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Direct observation of intense turbidity current activity in the Zaire submarine valley at 4000 m water depth

Alexis Khripounoff[a]*, Annick Vangriesheim[a], Nathalie Babonneau[b], Philippe Crassous[a], Bernard Dennielou[b] and Bruno Savoye[b]

[a]IFREMER, Département 'Environnement Profond', P.O.Box 70, 29280, Plouzané, France
[b]IFREMER, Département 'Géosciences Marines', P.O.Box 70, 29280, Plouzané, France

*: Corresponding author : Fax: +33-2-9822-4757 alexis.khripounoff@ifremer.fr

Abstract: A large turbidity current was detected in the Zaire submarine valley at 4000 m water depth. Current meters, turbidimeter and sediment trap deployed on a mooring located in the channel axis, although they were damaged, recorded the signature of a very high energy event. An average velocity of more than 121 cm s−1 was measured 150 m above the channel floor. Coarse sand and plant debris were collected at 40 m height. The turbidity current clearly overflowed the edges of the valley as demonstrated by the large quantity of turbiditic material (464 mg organic carbon m−2 d−1) found in the sediment trap moored 13 km south from the channel axis.

Keywords: turbidity current; Zaire channel; particle flux; particle composition; west equatorial Africa

Introduction

Direct observations of submarine avalanches called turbidity currents are rare and mostly concern continental slopes (Johnson et al., 2001; Prior et al., 1987). But their activity in the deep-sea has been suspected largely from indirect signs: sea floor morphology, cores, cable breaks (Heezen and Ewing, 1952). In this work, new data on these phenomena are reported from long-term instrumented moorings deployed at 4000 m depth in and near the Zaire valley area.

Canyons are often presented as natural conduits for the transfer of particulate matter from the shelf to the deep-sea (Carson et al., 1986; Gardner, 1989; Xu et al., 2002). The material transport is often imputed to gravity processes, mainly turbidity currents. Organic carbon budgets pointed out that hydrodynamics and morphology of the canyon system in relation with the continental source have a direct impact on the distribution of organic matter in the deep-sea (Buscail and Germain, 1997; Heussner et al., 1999; Schmidt et al., 2001).

The “Zaire deep-sea fan” appears to be one of the largest in the world still affected by turbidity sedimentation (Babonneau et al., in press; Savoye et al., 2000). It extends 760 km from the river mouth to the abyssal plain (>5100m), downslope from the Congo-Angola continental shelf and covering an estimated area of 300 000 km^2. The permanent connection between the river mouth and the abyssal plain via the canyon is one of the original characteristics of the Zaire system. It explains why the fan is still active during current high marine level. Heezen *et al.* (Heezen et al., 1964) showed the present-day activity of the Zaire by documenting submarine-cable breaks near the canyon between 500 and 2300 m water depth (estimated at around 60 per century) attributed to turbidity current activity related to river flood periods. Recent activity of the fan is also attested by deposition of more than 10 m of Holocene fine-grained turbidites identified in some cores located near the crest of the levee of the active channel (Van Weering and Van Iperen, 1984). But, no turbidity currents have been ever observed *in situ* in this region.

The consequence of the continental matter input on the deep-sea ecosystem development and functioning is one of the goals of the "Environnement Golfe de Guinée" project developed by Ifremer in partnership with TotalFinaElf. As part of that programme initiated in 2000, we were interested in the Zaire valley as a natural way for terrestrial material transport to the deep sea.

Materials and methods

In January 2001, two moorings were deployed at 4000 m water depth on two stations at the Angola-Congo margin foot (Fig. 1). The first was deployed on the Channel station located in a relatively rectilinear and low gradient portion of the Zaire channel (slope 2-4 m km^{-1}). On this mooring, two RCM8 Aanderra current meters (vector averaged current and temperature recorded each hour) were attached respectively at 30 m and 150 m above the bottom (a.b.) and one PPS5 Technicap sediment trap (diameter $1m^2$, 24 bottles, sampling period of 10 days) at 40 m a.b. One TBD turbidimeter (Vangriesheim et al., submitted) (instantaneous measurements of back scattering light and pressure recorded each two hours) was attached respectively on the sediment trap and on the vane of the current meter 30m a.b.. The position of the mooring in the channel was confirmed by direct observation during a dive of the ROV Victor.

