by currents. However, in spite of the low current speeds, there was some local activity in terms of particle concentration and particle flux (Figure 8, left, middle). Distinct peaks in turbidity, with corresponding increases of particle flux in the sediment trap (Figure 8, left, bottom), were measured in December 2001, March, June-July and October 2002 and in February, June and October 2003. No particle flux peak was associated with the turbidity peak in April 2003. There were no increases in current speed during these periods. The particle clouds reached the upper set of instruments above the rim of the channel (180 m a.b.) in March-April 2002 (Figure 8 right, middle and bottom). As for the lower level, turbidity increased without any noticeable increase in current speed.

Observations at site ZR' in 2004

At site ZR' at 3420 m depth in the Congo channel, a mooring was installed from late December 2003 until February 2005, but current data records ceased earlier at both levels (see Figure 3), as did particle flux data at the upper level.

At 60 m a.b., weak currents prevailed from 29 December 2003 to 23 January 2004 at 22:00, with a mean current speed of 3.3 cm s^{-1} and a maximum speed of 7.0 cm s^{-1} (Figure 9, left, top). On 23 January 2004, current speed suddenly increased to 43 cm s^{-1} at 23:00, slowing down to 14 cm s^{-1} at 24:00. Simultaneously, pressure increased 20 dbar, indicating that the mooring was leaning at an angle of 48° relative to its vertical position (the current meter was at 60 m above the bottom and the deepening was 20 m, thus the angle was $\cos^{-1}$ [40/60]). No changes were observed in the temperature data (Figure 9, left, middle). Two hours later, at 01:00 on 24 January 2004, current speed returned to previous values. However, pressure remained slightly higher (1 bit of raw data more, which is approximately 6 dbar), indicating that the mooring may have been displaced by the strong current toward a location 6 m deeper at most. In spite of a general NNE direction (up-channel) during the whole mooring period, the current direction was temporarily to the SW just before the peak, but the current meter rotor had stalled. The current direction turned to 85° and 63° during the current speed peaks. Unfortunately, recording of current speeds stopped shortly after the peak, but the pressure record did not show any indication of other similar peaks for the rest of the experiment.

The turbidity signal fluctuated greatly before, during and long after the current and pressure peaks, with high and up-to-saturated values until ca. 07 March 2004. After that, the signal remained variable, but reached saturated values less frequently.

Meanwhile, the amount of particles collected in the sediment trap increased drastically in the 15 day interval including the current and pressure peaks (23 January to 07 February 2004), from 6.5 to 30 g m^{-2} d^{-1}. The particles sampled during the current and pressure peaks consisted essentially of clay, with small biogenic debris and less than 5% of quartz ≤100µm. During the next sampling interval (07 to 22 February 2004), particle flux returned to the initial relatively low values, concomitant with a slow decrease in the turbidity signal.

After the event of 23 January 2004, several peaks in turbidity with corresponding increases in particle flux were observed in May, June, October, November and December 2004, but without noticeable change in pressure (current data were missing on these dates).

At 410 m a.b., currents were also very weak since the deployment of the mooring on 29 December 2003 until 23 January 2004 at 22:00, with a mean speed of 3.5 cm s^{-1} and a maximum speed of 8.0 cm s^{-1} (Figure 9, right, top). At 23:00 and 24:00, current speeds increased to 40 and 22 cm s^{-1}, respectively, while pressure increased 112 dbar. A pressure increase of 112 dbar at this level corresponds to an angle of 43°, an angle comparable to the 48° angle found at 60 m a.b. At 23:00, the temperature decreased from 2.34 to 2.27 °C. This sudden decrease of 0.07 °C exceeded the usual fluctuations recorded during the experiment (Figure 9, right, middle), and can be explained by the temporary deepening of the sensor. By this time, the current was in an inertial oscillation. The direction was thus slowly turning anticlockwise to the east with no jump during the peaks in current speed. As at the deeper level, the current speed record unfortunately stopped soon after the event, but pressure recordings did not show any indication of other similar events for the rest of the experiment.

The turbidity signal was low at the upper level, with much fewer peaks than at the lower level (Figure 9, right, middle). This observation is consistent with the lower flux of particles sampled by the sediment trap (Figure 9, right, bottom). At the upper level, there was no evidence of a turbid cloud related to the 23 January 2004 event, indicating that it did not reach the top of the valley.

Observations at site ZD' in 2004

After the deployments in 2002 and 2003, the mooring at site ZD’ in the Congo channel was deployed again late December 2003 for 1 yr at 4070 m depth, but it unexpectedly surfaced in October 2004.

At 60 m a.b**.** (Figure 10, left, top), current speed was low until 24 January 2004 at 18:00 with a mean of 2 cm s^{-1} and a maximum of 7 cm s^{-1}. On 24 January 2004, current speed suddenly increased to 61, 76 and 46 cm s^{-1}, at 18:00, 19:00 and 20:00, respectively, while pressure increased from 4026 dbar to 4088 dbar. After the event, pressure did not return to its previous value, remaining approximately 15 dbar higher, indicating that the mooring had been displaced to a deeper position. Taking this displacement into account, the mooring tilt angle would be approximately 64°. The current direction was roughly eastward or north-eastward before the peaks and stayed at 98°, 100° and 79° during the speed peaks.

Some substantial temperature fluctuations appeared a short time after the current speed peaks (Figure 10, left, middle) with a small peak at 2.414 C on 31 January 2004, i.e. one week later. These temperature increases were isolated and appeared only once in the data record.
The turbidity was low and stable in the initial part of the record, but became much more variable with higher values just before the 24 January 2004 event. During the event and until one week later, turbidity remained at saturated values, then decreased slowly during one month before returning to initial values in late February.
The high particle flux value of 130 g m^{-2} d^{-1} for the first sediment trap sample (08 January 2004 to 07 February 2004) that included the event confirmed the high intensity of the event. The collected material was very rich in quartz (60% of the >63 µm fraction) with very little biogenic debris.
After the January 2004 event, current, temperature and pressure data indicated a quiescent period for the rest of the experiment. However, in May 2004, a distinct turbidity peak occurred, corresponding to a high particle flux peak. Moreover, the last trap sample of October 2004, which was recovered when the mooring unexpectedly surfaced, was full of particles. The material collected in May and October 2004 was composed of diatom debris, clay and quartz ≤ 25µm.
At 190 m a.b., (Figure 10, right), the 24 January 2004 event was recorded at the same time as at 60 m a.b., but with higher speed values of 79, 96 and 49 cm s^{-1}, at 18:00, 19:00 and 20:00, respectively. Meanwhile, the pressure sensor registered an increase from 3904 to 4050 dbar which indicates again that the mooring line formed a wide angle relative to its vertical position. These pressure data gave a tilt angle of the mooring of 71°. There was no significant temperature change during the event (Figure 10, right, middle). By this time, the current was in inertial oscillation and was to the east, 111°, 99° and 77° during the speed peaks. After the event, the current speed record stopped on 31 January 2004 because the rotor stalled, possibly as a result of damage caused by the event. The pressure became 16 dbar higher due to displacement of the mooring. Temperature and pressure records again indicated very calm conditions without any events for the rest of the experiment.
After an initial period of low and stable values, turbidity increased one week after the event, after which it took one month to return to the initial low values (end of February 2004). This was the same pattern observed at the lower level, but with a one-week delay (Figure 10, right, middle). A similar delay was observed in particle flux, which showed a five-fold increase in the second sample (07 February 2004 to 08 March 2004) relative to the first sample. This delay probably reflects the time needed for the particle cloud to reach the altitude of the sediment trap at 180 m a.b. The material collected in the trap was essentially composed of clay during the entire experiment.
After the January 2004 event, turbidity and particle flux peaks as observed at 60 m a.b. in late May and at the end of the recording period were also recorded at 180 m a.b., again without simultaneous pressure change. The last trap sample also collected a large amount of particles (but less than at 180 m a.b.) when the mooring broke in October 2004.

