Open access • Journal Article • DOI:10.1016/J.DSR2.2013.05.036

Trawling-induced daily sediment resuspension in the flank of a Mediterranean submarine canyon — Source link

Jacobo Martín, Pere Puig, Albert Palanques, Marta Ribó

Institutions: Spanish National Research Council

Published on: 01 Jun 2014 - Deep-sea Research Part Ii-topical Studies in Oceanography (Elsevier)

Topics: Bottom trawling, Trawling, Submarine canyon, Nepheloid layer and Sediment

Trawling-induced daily sediment resuspension in the flank of a Mediterranean submarine canyon

Jacobo Martín*, Pere Puig, Albert Palanques, Marta Ribó

Institut de Ciències del Mar (CSIC), Passeig Marítim de la Barceloneta, 37-49, 08003 Barcelona, Spain.

*Corresponding author: jmartin@icm.csic.es;
Tf: +33 932309500(ext.1156); fax: +33 932309555

Abstract

Commercial bottom trawling is one of the anthropogenic activities causing the biggest impact on the seafloor due to its recurrence and global distribution. In particular, trawling has been proposed as a major driver of sediment dynamics at depths below the reach of storm waves, but the issue is at present poorly documented with direct observations. This work analyses changes in water turbidity in a tributary valley of the La Fonera (=Palamós) submarine canyon, whose flanks are routinely exploited by a local trawling fleet down to depths of 800 m. A string of turbidimeters was deployed at 980 m water depth inside the tributary for two consecutive years, 2010-2011. The second year, an ADCP profiled the currents 80 m above the seafloor. The results illustrate that near-bottom water turbidity at the study site is heavily dominated, both in its recurrence and its magnitude and temporal patterns, by trawling-induced sediment resuspension at the fishing ground. Resuspended sediments are channelized along the tributary in the form of sediment gravity flows, being recorded only during working days and working hours of the trawling fleet. These sediment gravity flows generate turbid plumes that extend to at least 100 m above the bottom, reaching suspended sediment concentrations up to 236 mg l^{-1} close to the seafloor (5 m above bottom). Few hours after the end of daily trawling activities, water turbidity progressively decreases but resuspended particles remain in suspension for several hours, developing bottom and intermediate nepheloid layers that reach background levels ~2 mg l^{-1} before trawling activities resume the day after. The presence of these nepheloid layers was recorded in a CTD+turbidimeter transect conducted across the fishing ground few hours after the end of a working day. These results highlight that deep bottom trawling can effectively replace natural processes as the main driving force of sediment resuspension on continental slope regions and generate increased near-bottom water turbidity that propagates from fishing grounds to wider and deeper areas via sediment gravity flows and nepheloid layer development.

Keywords: Trawling; Man-induced effects; Submarine canyons; Sediment dynamics; Resuspension; Nepheloid layers; Northwestern Mediterranean

1. Introduction

Bottom trawling is a fishing technique that consists in pulling nets along the seafloor to harvest benthic and demersal living resources. The means to keep the net open and close to the bottom are diverse but invariably imply the use of heavy devices such as otter boards, bobbins, sweeplines or chains, that are in contact with the seafloor continuously or intermittently. In certain cases, beams or dredges designed to actively bulldoze the seafloor are used. Aside from the direct impacts on benthic fauna and their habitats, the dragging of these gears along the seafloor injects large amounts of surface sediments into the water column, particularly when trawling is carried out over soft bottoms (Black and Parry, 1994; Pilskaln et al., 1998). In fact, in certain trawling modalities such as otter trawling, the clouds of resuspended sediments constitute an integral part of the fishing strategy by "herding" fish swarms towards the mouth of the net (Main and Sangster, 1981). Given the global dimension and recurrence of commercial trawling (World Resources Institute, 2000; Bensch et al., 2009; Puig et al., 2012), the question arises whether this human activity can make a sizeable contribution to present-day sediment resuspension and water column turbidity over extensive areas of the world's continental margins. Churchill (1989) brought the issue into focus, proposing that trawling activities were able to rival storms as the main agent for sediment resuspension and transport on the middle and outer continental shelf of the Middle Atlantic Bight. More than 20 years after this pioneering work, the body of literature addressing this subject it still relatively slim and mainly devoted to coastal and continental shelf settings (Pilskaln et al., 1998; Palanques et al., 2001; Durrieu de Madron et al., 2005; Tragou et al., 2005; Dellapenna et al., 2006; Ferré et al., 2008), which leaves a big gap of knowledge on the effects of this practice at depths beyond the shelf-break. Filling this gap is a pressing issue because of two overlapping factors. First, bottom fisheries have progressively extended their activities from traditional shallow grounds towards the continental slope and further offshore during the last decades (Morato et al. 2006, Bensch et al., 2009; Benn et al., 2010). Second, it is generally agreed (though scarcely documented) that artificial disturbances of the seafloor tend to be more severe and long-lasting in deep-sea than in shallow water environments, due to the fact that the natural processes capable of overcoming human imprints are in general weaker in the former (Theil and Schriever, 1990; Kaiser et al., 2002).