The second mooring was deployed on the Levee station located 18 km in the Southwest of the Channel station corresponding to the external side of the channel levee. This location was chosen to measure the expansion of the particle plume produced by the turbidity currents in the vicinity of the Zaire valley. The mooring consisted of two PPS5 Technicap sediment traps respectively at 30 m and 400 m a.b. and two RCM8 Aanderra current meters 10m above each trap. One TBD turbidimeter was attached to each sediment trap.

Results and discussions

On the 9th of March 2001, the Argos CLS positioning system detected the Channel mooring at the sea surface. After its recovery ten days later, we observed that the mooring wire was splitted just above the anchor, allowing instrument packages to float free. Equipments on the mooring experienced various degrees of damage. The sediment trap was exploded and was full of compact sediment. All sampling bottles (24 samples) were filled with sediment. Rotor, frame and vane of the current meter 30 m a.b. were broken off or bent. Current meter housing and acoustic release were abraded and stripped. The turbidimeter on the vane of the current meter was lost and the one on the trap was partly broken. Fortunately, data from current meters and from the upper turbidimeter had been saved. The current meter 150 m a.b. was still working. The second mooring on the Levee station was recovered as previously planed in October 2001. The sediment trap 30 m a.b. had partially worked.

Data from the two current meters and the turbidimeter moored in the channel (Fig. 2) showed that no particular events occurred during the first three months of the experiment. The current speed was slightly higher at 30m a.b. (mean =3.4 cm s^{-1}, maximum = 7.9 cm s^{-1}) than at 150 m a.b. (mean =2.8 cm s^{-1}, maximum = 6.4 cm s^{-1}) and the current direction was more canalised near the bottom. Small peaks of turbidity occurred several times (Fig. 2). Temperature was very stable at 2.35°C.

At 22 hours on 8th of March 2001, a sudden velocity pulse was recorded at the same time by both current meters. A strong increase of turbidity was also observed at the same time (zoom Fig. 2) and the temperature rose by 0.04°C near the bottom. The pressure probe of the turbidimeter indicated that the sediment trap sank of about 40 m and certainly scrapped the channel floor. At the next record (one hour later), the current meter 30 m a.b. broke. The current meter 150 m a.b. was still working and recorded a speed of 121.4 cm s^{-1}. As this value was the result of one hour integration (vector averaged value), much higher instantaneous speeds may have occurred during this hour. Moreover, this speed is even undervalued because the equipment was probably tilted due to the very high current speed. The following record (at midnight) showed that the mooring was lifting up (1700 m depth and temperature 3.64°C). The sampling bottle (n° 6) under the sediment trap aperture was full up with large plants debris (wood, leaves, roots) and fine sand (quartz). The other sampling bottles, theoretically isolated from the ambient water, were also filled, mainly with well-sorted fine sand (median 150-200μm), clay and small plant debris. The chemical composition of particles undertaken by LECO CNS-2000 and EDAX l X-ray spectrometry confirmed the abundance of Si (sand) and organic carbon (plant remains) and the paucity of Al, Ca and N certainly due to the evolution of the organic matter (Table 1). Radiocarbon dating (C_{14}) gave a modern age for the wood fragments in the bottle n°6 (enclosing the event date) and an age of 895±40 years for plant debris in bottle n°3 sampled before the event.