Observations at site Lobe in 2004

At site Lobe at 4790 m depth in the Congo channel, a mooring was installed from January 2004 until February 2005. The large amount of particles collected in the lower trap from 23 January to 22 February 2004 (not shown) indicated the occurrence of a turbidity event. Although the other types of data do not show it as clearly as at other sites, they are examined to determine when the event occurred.
At 60 m a.b., no drastic changes were observed in pressure data (not shown), nor in current speed data (Figure 11), except for a slight peak at 8.4 cm s^{-1} at 17:00 on 04 February 2004. As there was no turbidimeter on this mooring, it is difficult to confirm whether this increase is the signature of a turbidity event. However, the correlation with increased variability in temperature observed at the same period gives reason to assume that some type of unusual phenomenon occurred. The temperature started to rise to higher values with higher variability

on 31 January 2004 at 04:00, i.e. slightly earlier than the current speed peak. These are the only indications of the possible arrival of an event. No signs of other similar events were observed in the records. By this time, the first trap sample collected a small amount of particles, but the second and third samples (23 January 2004 to 22 Febraury 2004, time period which would include the putative event) were completely filled with particles (not shown). Due to this very intense deposition event, the trap was clogged and subsequently failed shortly after the event. The collected material contained abundant small quartz (≤ 50µm) diatom debris, amorphous particles and plant debris.

At 410 m a.b., no significant changes appeared, neither in current speed nor in pressure or in temperature data (not shown). Unfortunately, the sediment trap at 410 m a.b. failed.

5. Discussion

5.1. Hydrodynamic variability in the Gulf of Guinea

The most conspicuous feature of the deep currents in the Gulf of Guinea was the very weak currents affected by high temporal variability in three distinct period bands: semi-diurnal tidal oscillations, inertial oscillations (4-5 days) and 15 day oscillations. Biweekly oscillations have been previously reported at the BIOZAIRE site ZA (Vangriesheim *et al.*, 2005) and were attributed to coastal-trapped waves (CTW) by Guiavarc'h (2007) and Guiavarc'h *et al.* (2008). By means of a high-resolution model, these authors demonstrated that 15 day oscillations are not tide related, but forced remotely by equatorial winds. It is interesting to note that CTW propagate near the Congo channel down to depths of 3100-3400 m (sites Regab and ZR'), 4000 m (site ZD), and 4800 m (site Lobe), but much less at site ZC which is also located at 4000 m. CTW were more energetic at site Regab where they appear to be bottom-intensified, as at site ZA. However, at site Regab, the oscillations were well polarized along a WNW-ESE direction (283°) probably following the orientation of the Congo channel, while those at site ZA were parallel to the margin (i.e. 333°) (Guiavarc'h *et al.,* 2008). In future research, it would be relevant to study the influence of the Congo canyon/channel on the propagation of CTW.

The residual currents calculated for each of the deep sites outside the Congo channel (Figure 6) were in agreement with the expected direction (east and/or south) of the deep-water flow in this area (Arhan *et al.*, 2003). Residual currents calculated for the upper levels at channel sites ZR' and ZD' had the same features seen at other deep sites. In contrast, the currents at the lower levels, below the channel rim, were very topographically controlled. They were almost continuously oriented up-channel (Figure 6) which is consistent with the residual currents at the outside-channel sites.

5.2. Turbidity events and their velocities in the Congo channel

Our observations showed two different kinds of turbidity events inside the channel. The first is sudden, short and very intense particle events (recorded as peaks in turbidity and particle flux) associated with strong current events, e.g. January 2004, similar to the 2001 event already described in Khripounoff *et al.* (2003). The second kind of event is characterized by particle events (also recorded as peaks in turbidity and particle flux), but without corresponding change in current speed. Below, we discuss the different observations in more detail.

The 2004 data from three moorings along the channel allowed a better understanding of the first type of turbidity events. At this stage, we must mention that it is obvious that, during the events, the current speeds recorded by the RCM8 current meter greatly underestimated the maximum speed reached during the 1 h averaging interval. For example, a current speed value of 100 cm s^{-1}, obtained by averaging over 1 h could result from 45 minutes at 3 cm s^{-1} (the background mean speed) and 15 minutes at 400 cm s^{-1}. In addition, the tilt of the moorings caused the current meter rotors to function poorly. This underestimation explains why the tilt angles of the moorings were so high (43-48° at site ZR' and 64-71° at site ZD') during the events compared to the current speed values recorded. Moreover, the high particle load in the water during the events probably increased the drag on instruments thereby increasing the tilt angle of the mooring. In the following, we discuss the current speed values during the events, keeping in mind that they are highly underestimated.

At site ZR', although the current peaks occurred at both levels, particle peaks were only seen in the lower trap. At site ZD', the current peaks arrived 19 hr later than at site ZR' and lasted for approximately 3 hours. There is evidence that the turbidity current event gained energy travelling from site ZR' to site ZD' where the current reached higher values and the mooring was more tilted and pulled 16 m deeper. Moreover, at site ZR', the maximum speeds recorded at the two levels were of the same order (43 cm s^{-1} at 60 m a.b. and 40 cm s^{-1} at 410 m a.b.) while at site ZD', current speed was higher at 190 m a.b. (96 cm s^{-1}) than at 60 m a.b. (76 cm s^{-1}). In addition, at ZD', large particles arrived in greater amounts at the lower level (130 g m^{-2} d^{-1} at ZD' compared to 30 g m^{-2} d^{-1} at ZR') during the event and even reached the upper level—as did the fine particle cloud—at this site, but not at ZR'. From the 19 hr time difference between the arrival of the event at sites ZR' and ZD' and the 240 km distance between the two mooring sites (measured following the meanders; Babonneau *et al.,* 2002), we estimated the velocity of the event at 3.5 m s^{-1} (12.6 km h^{-1}). This velocity is consistent with current speeds possibly reached during the time interval of our current measurements. At site Lobe, the high particle deposition, which clogged the trap, was not linked to strong current speed and pressure signals as at ZR' and ZD'. The exact moment of its arrival cannot be determined from the 15 day interval during which the trap samples were taken. However, assuming that the simultaneous small changes in current speed and temperature observed at the lower set of instruments (Figure 11) are indeed due to the arrival of the turbidity event, we could estimate its velocity. There are 380 km (measured following the meanders) between ZD' and Lobe, thus the velocity of the event would be 0.7 m s^{-1} (2.4 km h^{-1}). This relatively low velocity, much less than between sites ZR' and ZD', is consistent with the lower energy and weaker signatures only observed in the lower set of instruments at Lobe.

The current direction data are more difficult to interpret as they are unreliable during high-speed events. According to the data, the deepest currents would have been up-channel during the events, an unexpected finding. At the upper levels, above the channel rim, currents were up-channel during an anti-clockwise inertial oscillation. However, due to the uncertainty as to the reliability of the vane and the compass readings when the current meter is tilted, these data most likely do not reflect the actual values reached during the turbidity current events.

This first direct observation of a turbidity event moving along the channel from 3420 m (site ZR'), to 4070 m (site ZD') and then to 4790 m (site Lobe) corroborates what geologists had previously inferred about the behaviour of such events (Babonneau *et al.*, 2002; Dennielou and Jouanneau, 2003). In particular, our observations confirm that at site ZR' at 3420 m, the vertical extent of the particle cloud was insufficient to reach the rim of the channel, while it spilled over the channel rim at ZD' at 4070 m. The 2001 event that occurred at site ZD' had higher energy than the January 2004 event reported here, with a current speed reaching 120 cm s^{-1} (Khripounoff *et al.*, 2003). As a result, its spillover had a much larger horizontal extent and was even recorded at site ZD, 13 km south of the channel axis.

To our knowledge, there are no other direct current observations along such channel as long as the Congo channel to compare our results with. Observations in the Monterey canyon (Xu *et al.*, 2004), also a river-connected canyon, are restricted to shallower depths at much shorter distances from the coast (we have no observations in the Congo canyon at comparable distances). Nevertheless, Xu *et al.* (2004) observed current speeds reaching 190 cm s^{-1} near the bottom and estimated the speed of propagation to be 1.7-2.8 m s^{-1} (6-10 km h^{-1}). At the lower levels in the Congo channel, we recorded lower maximum current speeds of 43 cm s^{-1} at ZR' and 76 cm s^{-1} at ZD', but velocities of 3.5 m s^{-1} and 0.7 m s^{-1} (12.6 and 2.4 km h^{-1}), respectively, which are similar to those recorded in the Monterey canyon at