Among deep-sea environments susceptible of being impacted by trawl industries, submarine canyons are regarded as relevant and fragile hotspots of biodiversity (WWF/IUCN, 2004; Fabri et al., 2013). Canyons incising the continental shelf act as preferential routes and/or traps for organic and inorganic particulate matter from both terrestrial and marine sources. Also, by promoting local upwelling, canyons can be sites of enhanced biological production (Allen et al., 2001). Their complex morphology offers diverse habitats and shelter to marine species, including some of high economic value and, consequently, prosperous fishing harbours are often based in the vicinity of submarine canyons (Würtz, 2012). La Fonera Canyon, also known as Palamós Canyon (Fig. 1), is one of the most prominent submarine canyons of the northwestern Mediterranean (Palanques et al., 2005; Martín et al., 2006; Lastras et al., 2011). Its flanks from ~400 to 800 m depth are intensely exploited by a local trawling fleet targeting the blue and red shrimp *Aristeus antennatus*. Trawlers are active on a daily basis and year round, except for weekends and holidays, mainly along the Sant Sebastià fishing ground in the northern canyon flank (Fig. 1). The same ground is usually swept several times a day, starting typically at 6-7 h (UTC) in an offshore direction. Subsequent hauls may be carried out until 15-16 h, when the boats head back to port. The bottom trawl gear used in this fishery consists of 2 otter boards, each up to 1 ton in weight, spread ~100 m apart during the trawling operation and connected to the net opening by 60-200 m-long sweeplines. The net measures 80-150 m in length and is ~50 m wide at its ballasted mouth. The daunting capacity of these otter trawling gears to resuspend big volumes of sediments is not new to fishermen: small trawlers' crews complain about their nets being clogged -and thus inoperative- by the mud propelled on the wake of the bigger trawlers sailing ahead (Alegret and Garrido, 2004). Studies conducted in 2001 showed that trawling gears operating in the Sant Sebastià fishing ground were able to trigger sediment gravity flows that were funnelled through a tributary valley (named Montgrí) and were observed reaching the main canyon axis at 1200 m depth (Palanques et al., 2006; Martín et al., 2007). Further studies also documented the consequences of these man-made flows in terms of downward sediment fluxes and sediment accumulation rates in the canyon axis (Martín et al., 2006, 2008). Recently, Puig et al. (2012) evidenced that the periodic sediment removal from La Fonera Canyon fishing grounds ultimately reshaped the continental slope morphology over large spatial scales.

This paper aims to improve our understanding of trawling-induced sediment resuspension events along the northern canyon flank, describing in detail the daily and seasonal variability of water turbidity and discussing also the implications of such resuspension process in the generation of nepheloid layers along continental margins.

2. Materials and methods

An instrumented mooring array was deployed in the Montgrí tributary traversing the northern flank of the La Fonera Canyon (red diamond in Fig. 1). The mooring line was positioned at 41°52.49'N; 3°20.66'E, in a water depth of 980 m, ~200 m deeper than the maximum working depth of the local trawling fleet, during two consecutive years. From 1 July to 7 November 2010, the line was equipped with 10 Seapoint turbidimeters (AQUA logger 520, AQUATEC; wavelength 880 nm, scatterance angles 15-150º) at 5, 10, 15, 20, 25, 30, 40, 50, 70 and 100 meters above the bottom (mab). These instruments were programmed to measure turbidity, expressed in Formazin Turbidity Units (FTU), at 1-min intervals in auto-gain mode. The mooring line was also equipped with a downward-looking 300 kHz Teledyne RDI Acoustic Doppler Current Profiler (ADCP) placed above the turbidimeters. Unfortunately, during 2010 the ADCP did not record data due to a technical issue affecting the Firmware 5x.37-5x.39 of RDI Workhorse sentinel platforms (Teledyne Field Service Bulletin FSB-194; 08/11/2010) and the 20 mab turbidimeter ceased prematurely to record due to a problem with the batteries. The same site was reoccupied from 10 May to 12 October 2011. In this occasion, 3 turbidimeters were placed at 5, 20 and 50 mab and the ADCP provided valid current data from 12 to 78 mab in 2 m-wide bins at 5-min intervals. The N-E current components were rotated to obtain along- and across-slope components taking into account the main orientation of the tributary valley (191º from North). To complement these measurements with observations of the horizontal distribution of resuspended particles in the water column, a CTD transect (see Fig. 1 for CTD cast positions) crossing the northern canyon flank was conducted on 11 May 2011 after the end of the daily trawling activity. A Seabird SBE 911 CTD probe equipped with a Seapoint turbidimeter was used.

FTU readings from the CTD and moored turbidimeters were converted to estimates of suspended sediment concentration (SSC) after the general calibration by Guillén et al. (2000):

$SSC\ (mg\ l^{-1}) = 1.74 \times (FTU - FTU_{min})$,

where FTU_{min} is the minimum turbidity recorded by the sensor during a given deployment period.

3. Results

Figure 2 presents the complete time-series of SSC measured by selected turbidimeters from both years/deployments 2010 and 2011. An 18-day zoom from each of the two monitored years is shown in Figures 3 and 4 respectively, the latter also including current speed and direction.