At the Levee station located 18 km in the Southwest of the Channel station, the consequence of the turbiditic event was also observed (Fig. 3). From the 11th of January to the 2nd of March 2001, the mean total mass flux was 53.7 and 96.6 mg m^{-2} d^{-1} respectively 400 m and 30 m a.b.. The visual observation and chemical analysis of particles (Table 1) indicated pelagic origin at both levels. They were composed of whole tests of diatoms, foraminifera radiolaria and abundant calcareous nannofossils. But the next sample was quite different. The bottle n°6 at 30m a.b. was almost full of brown clay (total mass flux = 3280 mg m^{-2} d^{-1} for 10 days). Compared with the pelagic particles collected during the previous periods, it distinguished by abundant silty quartz and plant fragments and by high concentration of Al and Fe and low concentration of Ca (Table 1). The absence of foraminifera and calcareous nannoplankton explains this low value. Considering this sudden and very high increase of particle flux in this sediment trap sample, its composition and the synchronism with the channel event, we assume that the turbidity current observed in the channel was responsible for the very large and unpredictable input of particulate matter at this location.

During the turbiditic event, the particle flux 400 m a.b. remained weak (Fig. 3) and its composition was similar to these of the pelagic flux. The concentration of fine particles measured with the turbidimeter on the sediment trap did not show any significant variation (Fig. 3) indicating that the turbidity overflow cloud never reached this altitude.

The bottom transport mechanism from the channel to the Levee station remains not clear. The delay between the beginning of the turbiditic event in the channel and its detection at the Levee station is calculated at 3 days maximum according to the sediment trap data (9th March, starting of the turbidity, to 12th March 00h00, moving up trap bottle 6 to bottle 7). The total particle flux calculated for this interval is estimated at 11,000 mg m^{-2} d^{-1}. The main area of turbidity overflow in the channel is assumed to be located 30 km on the East of the Levee station, where the channel direction strongly changes from East-West to South-North (Fig. 1). The slope and the mean current at this moment were also in favour of this hypothesis. On this assumption, the mean speed of the cloud should be more than 11 cm s^{-1} during these three days whereas the current velocity measured at the same time is only 6.5 cm s^{-1} maximum. During the same period, no significant signal was recorded by the turbidimeter (Fig. 3). Turbidimeter is only sensitive to small particles whereas sediment trap mainly collects large particles settling quickly. On the other hand, the current meter at 40 m a.b. recorded no speed increase between the 9th and 12th March. The first hypothesis is that the overflow, with high speed, was less than 40 m thick but had enough energy to raise large particles up to the sediment trap level. The second solution is a flow speed which should be higher just near the overflow point and decreased on the way to the Levee station on a layer > 40 m. The advective current played probably second fiddle in this large particle overflow transport.

The next sample of the sediment trap (12th-22nd March) showed a decrease of the particle flux (total flux = 1215 mg m^{-2} d^{-1}). From this result, the duration of the turbiditic event is estimated to be about 10 days. The briefness of the turbiditic signal on the Levee station (maximum during only 3 days: 9th to 12th March) indicates that the origin of collected material was restricted to one place of overflow.

The total fluxes, measured from the last two samples (bottles 8 and 9 at the Fig. 3) of the sediment trap at 30 m a.b. before the failure, reached the same values than at the beginning of the experiment (56.6 mg m^{-2} d^{-1}). Nevertheless, visual observation and chemical composition are similar to the turbiditic particles sampled in the channel (Table 1). This composition is in relation with the strong peak of particle concentration measured with the turbidimeter, 15 days after the peak of particles in the trap (Fig. 3). At that moment, the mooring was surrounded by a dense cloud of very fine and slowly settling particles. The almost lack of Ca in the particles signifies that very few pelagic particles can reach the bottom due to an increasing density of water made by the particle cloud which could prevent their settling (umbrella effect).

The advective current measured in this area was sufficient to carry fine material from the channel to the Levee station. A possible local fragmentation of fresh large particles on the bottom by bacteria activity followed by a resuspension by the current (Auffret et al., 1994; Vangriesheim et al., 2001) could also explain the presence of the dense cloud of fine particles for several months (Fig. 3).

Conclusion

Our observation of a turbidity current over a very short monitoring period indicates that the Zaire deep-sea fan is a very active system. At the local scale of this study (4000 m depth), the factors responsible for the initiation of the turbiditic flow cannot be established because they start certainly far away in the upper part of the canyon. The observation of the turbidity current in March points that the Zaire River floods, recorded in June and December (Moguedet, 1988), are not the direct trigger of the turbidity event (no synchronism) even though they are the source of material.