much shallower depths. In the Congo channel, the event reached great distance and depth, with high velocity in spite of the numerous meanders that could have reduced the progression speed. This suggests that the turbidity event we observed had particularly high energy.
The origin of these turbidity events is usually attributed either to instability of accumulated sediments, to bad weather conditions onshore, to river floods or, less frequently, to earthquakes or human activities. Meteorological conditions play a more important role in areas where the continental shelf separates the canyon from the coast, and where storms and swell on the shelf trigger sediment instability in the canyon head (Puig *et al.*, 2003; Palanques *et al.*, 2006; Xu *et al.*, 2004). In the Congo canyon, where there is no shelf sediment accumulation between the river and the canyon, turbidity events probably originate with the flooding of the Congo River which usually occurs around December. River floods feed the canyon with terrigenous sediments which accumulate in the head until they become instable under their increasing load. The previous strong event described by Khripounoff *et al.* (2003) occurred in early March 2001, while the major event described in the present study occurred in late January 2004 (i.e. a difference of only one month). We have no data on Congo River floods in 2004 to confirm a correlation with the turbidity events. In 2004, a slight positive temperature anomaly was observed during the passage of the turbidity event at sites ZD’ and Lobe. These temperature increases are consistent with a rapid transport of warmer water from up-canyon. However, at site ZR’, no such positive temperature anomaly was recorded during the event. Although rapid water transport from the river mouth probably induces a significant temperature change at shallower depths, the higher natural variability at these depths may obscure any changes in temperature due to the arrival of waters of shallower origin. Thus, we can only assume that the 2004 event was related to increased sediment discharge during the Congo River flood season, but we cannot infer at what depth the event started, whether it comes directly from the river mouth at this moment or from an other location between the mouth and site ZR’. Mulder and Syvitski (1995) discount the possibility of direct underflow from the Congo River. In this case, turbidity events are probably triggered by the instability of accumulated sediments.

The second kind of particle event is not related to current events (increase in current speed and/or pressure changes). At site ZD’, this type of turbidity event was observed in 2002-2003 and at sites ZR’ and ZD’ after the January 2004 event. It is not clear how to interpret these particle clouds, which rose to at least 410 m in height above the channel bed at ZR’ and 190 m high at site ZD’. We assume that the intense turbidity currents observed in 2001 (Khripounoff *et al.*, 2003) and in 2004, rich in sand, eroded the channel walls. The observed particle clouds could then be the result of unstable sediment slumping from the channel walls as previously suggested by Babonneau *et al.* (2002). The particles were essentially composed of clay during these events, which is in good agreement with our erosion hypothesis.
Nevertheless, even if these particle clouds do not come from an extreme turbidity event originating in the Congo River estuary, it is likely that they could travel slowly along a part of the channel. For example, the turbidity and particle flux increases observed in May 2004 at both ZR’ and ZD’ occurred with an 11 day lag. These increases happened during a period when the current (at ZD’ only since the data at ZR’ are missing) reversed to the south-west instead of the more frequent up-channel direction. This change in direction supports the hypothesis of slow particle transport down the channel.

Finally, on 7 October 2004, in spite of very quiet current conditions (Figure 10), the mooring line at site ZD’ broke and the mooring came to the surface. There was no sign on the mooring gear or in the current and turbidity data indicating that this break was due to a new strong turbidity event. However, the sediment traps at both depth levels collected a large amount of particles during the three days before the mooring surfaced. From numerous other sediment trap studies, we know that the amount of particles collected while the trap rises (surfacing within a few hours) is negligible compared to those collected when the mooring was in place (a few days, weeks or months). Moreover, in the present case, the particle composition was that of a deep layer, not the water column. At site ZR', one of the turbidity peaks with high associated particle flux following the January 2004 event occurred on 7 October 2004, thus corresponding to when the ZD' mooring broke. This coincidence may indicate a very rapid event travelling from ZR' to ZD'. Unfortunately, current speed data are lacking for both depth levels (due to a stalled rotor) for this interval at site ZR' and sediment trap data for the upper level is also missing. Even without conclusive data, the above observations provide circumstantial evidence to suspect that a sudden and energetic turbidity event was responsible for the mooring line break at site ZD' on 7 October. Hence, this turbidity event would be the third turbidity current event, similar to those previously observed (March 2001, January 2004).

Whatever the exact starting location of the turbidity events, we observed that particle transport may reach the lobe area on the extreme end of the Congo channel, more than 1000 km (following the meanders along the channel axis) from the Congo estuary. Before reaching this point, however, turbidity currents may sometimes spill over the edges of the channel and spread far over the channel levees. This type of overflow can be deduced from geological observations (Babonneau, 2002), and was directly observed at site ZD during the 2001 event (Khripounoff *et al.*, 2003), but not during the 2004 events. According to Babonneau (2002), spillover only becomes possible when the valley relief decreases enough, i.e. at approximately 4000 m. Like Van Bennekom (1996), we assume that there is a relationship between the spillover of turbidity currents and the oxygen and nutrient anomalies observed in the near-bottom water column at approximately 4000 m depth (Braga *et al.*, 2004; Vangriesheim *et al.*, this volume). The remineralisation of particulate organic matter supplied by turbidity currents consumes oxygen from the near-bottom water and releases nutrients. On a CTD section performed along the canyon/channel (Vangriesheim *et al.*, this volume), these anomalies appear near the bottom at approximately 4000 m, never shallower. These anomalies then propagate horizontally in the water column at greater depths staying at approximately 4000 m with a slight rising. At the Lobe CTD station (4800 m), in addition to the 4000 m anomaly, a second, similar, but less intense anomaly appeared directly on the bottom. It is again interpreted as the consequence of the organic carbon remineralization of the organic particulate matter arriving in large amounts on the seafloor at the lobe. This strongly suggests that depths of 4000 m and the lobe are areas where the input of turbiditic sediments from the Congo channel is the highest. At approximately 4000 m, overflows are probably more erratic and variable in intensity. At the lobe, the sediment arrivals are probably more frequent and less intense, due to the lower energy of the events at this location. At this location, the surface sediment of the seafloor is directly influenced by these inputs (Rabouille *et al*., *this volume* and Ragueneau *et al.*, *this volume*) which may have consequences on the fauna living in the sediment surface layer compared to those living at other depths in the Gulf of Guinea basin.

6. Conclusion

The long-term moorings installed in and around the Congo submarine channel from late 2001 to early 2005 that measured current, temperature, pressure, turbidity and particle flux enabled us to identify two kinds of turbidity events: those associated with high energy and sediment transport and those without significant changes in current intensity.
In January 2004, a strong turbidity event was observed at all three moorings deployed along the channel at different depths (3420 m, 4070 m and 4790 m). It caused sudden jumps in current speed and moorings were tilted and displaced at sites ZR' (3420 m) and ZD' (4070 m). The turbidity and particle flux peaks reached the instruments located nearest the

bottom of the channel at sites ZR', ZD' and Lobe (30, 50 and 30 m a.b. respectively), but also reached the upper level instruments (180 m a.b.) at site ZD'. This is congruent with the possibility of overflows near the site ZD' as suggested by geological observations. However, the 2004 overflow did not reach site ZD, 13 km south of the channel, indicating that the energy of the 2004 event was lower than the 2001 event (Khripounoff *et al.*, 2003). There is evidence that the 2004 event gained energy between sites ZR' and ZD', but lost energy between sites ZD' and Lobe. The average velocity of the event along the channel meanders was calculated to be 3.5 m s^{-1} between ZR' and ZD' and 0.7 m s^{-1} between ZD' and Lobe. As for the 2001 event, the origin of the event may be related to the Congo River flood season.
The mooring line break in October 2004 at site ZD' was probably due to the same type of event. Though no current and turbidity peaks were recorded, the traps at both depth levels collected a large amount of particles. Almost simultaneous peaks in turbidity and particle flux at site ZR' support the hypothesis that a very sudden event propagating along the channel caused the mooring line to break, as in the 2001 event.
Between the strong turbidity events, smaller events were observed in turbidity and particle flux without obvious changes in current speed, pressure or temperature. As there was no indication of strong energy transporting these small turbidity events from far up in the valley, we assume that they were of local origin, possibly related to sediment slumping from the channel walls and/or terraces. However, there are indications that these clouds could be sometimes slowly transported over long distances, although more observations are needed to confirm this.
The results of the present study show that the Congo channel is a very active system with highly energetic turbidity currents causing rapid transport of large quantities of sediment over very long distances. Our observations at 3420 m and 4070 m are in accordance with hypotheses based on geological data that these flows with high concentrations of sediment rich in organic matter can only overflow the channel when the trough height is sufficiently shallow, i.e. at water depths higher than approximately 4000m. The existence of water column anomalies in oxygen and nutrients near the bottom at approximately 4000 m (Vangriesheim *et al.*, this volume) related to remineralisation of particulate organic matter discharged by turbidity currents, indicates that it is around this depth that the turbiditic particle overflow is at a maximum. Similar, but less distinct, bottom water anomalies at the lobe site suggest that this area has also a high particulate organic matter input.