3.1. Suspended sediment concentrations in the Montgrí tributary

The time-series of SSC at the sampling site document the occurrence of frequent events of very high turbidity, reaching near-bottom SSCs of more than 100 mg l^{-1} (Fig. 2). These events were recorded only during working days of the local trawling fleet, while turbidity remained low during weekends and holidays (Figs. 3, 4). Several consecutive peaks of SSC were often observed in a same working day between 8 h and 16 h UTC. The suspended sediment increases occurred sharply, as SSC peaks 1-2 orders of magnitude above background values of ~1-3 mg l^{-1}, and then faded out in the following few hours. Water turbidity during these events increased first close to the bottom and was then subsequently observed propagating upwards in a few minutes, often reaching the topmost turbidimeter (100 mab in 2010; 50 mab in 2011). Maximum SSCs recorded by the bottommost turbidimeter (5 mab) during each deployment were 180 mg l^{-1} on 2 July 2010 (11:30 h UTC) and 236 mg l^{-1} on 24 May 2011 (13:46 h UTC).

During the 2010 deployment, high turbidity events were particularly frequent and intense during the first month of measurements (July), and tended to weaken progressively along the following months. Nonetheless, SSC peaks in the range 10-30 mg l^{-1} were still measured in late summer. The 2011 recording period started earlier in the year (May) allowing to complement the previous temporal trend. In this case, suspended sediment peaks also tended to decrease in frequency and concentration towards autumn, and were maximal during late spring-early summer (Fig. 2).

A detailed view of the shape and daily evolution of consecutive resuspension plumes recorded during a working day is given in Figure 5, where turbidity data from 10 depths is integrated from 0 to 24 h of Friday 2 July 2010. From midnight to 8 h UTC, water turbidity remained below 4 mg l^{-1} from 5 to 20 mab and below 2 mg l^{-1} from 20 to 100 mab. Some minutes before 9 h UTC, a sharp increase of turbidity was observed to a minimum height of 70 mab (SSC in the range 20-50 mg l^{-1}). At 11:30 near-bottom SSC peaked at 180 mg l^{-1} and subsequent relatively high turbidity bursts occurred until 15-16 h UTC (Fig. 5). During these high turbidity events, SSC increased first near the bottom and the signal propagated upwards afterwards. Towards the end of the working day, SSC progressively faded out near the bottom, and around 20:30 h UTC the suspended sediment plume was apparently detached from the seafloor, showing higher concentrations at mid-water depths between 50 and 100 mab, while turbidity near the seafloor was lower (Fig. 5).

3.2. Near-bottom currents

The speed and direction of water currents measured by the ADCP during a period representative of the 2011 mooring deployment are shown in Figure 4, while the across- and along-gully components of current speed are shown in detail together with SSC during two working days in Figure 6. Increases of current speed in the range 20-40 cm s^{-1} were coherent with high SSC events and, like these, matched the time schedule of trawling activities. The ADCP measurements also showed higher velocities near the bottom, decreasing upwards (Fig. 4). Such maximum velocities were oriented along the gully and down-slope, in agreement with the development of sediment gravity flows, while the across-gully component during these events was less clearly oriented and showed values <12 cm s^{-1} (Fig. 6). On occasions, the simultaneous increases of down-gully current speed and SSC were restricted to <50 mab while, above, the water flow was reversed and directed up-slope, suggesting a compensation flow in the opposite direction of the gravity current (see second turbidity peak in Fig. 6). Outside events of high turbidity, current speed remained below 10 cm s^{-1} (Fig. 4).

3.3. Daily evolution of SSC

Figure 7 integrates all the available SSC data at selected heights above the bottom from each deployment, ordered by the time of day. The time-averaged water turbidity at 5-50 mab increases abruptly around 8 h UTC in agreement with the passage of the trawling fleet upslope of the mooring site. Time-averaged maximum turbidity values at 100 mab show an apparent delay of several hours with respect to near-bottom values, although instantaneous SSC increases occurred often simultaneously during high turbidity events. The distribution of high turbidity events is roughly bimodal in 2011, with one maximum centred on 9-10 h UTC and a second one around 14 h UTC. The first peak roughly corresponds to the time when the trawling fleet goes offshore and the second one when it heads back to port. This bimodal trend is less obvious in 2010 but still visible. After the end of the trawling period (15-16 h UTC), turbidity values drop steadily towards daily minimum values just before trawling activities are resumed the following day.

3.4. CTD transect across the Sant Sebastià fishing ground

Vertical profiles of hydrographic parameters and suspended sediment concentration from a CTD transect across the Sant Sebastià fishing ground are shown in Figure 8. This transect was carried out at the end of a working day (11 May 2011), eastwards from the mooring site and outside any identifiable canyon tributary valley (Fig. 1). A conspicuous bottom nepheloid layer (BNL) was observed at the profiles intersecting the range of fishing depths (station 3 and 4). In particular, a 20 m thick BNL with SSC increasing towards the seafloor up to maximum ~5.0 mg l^{-1} at 5 mab (according to the altimeter) was observed at station 3 (670 m depth). At station 4 (498 m depth) a 43 m thick BNL with maximum SSC 3.8 mg l^{-1} was also present. This BNL appears to detach from the canyon flank and generate the intermediate nepheloid layer (INL) observed at 500-600 m depth in station 3. No obvious INL detachments were observed deeper inside the main canyon valley (stations 1 and 2), although a slightly higher water turbidity was observed at 700-1100 m depth. An additional INL was apparent at the shallowest stations 4-6 between 150 and 220 m depth (i.e., at shelf-break depths) and constrained by the density gradient between Atlantic Waters and Levantine Intermediate Waters (Fig. 8).