The maximum velocity of 121.4 cm s^{-1} recorded at 150 m above the channel floor during the event was certainly an underestimation. The instantaneous current speed close to the channel bottom would have been incredible higher. The flow event had enough energy to carry large quantity of sand and big plant remains.

The flow thickness exceeded the channel depth (150 m) and continental material overflowed outside the channel by external turbidity over several tens of kilometers.

The huge organic carbon flux measured on the Levee station, about 100 times higher than the normal flux on this area, proves that the transport of terrestrial carbon in turbid underflows cannot be neglicted in the carbon budget of the whole Congo-Angola margin. The oxygen deficit anomaly in the deep water discussed by (Braga et al., submitted) in this area can be attributed to remineralisation of this strong organic matter input.

Our results show that the Zaire submarine area is a perfect natural laboratory to investigate the dynamics of continental material transport and its consequences on the deep benthic ecosystems and the water column chemistry. Now, the challenge is to conceive original equipments able to monitor deep stations under severe conditions for several years.

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Table 1:Elemental composition of particles sampled in the Zaire channel and in its vicinity

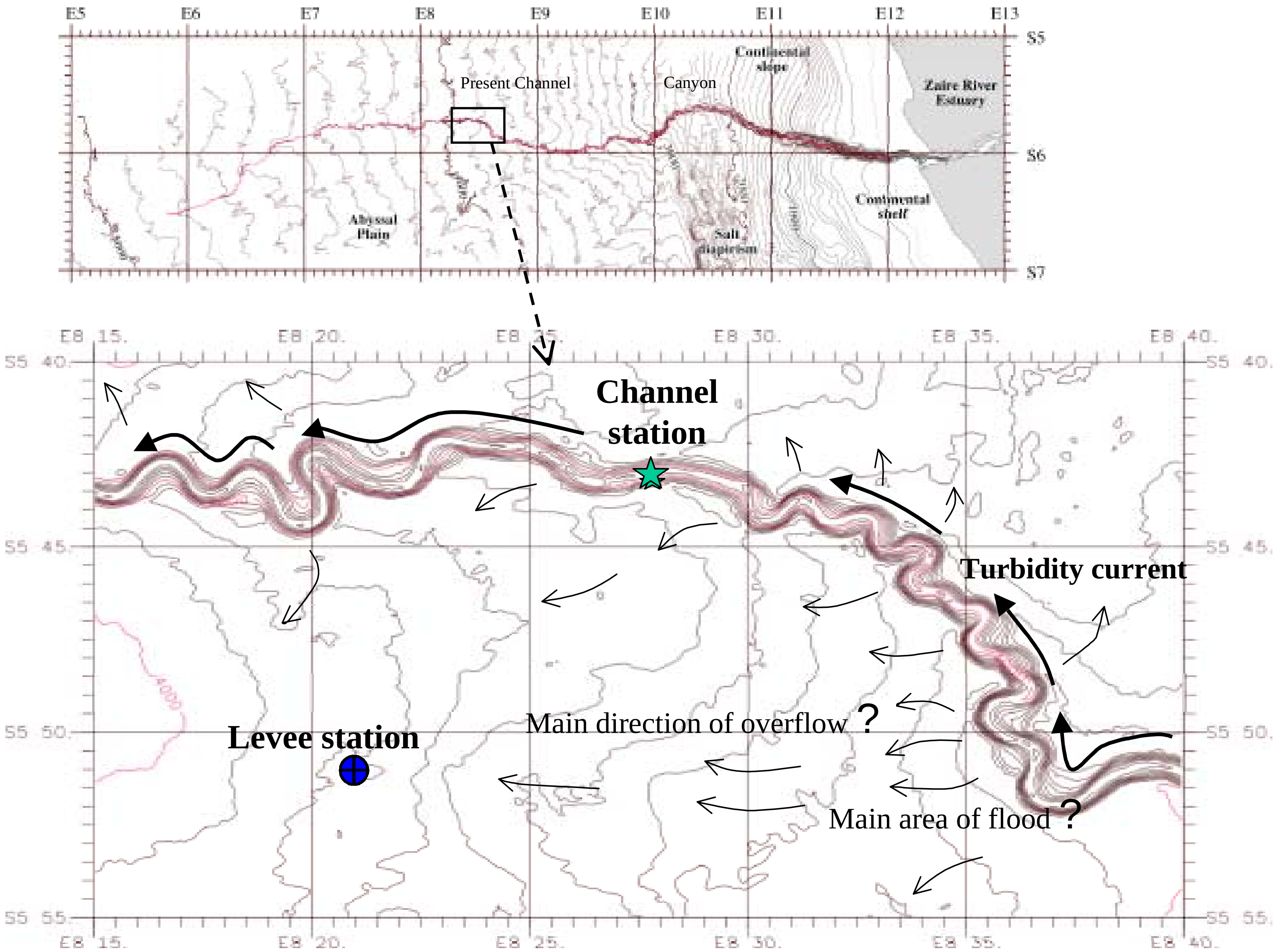
	Station			
	Channel	Levee	Levee	Levee
	Particles from the turbidity	Particles before the event	Particles at the maximum flux	Particles after the event
Total particle flux (mg m^{-2} d^{-1})	?	96.6	10933	56.5
Organic carbon flux (mg m^{-2} d^{-1})	?	6.3	464	2.4
Chemical elements (%)				
Al	7.3	5.8	13.7	14.0
Si	27.2	22.2	21.3	21.8
S	0.6	0.3	0.4	0.3
Ca	0.9	8.4	1.0	0.6
Ti	0.4	0.2	0.6	0.7
Fe	2.8	2.7	6.9	7.3
Organic. C	5.1	6.1	4.2	4.3
N	0.1	0.9	0.5	0.4