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Tables

Table 1:
Geographical positions (degrees and decimal minutes) and depths of the long-term moorings installed during the BIOZAIRE programme (map shown in Figure 1).

	2000	2001	2002	2003	2004-2005
Site ZC	S 07° 40.451 E 009° 59.954 4000 m	S 07° 40.500 E 009° 59.890 3981 m	S 07° 40.333 E 009° 59.405 3996 m	S 07° 40.422 E 009° 59.288 4000 m	
Site Regab				S 05° 47.947 E 009° 42.675 3151 m	
Site ZD	S 05° 50.657 E 008° 20.927 3963 m	S 05° 50.700 E 008° 21.260 3951 m	S 05° 51.427 E 008° 20.659 3958 m	S 05° 50.915 E 008° 20.983 4000 m	S 05° 50.237 E 008° 20.517 3974 m
Site ZR'					S° 05 51.171 E 009 39.955 3420 m
Site ZD'		S 05° 43.160 E 008° 26.992 4051 m	S 05° 43.118 E 008° 27.003 3975 m	S 05° 43.100 E 008° 26.975 4053 m	S 05° 43.139 E 008° 27.033 4067 m
Site Lobe					S 06° 28.143 E 006° 02.069 4788 m

Table 2:
Statistics for the current speed data series obtained during the BIOZAIRE programme. For each site, the top line corresponds to the upper level of measurements and the bottom line corresponds to the lower level of measurements; the distance in meters above the bottom (m a.b.) is indicated. For these computations, measurements during extreme conditions were removed from the data series.

Site	**years**	**m a.b. (m)**	**Duration (days)**	**Max speed (cm s^{-1})**	**Mean speed (cm s^{-1})**	**% speeds less than 5 cm s^{-1}**	**% speeds between 5 and 10 cm s^{-1}**	**% speeds higher than 10 cm s^{-1}**
Site ZC	2001-2002	410	753	10	3	85.9	14.1	0
	2000-2002	30	1035	11	3	85.3	14.7	0 *(0.03)*
Site Regab	2003	360	330	8.9	3.6	79.6	20.4	0
	2003	15	330	12.3	4.1	70.8	29.0	0.2
Site ZD	2000-2004	410	1769	9.1	2.5	95.7	04.2	0
	2000-2002	30	1021	9.7	3	93.7	06.3	0
Site ZR'	2004	410	133	9.9	3.4	81.4	18.6	0
	2004	60	50	8.7	3.4	83.6	16.4	0
Site ZD'	2001-2003	190	659	8.7	2.4	74.6	0.90	0
	2001-2004	60	1101	7.8	2.4	97.5	02.5	0
Site Lobe	2004	410	237	6.3	1.9	99.4	0.60	0
	2004	60	414	8.4	3.4	89.8	10.2	0

Figures

Figure 1

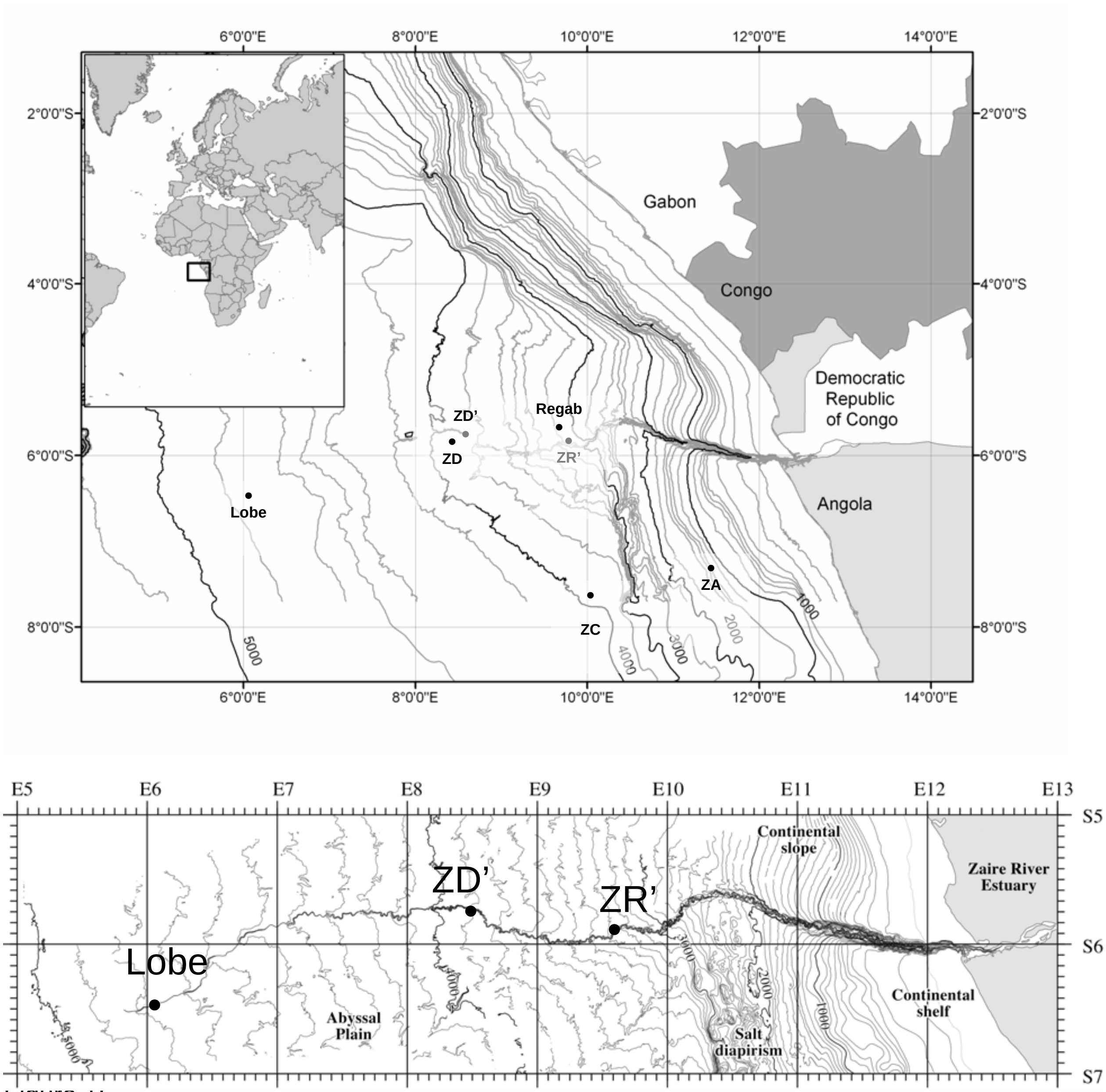

Figure 1:
Top: Locations of the long term moorings installed during the BIOZAIRE programme.
Bottom: Bathymetry of the Congo channel area (from Babonneau *et al.*, 2002) with locations of the long-term moorings installed in the valley at sites ZR', ZD' and Lobe.

Figure 2

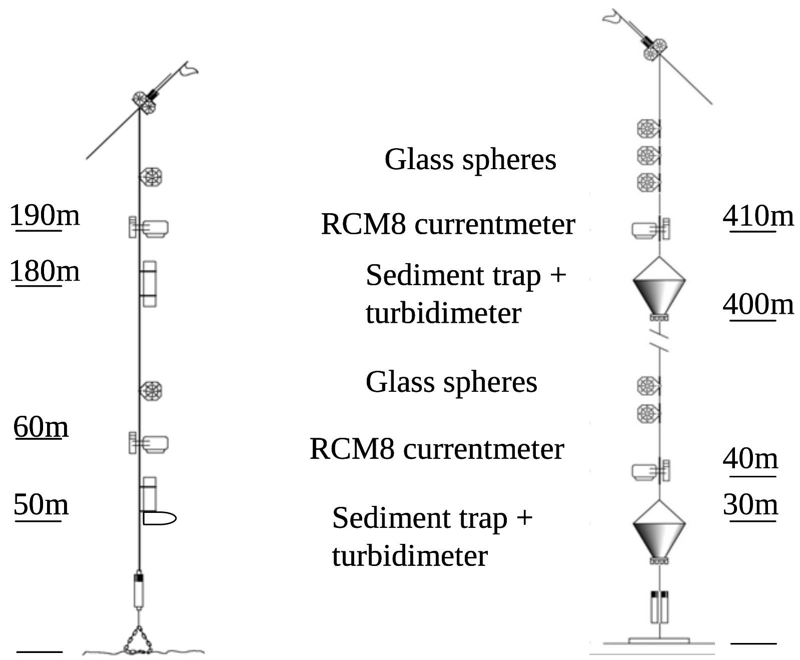

Figure 2:
Diagrammes of the moorings deployed at sites ZD’ (left), ZR’ and Lobe (right).