4. Discussion

4.1. Trawling-induced resuspension events

The time-series of suspended sediment concentration in the Montgrí tributary valley revealed the occurrence of frequent events of very high turbidity, induced by trawling as evidenced by the tight coupling between the temporal distribution of these events and the working schedule of the fishing fleet operating in the neighbouring fishing ground (Figs. 3, 4, 7).

The downslope sediment transport events detected deeper than the fishing grounds are attributable to the generation of sediment gravity flows (i.e. flows by which water moves downslope due to the contribution of suspended sediment load to the density of the fluid, creating negative buoyancy; see Middleton and Hampton, 1976). Such type of flows were identified by measurements from single point current meters deployed in 2001 at the confluence of the Montgrí tributary valley with La Fonera canyon axis (Palanques et al., 2006) and confirmed by currents recorded by the ADCP deployed during this study (Puig et al., 2012; Figs. 4, 6). This rapid flushing of sediments through the tributary valley causes the sharpness of turbidity increases, the subsequent propagation of the signal from the bottom upwards and the relatively fast fading out of the turbid signal afterwards (Fig. 5). The high-turbidity events observed in the tributary had a frequency and intensity that surpassed our previous observations. Events with an almost daily recurrence and near-bottom sediment loads up to 236 mg l^{-1} at 5 mab in the Montgrí tributary valley at 980 m depth contrast with more sporadic and less turbid events (maximum 30 mg l^{-1} at 12 mab) measured in the canyon axis at 1200 m depth by Palanques et al. (2006).

The lack of any significant resuspension event outside working days and working hours in 284 days of continuous recordings (Figs. 3, 4, 7) testifies to the weakness or rarity of natural processes capable of producing similar effects at this location and depth. Consequently, we can assert that the present-day near-bottom water turbidity in the Montgrí tributary valley is, both in timing and magnitude, basically anthropogenic. The consistence of observations between two consecutive years further indicates a durable situation of altered natural patterns, which could have been occurring since 1960s-1970s as inferred by changes in sediment accumulation rates within the canyon axis linked to the increase of total engine power of the trawling fleet working in the study area (Martín et al., 2008).

The thickness of the sediment plumes generated by the sediment gravity flows, often extending 100 m above the bottom, is also remarkable. In the Gulf of Lions shelf, Durrieu de Madron et al. (2005) reported trawling-induced bottom nepheloid layers (BNL) 3-6 m thick with average SSC of 50 mg l^{-1} close to the bottom, rapidly declining upwards. Palanques et al. (2001) on the inner shelf off Barcelona measured SSC increasing up to 6 mg l^{-1} and BNL thickness up to 15 m after the passage of otter trawlers. These observations conducted in continental shelf environments indicate lower concentrations and thinner turbid plumes compared with the much higher sediment loads reaching greater distances above the bottom observed in this study. This fact seems to confirm the previously held (but largely unsupported by direct observations) idea that trawling fisheries at slope depths might produce greater physical impacts than shallow-water correlatives. To account for these large differences, first it must be taken into account that deep-sea trawling in general requires heavier and bigger gears dragged by more powerful engines than shallow water counterparts, resulting in an enhanced capacity to impact the seafloor (e.g. Ragnarsson and Steingrímsson, 2003). Also, the sediment grain size of surface sediments tends to be finer on continental slopes than on shelves, hence, clouds of resuspended particles could have longer residence times in the water column in the former case. Surface sediments at the Sant Sebastià fishing ground near the Montgrí gully are basically composed of silty mud, with sand contents <3% (mean φ = 7.4) (unpublished results). Additionally, steeper bathymetries of continental slopes, and in particular on the rims of submarine canyons, compared to gently-sloping shelves, can promote sediment gravity flows, while the topographic constrain of the tributary valley may act as a funnel, focusing and channelling resuspended particles toward greater depths. Such factors contribute to promote sediment gravity flows and further enhance the propagation of resuspended sediments far from their source.

4.2. Seasonal evolution of water turbidity in the Montgrí tributary

A remarkable aspect of the turbidity time series recorded in the Montgrí tributary valley is the decline in frequency and intensity of high-turbidity episodes from late spring/early summer through autumn (Fig. 2). This temporal trend is coherent with previous observations of downward particle fluxes in the canyon axis at 1200 m depth downslope from the Montgrí tributary valley), which were high from May to July 2001 and declined markedly from mid-August (Martín et al., 2006). It also makes sense in light of the general mobility patterns of the fishing fleet, which in turn follows the seasonal displacements of the targeted species. *Aristeus antennatus* tends to form aggregations at depths of 400-900 m during the reproductive period in spring and early summer, and moves to shallower depths by late summer (Sardà et al., 1994), being fished at 400-600 m from autumn through winter (Demestre and Martín, 1993) The spring-early summer deep aggregations are mainly composed of highly priced mature females, hence maximum captures and working depths take place during that period (Demestre and Martín, 1993; Tobar and Sardà, 1987).