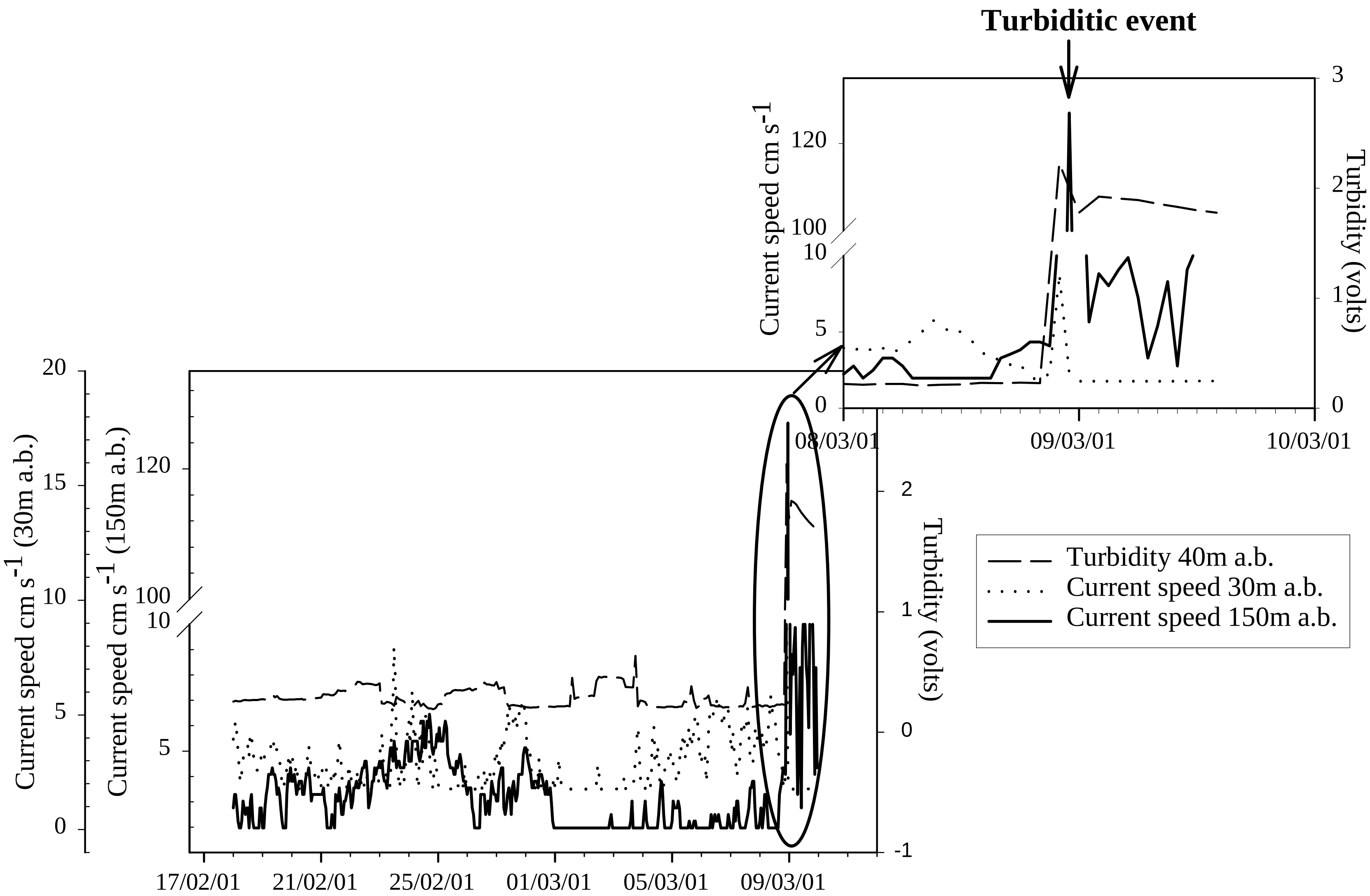
Figure captions

Fig. 1. Bathymetric chart (contour interval =20m, EM12 bahymetric data) of the Zaire fan and locations of monitoring stations (large arrows = turbidity current direction, fine arrows = overflow directions)