Figure 3

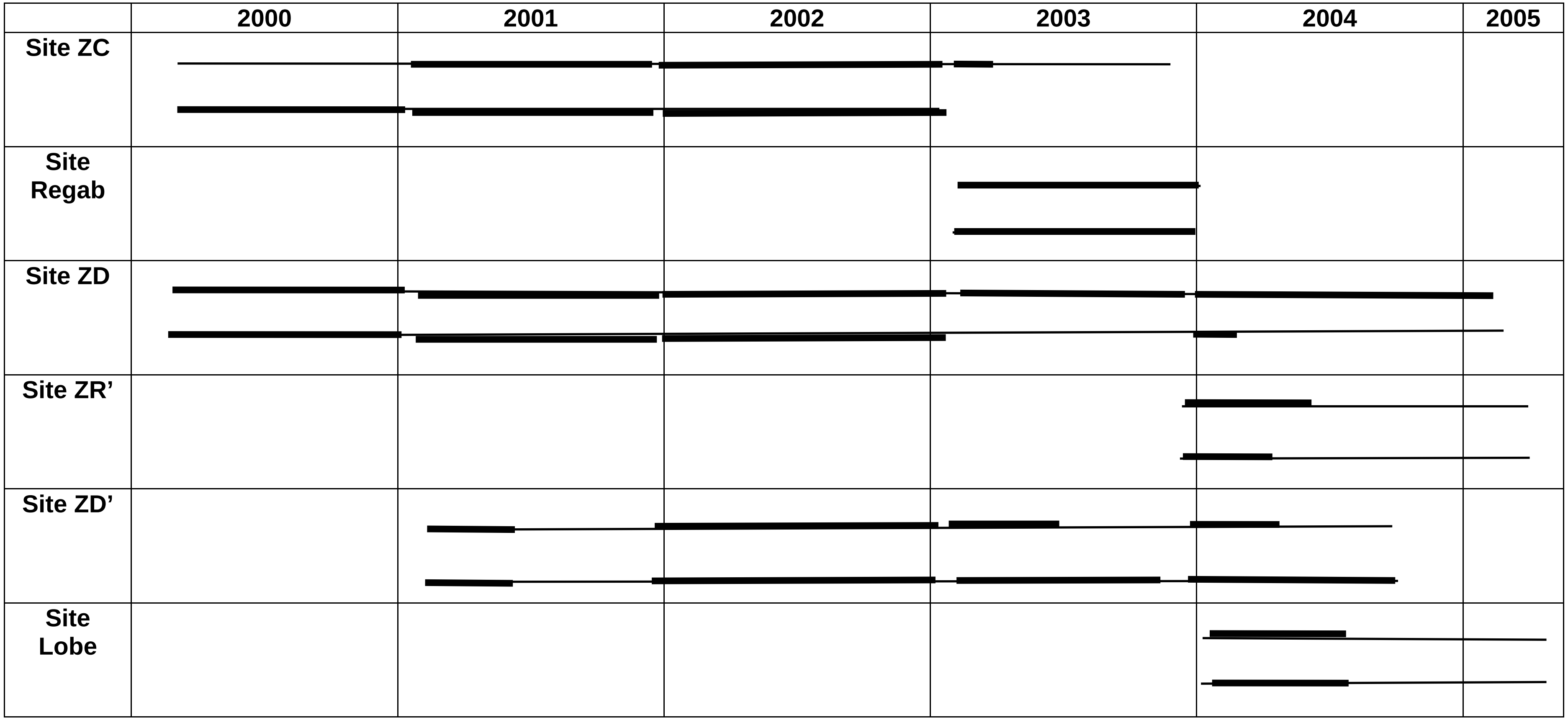

Figure 3:
Duration of the long-term moorings installed during the Biozaire programme. For each site, the upper and lower lines represent the mooring deployment periods at the upper and lower levels of measurement, respectively. The bold lines are the time periods over which current data was properly recorded.

Figure 4

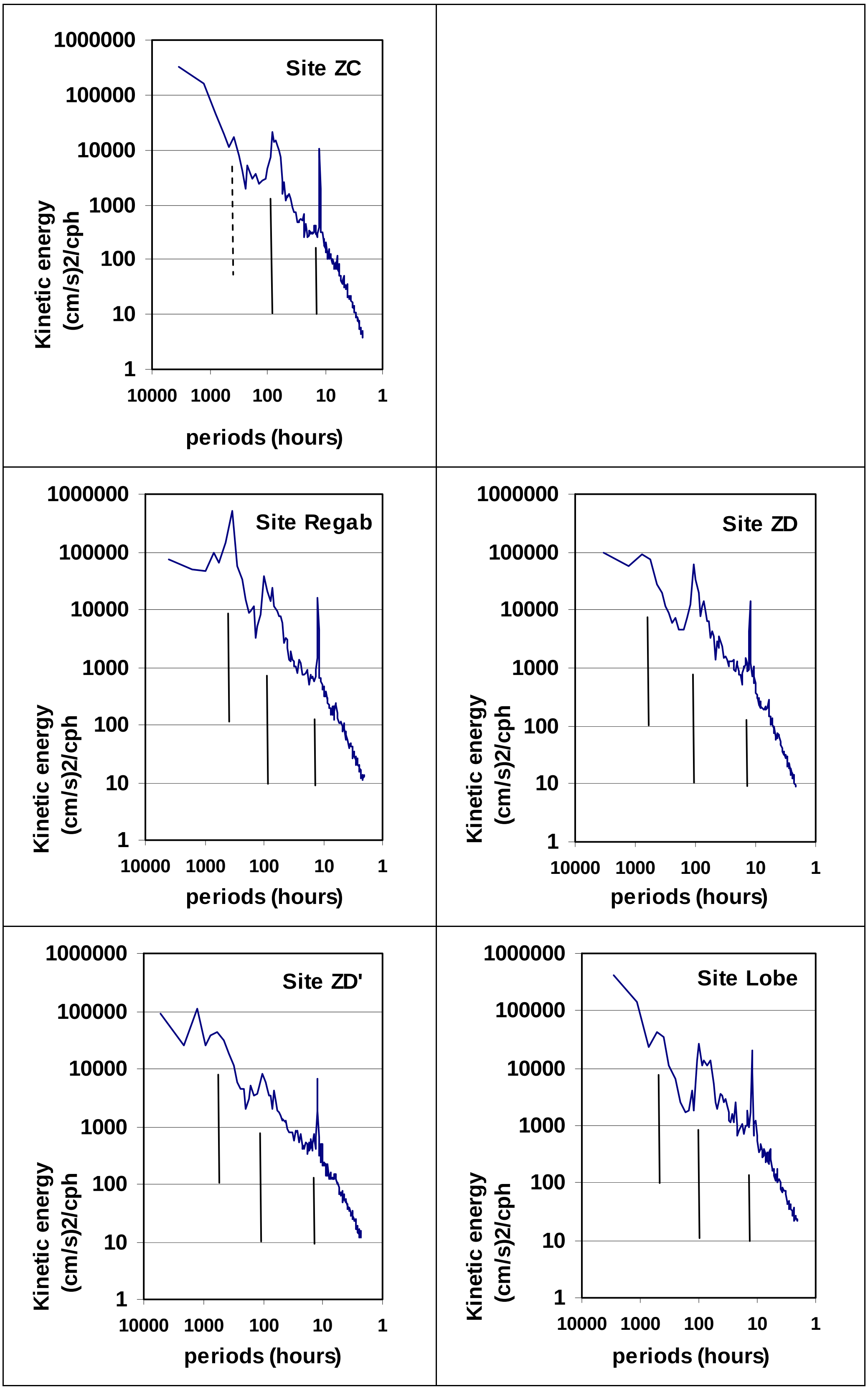

Figure 4:

Kinetic energy spectra for the longest instantaneous time series (time interval: 1 h) without gaps at the lower levels at the reference site ZC (433 days), at the sites Regab (330 days) and ZD (431 days) and at the sites ZD' (431 days) and Lobe (237 days) in the Congo channel. The site ZR' site was omitted as the time series was too short. The three main peaks at the 15 day, inertial and semi-diurnal periods are indicated. To calculate the spectra, mean values were removed from the time series which were processed using a Hanning window. Energy densities were then averaged over adjacent frequency bands depending on the time covered by the series.