It is worth to note that the data set shown in Fig. 2 suggests a disruption of the general annual cycle of sediment transport in the Northwest Mediterranean continental margin, where particle fluxes tend to be higher in autumn-winter and lower in spring-summer due to the seasonal dynamics of the coastal and slope currents and the occurrence of storms and river discharges (Heussner et al., 1996). Changes in the annual trends of sediment resuspension as a consequence of trawling activities were also noted by Floderus and Pihl (1990) at shallow depths in the Kattegat.

4.3. Can bottom trawling contribute to feed nepheloid layers?

Hydrographical profiles conducted after the passage of the trawling fleet over the Sant Sebastià fishing ground reveal the presence of slope BNLs and detachments of INLs from the canyon flank (Fig. 8). At the shallowest stations 4-6 a diluted INL is apparent at approximately 150-220 m depth, likely generated by natural processes causing detachments of suspended particles at the shelf-break that spread constrained by the density gradient between Atlantic Water (AW) and Levantine Intermediate Water (LIW). On the other hand, the well developed and concentrated (4-5 mg l^{-1}) BNL and the deep INL recorded in the area where trawling takes place (stations 3 and 4) are likely related to trawling-induced resuspension. The across-canyon transect shown in Figure 8 was conducted at the end of a working day and hence reflects turbidity values corresponding to the aftermath of the passage of trawling gears.

Observations at the mooring site reveal that the residual part of the sediment that remains in suspension after the passage of the sediment gravity flows contribute to feed a BNL, maintaining relatively high turbidity values near the seafloor for several hours until the trawling activities resume the day after (Fig. 7). Additionally, the lighter and presumably finer fraction of the resuspended particles tends to be detached from the seafloor and uplifted into the water column at the end of a working day (Fig. 5), contributing to the development of an INL at mid water depths. In fact, the INL detachment observed at station 3 around 500-600 m depth seems to be generated by trawling activities in shallower areas (around station 4) from where resuspended particles could be detached and retained by the density gradient between the Levantine Intermediate Water (LIW) and the Western Mediterranean Deep Water (WMDW) (Fig. 8).

Internal waves being propagated along shelf-slope density fronts have been proposed as a mechanism to create resuspension and/or maintenance of particles in suspension generating nepheloid layers in continental slope regions, which tend to be detached from the seafloor into the ocean interior (Gardner, 1989; Puig and Palanques, 1998; Puig et al., 2004; McPhee-Shaw, 2006). Our data suggest that besides internal wave activity, resuspension induced by trawling gears can also play a significant role as initiator of sediment resuspension at slope depths generating localized bottom and intermediate nepheloid layers over and around fishing grounds. The fact that the intermediate nepheloid layer detachments on the La Fonera canyon flank were not observed in the deepest hydrographic stations (1 and 2 in Fig. 8) suggests that the resuspended particles are preferentially advected along-margin by ambient currents, following the isobaths, despite the fact that such currents show relatively weak velocities (<10 cm s^{-1}; Fig. 6).

These observations are also consistent with a previous study, where a set of CTD profiles collected in 2001 (Palanques et al., 2005) suggested enhanced near-bottom turbidity on the northern canyon flank during spring-summer. Zúñiga et al. (2009) also observed in the neighbouring Blanes Canyon (where the *Aristeus antennatus* fishery is also active at similar depths) a consistent intermediate nepheloid layer at 600-800 m depth detaching from the eastern canyon flank.

4.4. Ecological consequences and global implications

Deep-sea ecosystems are in general adapted to a limited variability of physical conditions, resulting in a high vulnerability to artificial changes in their habitats, matter and energy inputs or hydrodynamic stress (Glover and Smith, 2003). Consequently, increases of water turbidity 2 orders of magnitude above the background levels and the replacement of natural cycles in temporal scales from diurnal to annual by a man-made schedule, as observed in this study, must have favoured adaptation strategies and communities different to those inhabiting the study area before intensive trawling times. Our observations also confirm that the effects of bottom trawling can propagate downslope from the areas actually exploited by trawlers, affecting larger and deeper areas. An extension of trawling impacts beyond fishing grounds has been documented in the NE Atlantic by Priede et al. (2011), who observed that the total abundance of demersal fishes had decreased 1000 m downslope from the trawled depth range (500-1500 m depth). Priede et al. (2011) invoked the removal of eurybathic deep-sea fishes at the shallow end of their depth range to explain the observed decrease in fish abundance. Without contradicting that interpretation, our results also suggest that trawling-induced physical impacts themselves can also propagate downslope from fishing grounds as sediment gravity flows and eventually as nepheloid layers. This could in turn compromise the survival rates of deep-sea animals through suffocation and clogging of respiratory surfaces or by preventing the normal settlement of larvae, among other effects that may derive from a substantial change in the amount of suspended solids in the water column (Jones, 1992). This may have as well implications for the management of the deep-sea and the definition of protected areas. Conservation measures such as the ban on bottom trawling beyond the 1000-m isobath, recommended by the General Fisheries Council for the Mediterranean in 2005 (GFCM, 2005), might not be enough to guarantee the protection of vulnerable deep-sea ecosystems below that depth.