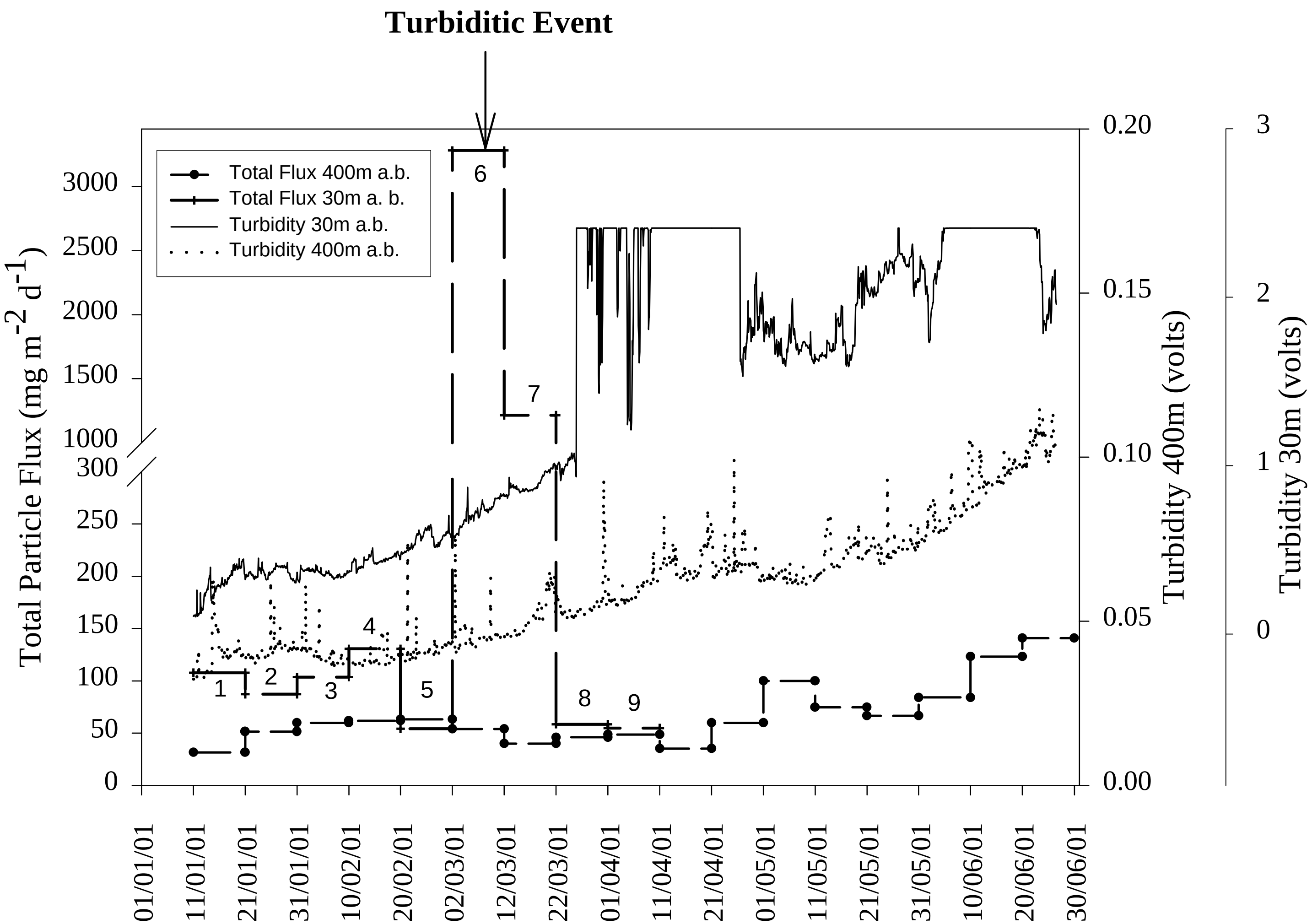
Fig. 2. Part of the current meter and turbidimeter records twenty days before and during the turbidity event at the Channel station (black line = turbidity 40m above the bottom, green line = current speed 30m a.b., red line = current speed = 150m a.b.)

Fig. 3. Particle flux and turbidity at 400m and 30m above the bottom (a.b.) at the Levee station, 18km Southwest of the channel (black line = turbidity 30m a.b., blue line = turbidity 400m a.b, green line = total flux 30m a.b, red line = total flux 400m a.b.)


E5
E6
E7
E8
E9
E10
E11
E12
E13
S5
S6
S7
Continental slope
Present Channel
Canyon
Zaire River Estuary
Continental shelf
Abyssal Plain
Salt diapirism
E8 15.
E8 20.
E8 25.
E8 30.
E8 35.
E8 40.
S5 40.
S5 45.
S5 50.
S5 55.
Channel station
Turbidity current
Main direction of overflow ?
Levee station
Main area of flood ?
4000



Turbiditic event
Current speed cm s-1
Turbidity (volts)
08/03/01
09/03/01
10/03/01
Current speed cm s-1 (30m a.b.)
Current speed cm s-1 (150m a.b.)
17/02/01
21/02/01
25/02/01
01/03/01
05/03/01
09/03/01
Turbidity 40m a.b.
Current speed 30m a.b.
Current speed 150m a.b.



Turbiditic Event
Total Flux 400m a.b.
Total Flux 30m a. b.
Turbidity 30m a.b.
Turbidity 400m a.b.
Total Particle Flux (mg m-2 d-1)
Turbidity 400m (volts)
Turbidity 30m (volts)
0
50
100
150
200
250
300
1000
1500
2000
2500
3000
0.00
0.05
0.10
0.15
0.20
0
1
2
3
1
2
3
4
5
6
7
8
9
01/01/01
11/01/01
21/01/01
31/01/01
10/02/01
20/02/01
02/03/01
12/03/01
22/03/01
01/04/01
11/04/01
21/04/01
01/05/01
11/05/01
21/05/01
31/05/01
10/06/01
20/06/01
30/06/01