Figure 5

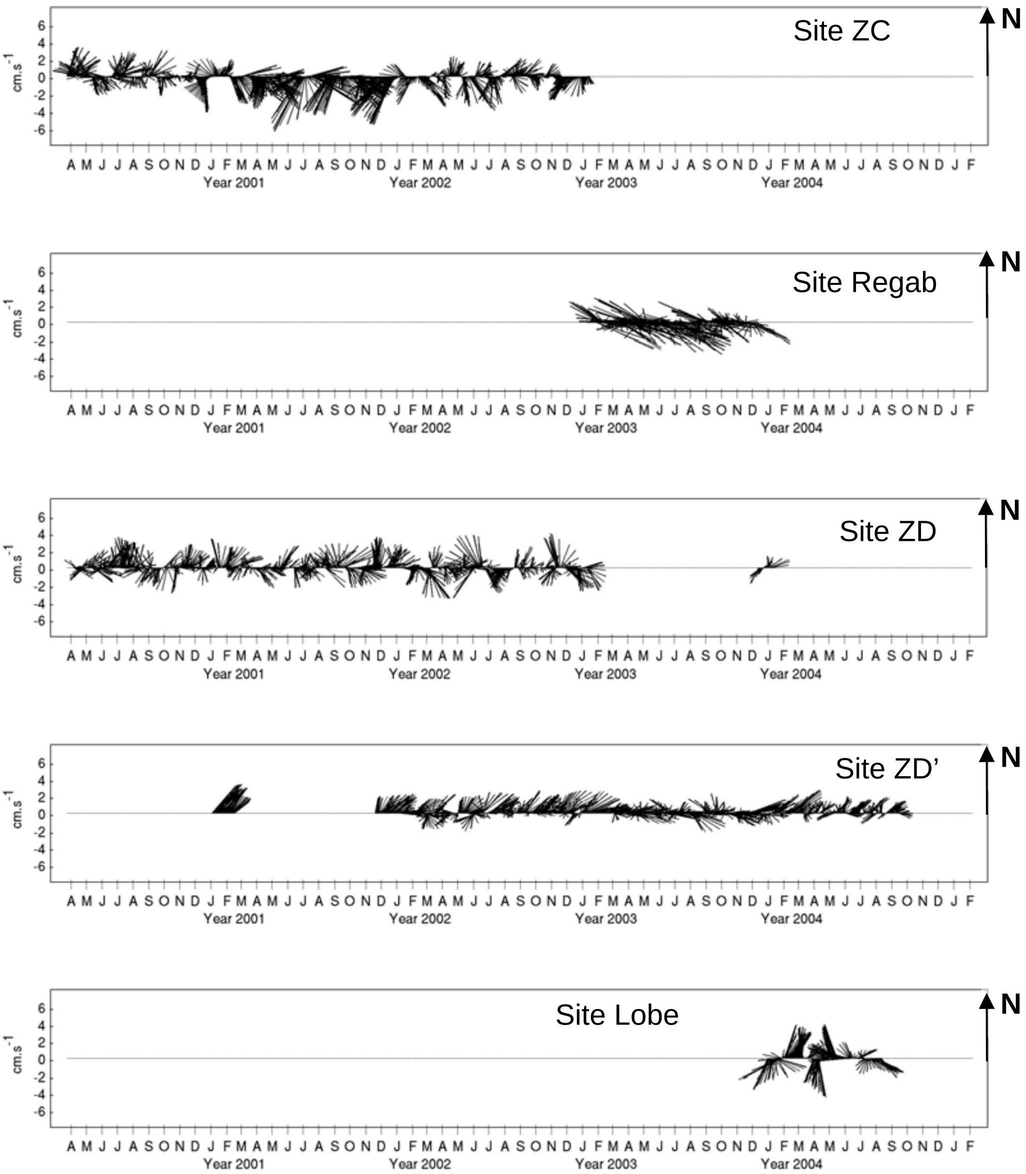

Figure 5:
Vector plots (low pass filtered data, cut-off at 6 days) of the currents measured at the lower levels at the reference site ZC, at the sites Regab and ZD and at the sites ZD' and Lobe in the Congo channel. No plot is given for the site ZR' where the time series was too short.

Figure 6

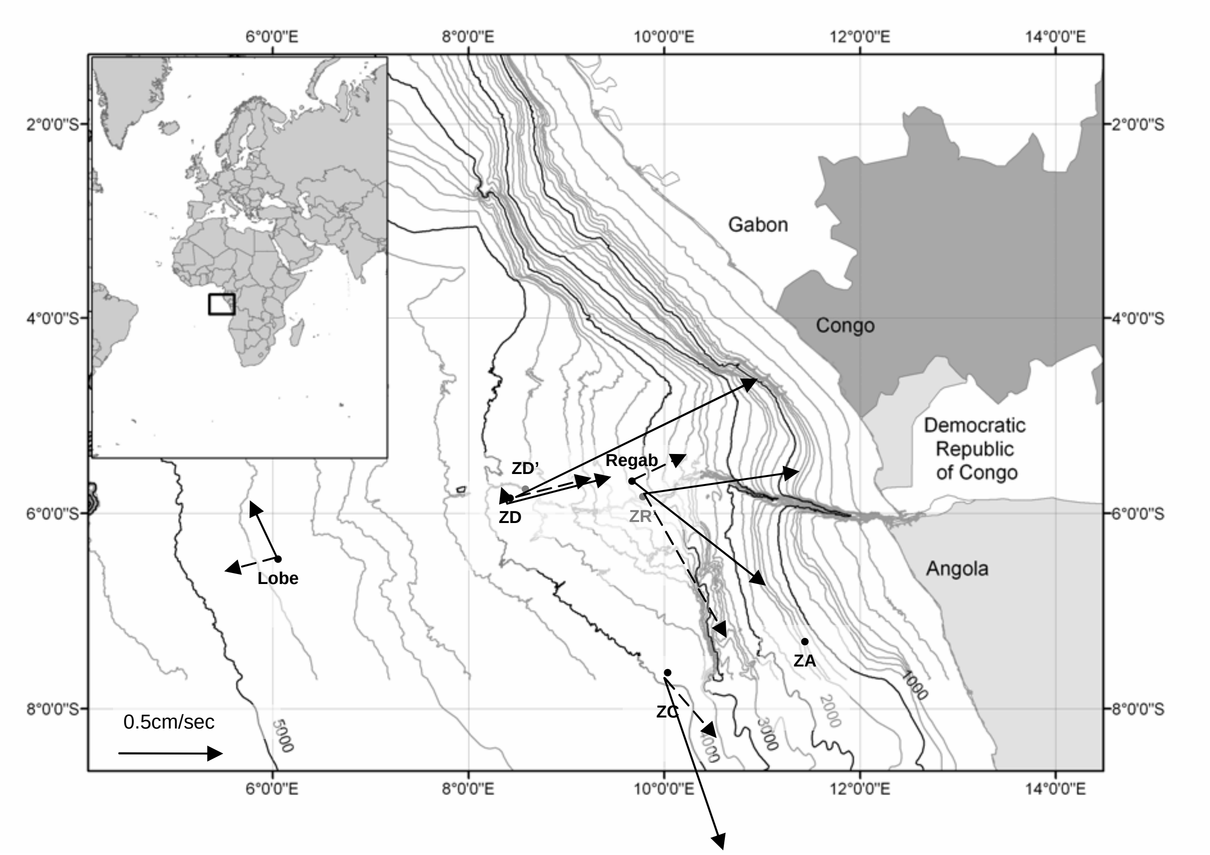

Figure 6:
Residual currents averaged over the whole time series obtained at each lower-level of the moorings. The dashed line is the upper level and the solid line is the lower level. The durations of the time series at the upper and lower levels were, respectively, 743 and 1025 days at site ZC, 1766 and 1039 days at site ZD, 667 and 1080 days at site ZD', 330 and 330 days at site Regab, 123 and 37 days at site ZR' and 225 and 225 days at site Lobe. Mean north and east components were calculated taking gaps into account to obtain the mean vectorial current over the longest time series.