Deep-sea fisheries at slope depths and in the vicinity of steep environments such as submarine canyons, ridges and seamounts are not exclusive of the study area but fairly widespread and recently estimated as 4.4 million km^2 only on continental slopes (Puig et al., 2012) and 20 million km^2 comprising all marine trawled areas (World Resources Institute, 2000). In the light of these facts, the global scale implications of bottom trawling activities for deep-sea ecosystems and biogeochemical cycles deserve further interest from the scientific community.

5. Concluding remarks

This study conducted in the La Fonera (=Palamós) Canyon at 980 m depth showed that commercial trawling on the northern canyon flank controls water turbidity in a neighbouring tributary to at least 100 m above the bottom. Trawling-induced resuspension causes turbidity increases near the bottom up to 2 orders of magnitude higher than background levels. No significant increases in turbidity were recorded outside working hours and working days, implying that natural processes capable of resuspending sediments are weak at the mooring site, and consequently, that man-made resuspension is the major driver of sediment dynamics.

This study also suggests that, aside from the generation of sediment gravity flows, bottom trawling can contribute to the development of slope nepheloid layers, and in this way, its effects can effectively propagate away from fishing grounds. Since deep-sea trawling is not exclusive of the study area but increasingly spread around the global ocean, the present study raises the alert whether natural patterns of sediment resuspension and water column turbidity in the deep sea are being replaced by a man-made schedule, with unknown consequences for global biogeochemical cycles and deep-sea ecosystems.

Acknowledgements

We are grateful to the crew and officers of B/O García del Cid (CSIC) and “Lluerna” (Generalitat de Catalunya) and to the participants in the HERMIONE-I & II surveys for their help at sea. This work is funded by the HERMIONE project (Grant agreement 226354) under the European Commission's 7th Framework Programme. J. Martín was funded through a JAE-DOC contract within the Program «Junta para la Ampliación de Estudios», granted by Consejo Superior de Investigaciones Científicas and co-financed by the European Social Fund. We thank the two anonymous reviewers who helped to improve the submitted manuscript through their constructive comments.

References

Alegret, J.L., Garrido, A., 2004. Historia de la Confraria de Pescadors de Palamós. Confraria de Pescadors de Palamós. Palamós, Spain.

Allen, S.E., Vindeirinho, C., Thomson, R.E., Foreman, M.G.G., Mackas, D.L., 2001. Physical and biological processes over a submarine canyon during an upwelling event. Can. J. Fish. Aquat. Sci. 58, 4411-4421.

Benn, A.R., Weaver, P.P., Billet, D.S.M., van den Hove, S., Murdock A.P., Doneghan, G. B., Le Bas, T., Roopnarine, P., 2010. Human Activities on the Deep Seafloor in the North East Atlantic: An Assessment of Spatial Extent. PLoS ONE 5(9), e12730. doi:10.1371/journal.pone.0012730.

Bensch, A., Gianni, M., Greboval, D., Sanders, J., Hjort, A., 2009. Worldwide review of bottom fisheries in the high seas. FAO Fisheries and Aquaculture Technical Paper Rome. ftp://ftp.fao.org/docrep/fao/011/i0540e/i0540e.zip

Black, K.P., Parry, G.D., 1994. Sediment transport rates and sediment disturbance due to scallop dredging in Port Phillip Bay. Mem. Queensl. Mus. 36(2), 327-341.

Churchill, J.H., 1989. The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental-shelf. Cont. Shelf Res. 9, 841-864.

Dellapenna, T.M., Allison, M.A., Gill, G.A., Lehman, R.D., Warnken, K.W., 2006. The impact of shrimp trawling and associated sediment resuspension in mud dominated, shallow estuaries. Estuar. Coast. Shelf Sci. 69(3-4), 519-530.

Demestre, M., Martín, P., 1993. Optimum exploitation of a demersal resource in the western Mediterranean: the fishery of the deep-water shrimp *Aristeus antennatus* (Risso, 1816). Sci. Mar. 57(2-3), 175-182.

Durrieu de Madron, X., Ferré, B., Le Corre, G., Grenz, C., Conan, P., Pujo-Pay, M., Bodiot, O., Buscail R., 2005. Trawling-induced resuspension and dispersal of muddy sediments and dissolved elements. Cont. Shelf Res. 25, 2387-2409.

Fabri, M.-C., Pedel, L., Beuck, L., Galgani, F., Hebbeln, D., Freiwald, A., 2013. Vulnerable Marine Ecosystems in French Continental Mediterranean Submarine Canyons: Spatial Distribution and Anthropogenic Impacts. Deep-Sea Res. II (this issue).

Ferré, B., Durrieu de Madron, X., Estournel, C., Ulses, C., Le Corré, G., 2008. Impact of natural (waves and currents) and anthropogenic (trawl) resuspension on the export of particulate matter to the open ocean: application to the Gulf of Lion (NW Mediterranean). Cont. Shelf Res. 28, 2071-2091.

Floderus, S., Pihl, L., 1990. Resuspension in the Kattegat: Impact of variation in wind climate and fishery. Estuar. Coast. Shelf Sci. 31(4), 487-498.

Gardner, W.D., 1989. Periodic resuspension in Baltimore Canyon by focusing of internal waves. J. Geophys. Res. 94, 18185-18194.