Figure 7

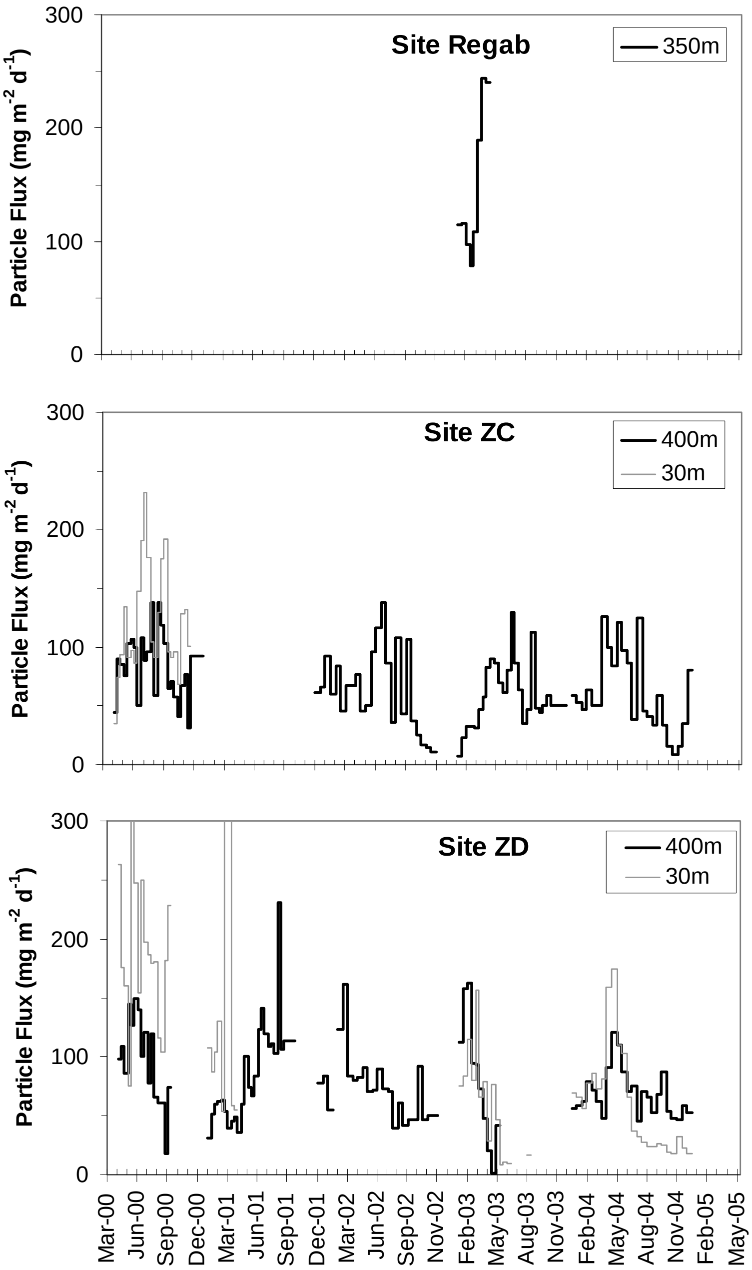

Figure 7:
Total particle fluxes for 2000-2004 at the out-of-channel sites: Regab, ZC, ZD (lower level of measurement in grey, upper level in black, when available).

Figure 8

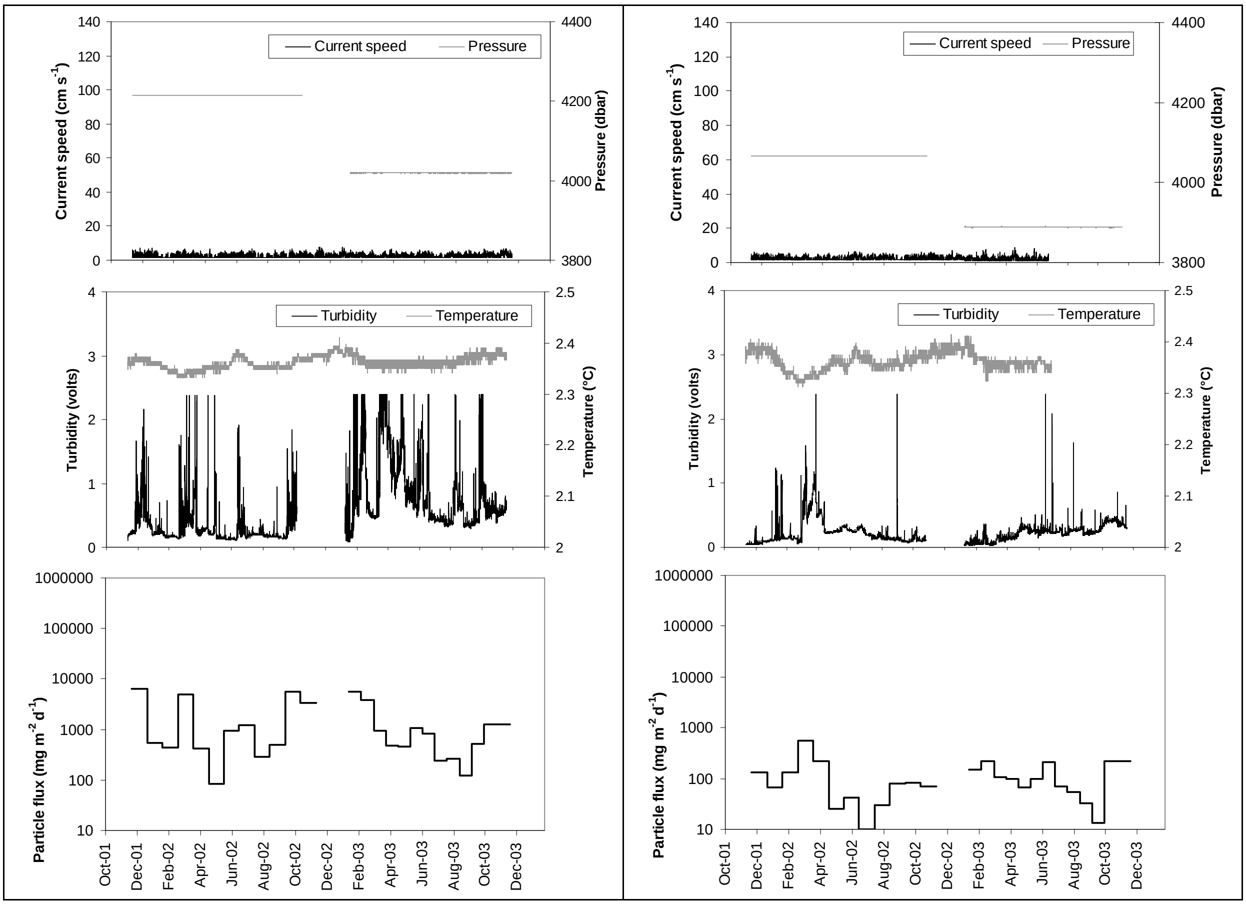

Figure 8:
Long-term measurements at site ZD’ in the channel in 2002 and 2003 (instantaneous data).
Left panels, measurements at the lower level; right panels, upper level.
Top panels, current speed and pressure (recorded using a TBD turbidimeter); middle panels, turbidity and temperature; bottom panels, total particle flux (note the logarithmic scale for the particle flux axis).
Due to battery failures, the two turbidimeter records cease before the end of the first mooring period. The pressure changed between the two data series because the second mooring was not at the exact same location as the first one (redeployment on 01 February 2003).