GFCM, 2005. REC.CM-GFCM/29/2005/1. Management of certain fisheries exploiting demersal and deepwater Species. ftp://ftp.fao.org/FI/DOCUMENT/gfcm/web/GFCM_Recommendations2005.pdf

Glover, A.G., Smith. C.R., 2003. The deep-sea floor ecosystem: current status and prospects of anthropogenic change by the year 2025. Environ. Conserv. 30, 219-241.

Guillén, J., Palanques, A., Puig, P., Durrieu de Madron, X., Nyffeler, F., 2000. Field calibration of optical sensors for measuring suspended sediment concentration in the western Mediterranean. Sci. Mar. 64, 427-435.

Heussner, S., Calafat, A., Palanques, A., 1996. Quantitative and qualitative features of particle fluxes in the North-Balearic Basin, in: Canals, M., Casamor, J.L., Cacho, I., Calafat, A., Monaco, A. (Eds.), EUROMARGE-NB Final Report, MAST II Programme, EU, vol. II, pp. 41-66.

Jones, J.B., 1992. Environmental impact of trawling on the seabed: A review. N. Z. J. Mar. Freshw. Res. 26, 59-67.

Kaiser, M.J., Collie, J.S., Hall, S.J., Jennings, S., Poiner, I.R., 2002. Modification of marine habitats by trawling activities: prognosis and solutions. Fish Fish. 3(2), 114-136.

Lastras, G., Canals, M., Amblas, D., Lavoie, C., Church, I., De Mol, B., Duran, R., Calafat, AM., Hughes-Clarke, JE., Smith, CJ., Heussner, S., 2011. Understanding sediment dynamics of two large submarine valleys from seafloor data: Blanes and La Fonera canyons, northwestern Mediterranean Sea. Mar. Geol. 280(1-4), 20-39.

Main, J., Sangster, G.I., 1981. A study of sand clouds produced by trawl boards and their possible effect on fish capture. Scottish Fisheries Research Report No. 20. Dept of Agriculture and Fisheries for Scotland. 19 pp.

Martín, J., Palanques, A., Puig, P., 2006. Composition and variability of downward particulate matter fluxes in the Palamós submarine canyon (NW Mediterranean). J. Mar. Syst. 60, 75-97.

Martín, J., Palanques, A., Puig, P., 2007. Horizontal transfer of suspended particulate matter in the Palamós submarine canyon. J. Mar. Res. 65, 193-218.

Martín, J., Puig, P., Palanques, A., Masqué, P., García-Orellana, J., 2008. Effect of commercial trawling on the deep sedimentation in a Mediterranean submarine canyon. Mar. Geol. 252, 150-155.

McPhee-Shaw, E., 2006. Boundary-interior exchange: Reviewing the idea that internal-wave mixing enhances lateral dispersal near continental margins. Deep-Sea Res. II 53, 42-59.

Middleton, G.V., Hampton, M.A., 1976. Subaqueous sediment transport and depositional by sediment gravity flows, in: Sediment Transport and Environmental Management, Stanley, D.J., Swift, D.J.P. (Eds.), John Wiley, pp. 197-218.

Morato, T., Watson, R., Pitcher, T. J., Pauly, D., 2006. Fishing down the deep. Fish. Fish. 7, 24-34.

Palanques, A., Guillén, J., Puig, P., 2001. Impact of bottom trawling on water turbidity and muddy sediment of an unfished continental shelf. Limnol. Oceanogr. 46, 1100-1110.

Palanques, A., García-Ladona, E., Gomis, D., Martín, J., Marcos, M., Pascual, A., Emelianov, M., Puig, P., Guillén, J., Gili, J.M., Tintoré, J., Jordi, A., Basterretxea, G., Font, J., Segura, M., Blasco, D., Montserrat, S., Ruiz, S., Pagès, F., 2005. A multidisciplinary program to study the dynamics and the ecology of a Northwestern Mediterranean submarine canyon: The Palamós Canyon. Prog. Oceanogr. 66 (2-4), 89-119.

Palanques, A., Martín, J., Puig, P., Guillén, J., Company, J.B., Sardà, F., 2006. Evidence of sediment gravity flows induced by trawling in the Palamós (Fonera) submarine canyon (northwestern Mediterranean). Deep-Sea Res. I 53, 201-214.

Pilskaln, C.H., Churchill, J.H., Mayer, L.M., 1998. Resuspension of sediment by bottom trawling in the Gulf of Maine and potential geochemical consequences. Conserv. Biol. 12, 1223-1229.

Priede, I.G., Godbold, J.A., Niedzielski, T., Collins, M.A., Bailey, D.M., Gordon, J.D.M., Zuur, A.F., 2011. A review of the spatial extent of fishery effects and species vulnerability of the deep-sea demersal fish assemblage of the Porcupine Seabight, Northeast Atlantic Ocean (ICES Subarea VII). ICES J. Mar. Sci. 68(2), 281-289.

Puig, P., Palanques A., 1998. Nepheloid structure and hydrographic control on the Barcelona continental margin, northwestern Mediterranean. Mar. Geol. 149, 39-54.

Puig, P., Palanques, A., Guillén, J., El Khatab, M., 2004. Role of internal waves in the generation of nepheloid layers on the northwestern Alboran slope: Implications for continental margin shaping. J. Geophys. Res. 109, C09011.