Figure 9

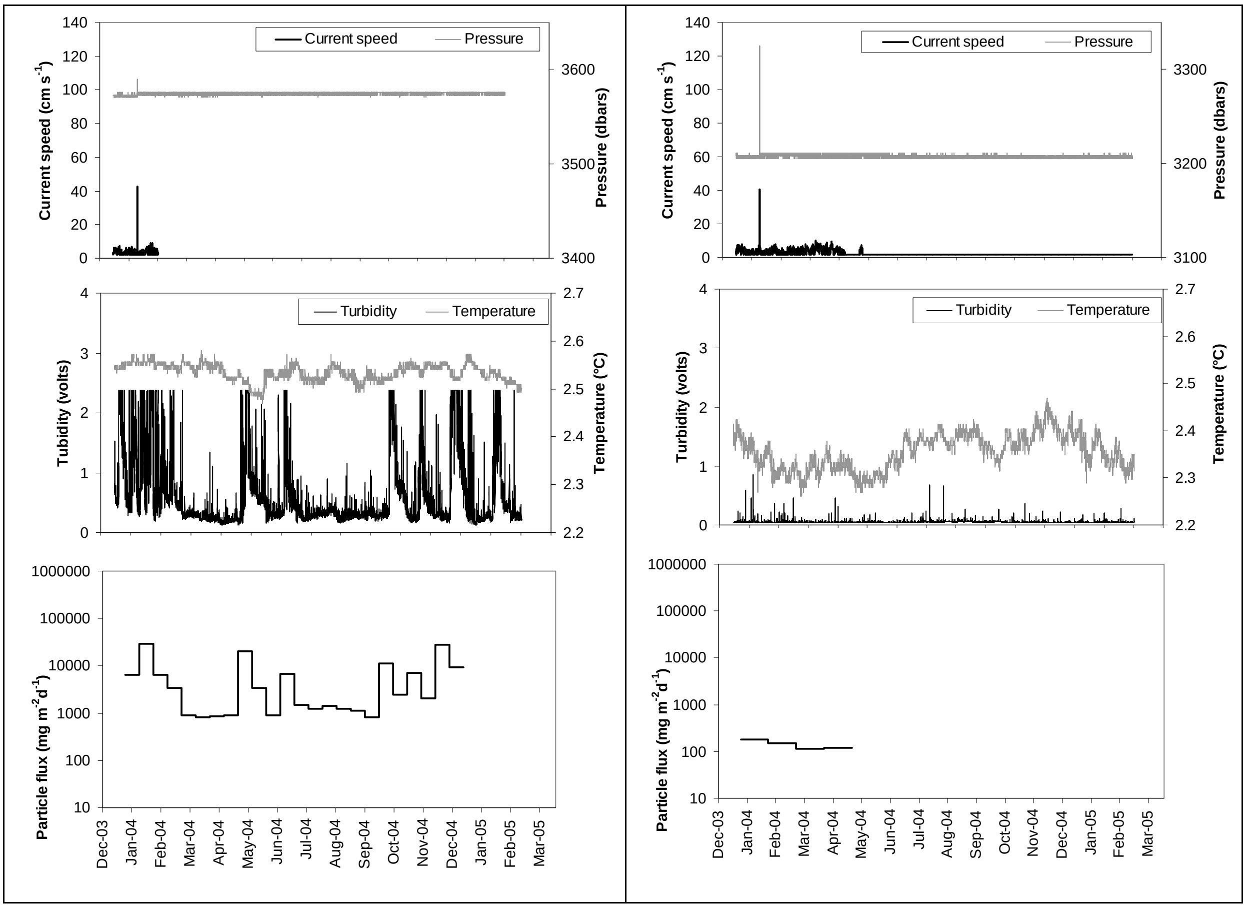

Figure 9:
Long-term measurements at site ZR' in the channel in 2004 (instantaneous data).
Left panels, measurements at the lower level; right panels, upper level.
Top panels, current speed and pressure; middle panels, turbidity and temperature; bottom panels, total particle flux (note the logarithmic scale for the particle flux axis).
The current speed data are reliable only until 15 February at 60 m a.b. and until 23 April at 410 m a.b. due to rotor failure.

Figure 10

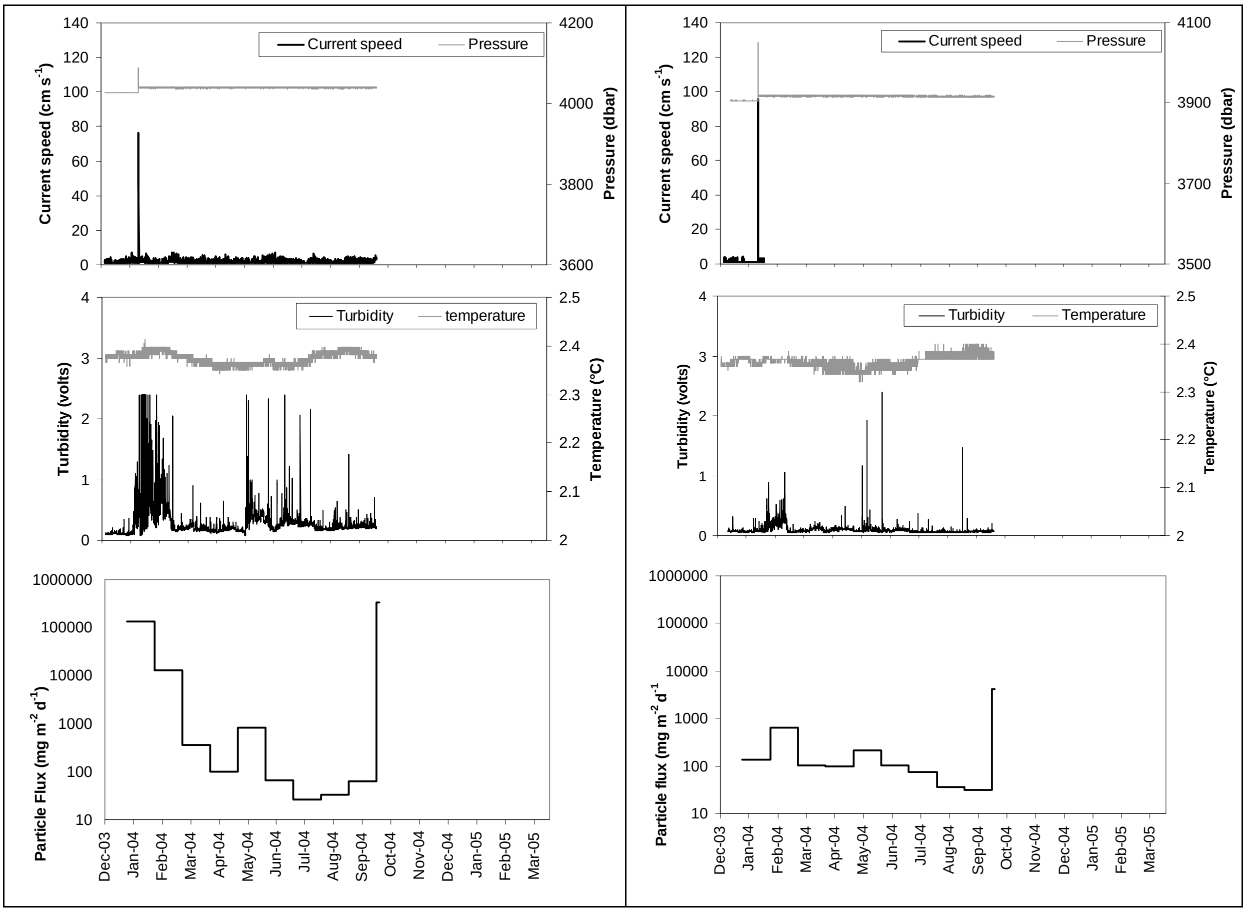

Figure 10:
Long term measurements at site ZD’ in the channel in 2004 (instantaneous data).
Left panels, measurements at the lower level; right panels, upper level.
Top panels, current speed and pressure; middle panels, turbidity and temperature; bottom panels, total particle flux (note the logarithmic scale for the particle flux axis).
The current speed data are reliable only until 31 January at 190 m a.b. due to rotor failure.

Figure 11

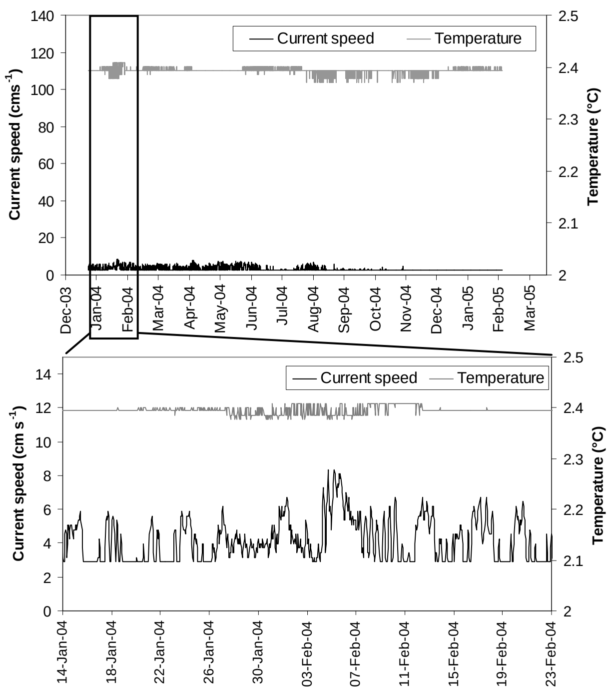

Figure 11:
Current speed and temperature at 60 m a.b. at the Lobe site in 2004 (instantaneous data). Top panel, current speed and temperature at over the entire experiment; bottom panel, detail around the putative date when the turbidity event occurred.
The current speed data are poor after late August, due to intermittent rotor failure.