Puig, P., Canals, M., Company, J.B., Martín, J., Amblas, D., Lastras, G., Palanques A., Calafat, A., 2012. Ploughing the deep sea floor. Nature 489, 286-289.

Ragnarsson, S.A., Steingrímsson, S.A., 2003. Spatial distribution of otter trawl effort in Icelandic waters: comparison of measures of effort and implications for benthic community effects of trawling activities. ICES J. Mar. Sci. 60, 1200-1215.

Sardà, F., Cartes, J.E., Norbis, W., 1994. Spatio-temporal structure of the deep-water shrimp Aristeus antennatus (Decapoda: Aristeidae) population in the western Mediterranean. Fishery Bulletin 92 (3), 599-607.

Theil, H., Schriever, G., 1990. Deep-sea mining, environmental impact and the DISCOL project. Ambio 19, 245-250.

Tobar, R., Sardà, F., 1987. Análisis de la evolución de las capturas de gamba rosada, *Aristeus antennatus* (Risso, 1816), en los últimos decenios en Cataluña. Inf. Técn. Inv. Pesq. 142, 3-20.

Tragou, E., Zervakis, V., Papageorgiou, E., Stavrakakis, S., Lykousis, V., 2005. Monitoring the physical forcing of resuspension events in the Thermaikos Gulf-NW Aegean during 2001–2002. Cont. Shelf Res. 25, 2315–2331.

WWF/IUCN, 2004. The Mediterranean deep-sea ecosystems: an overview of their diversity, structure, functioning and anthropogenic impacts, with a proposal for conservation. IUCN, Málaga and WWF, Rome.

World Resources Institute, 2000. A guide to world resources 2000-2001: People and Ecosystems: the Fraying web of life, World Resources Institute, Washington, USA.

Würtz, M., 2012. Mediterranean Submarine Canyons: Ecology and Governance. International Union for the Conservation of Nature. Gland, Switzerland and Málaga, Spain.

Zúñiga, D., Flexas, M.M., Sanchez-Vidal, A., Coenjaerts, J., Calafat, A., Jordà, G., García-Orellana, J., Puigdefàbregas, J., Canals, M., Espino, M., Sardà, F., Company, J.B., 2009. Particle fluxes dynamics in Blanes submarine canyon (Northwestern Mediterranean). Prog. Oceanogr. 82, 239-251.

Figure Captions

Figure 1. Bathymetric chart of the La Fonera (=Palamós) submarine canyon in the Northwestern Mediterranean, showing the position of the mooring line (red diamond) in the Montgrí tributary valley deployed in 2010 and 2011. The main fishing ground (Sant Sebastià) on the northern canyon flank is marked as a shadowed area. Crosses indicate the positions of consecutive CTD casts carried out during 11 May 2011.

Figure 2. Time series of suspended sediment concentration (SSC) in the Montgrí tributary valley over a total water depth of 980 m depth during two consecutive sampling periods. a: SSC at 5, 25, 50 and 100 meters above the bottom (mab) from July to early November 2010; b: SSC at 5, 20 and 50 mab from May to mid October 2011.

Figure 3. Detail of the time series of suspended sediment concentration in the Montgrí tributary valley during 2010. "mab" stands for meters above the sea bottom. Days of the week are indicated in the timeline, working days are shadowed in blue.

Figure 4. Detail of the time series of suspended sediment concentration and current speed (ADCP) records in the Montgrí tributary valley during 2011. Days of the week are indicated in the timeline, working days are shadowed in blue. The rest period from 23 to 26 June 2011 corresponds to the annual Palamos' Town Festival. Minor ticks in the time axis mark 4-hour intervals.

Figure 5. Contour plot of suspended sediment concentration (single-point measurements at 5, 10, 15, 20, 25, 30, 40, 50, 70, and 100 mab) in the Montgrí gully at 980 m water depth during

2 July 2010. Note the detachment of the turbid plume up into the water column after the passage of the sediment gravity flow.

Figure 6. Time series of current speed components (rotated along and across the direction of the main Montgrí tributary) and suspended sediment concentration at the Montgrí gully during 20-21 June 2011. Positive current speeds are directed down-slope and to the right when looking in a down-slope direction.

Figure 7. Integration of all SSC data (a: 1 July to 7 November 2010; b: 10 May to 12 October 2011) at selected heights over the sea bottom, ordered by time of day. Instantaneous data (sampling rate = 1 min) are displayed as dots and 1-min averages in solid line. The range of working hours during fishing days of trawlers at the Sant Sebastià fishing ground is shown as a shaded area on the timeline.

Figure 8. CTD vertical profiles of water potential temperature, salinity, potential density anomaly (sigma-theta), and suspended sediment concentration (SSC) from 100 m depth to 5 meters above the seafloor, along a transect carried out on 11 March 2011 across the north flank of the La Fonera Canyon. The time (UTC) of cast start is given on top of the profiles. Shaded areas correspond to SSC values above the baseline at the depths of trawling activities (400-800 m) in the Sant Sebastià fishing ground. Note that only stations 3 and 4 are within the fishing ground (see Fig. 1 for positions of CTD stations). AW, LIW and WDMW stand for Atlantic Water, Levantine Intermediate Water and Western Mediterranean Deep Water respectively. INL= Intermediate nepheloid layer; BNL = Bottom nepheloid layer.

Figure 1

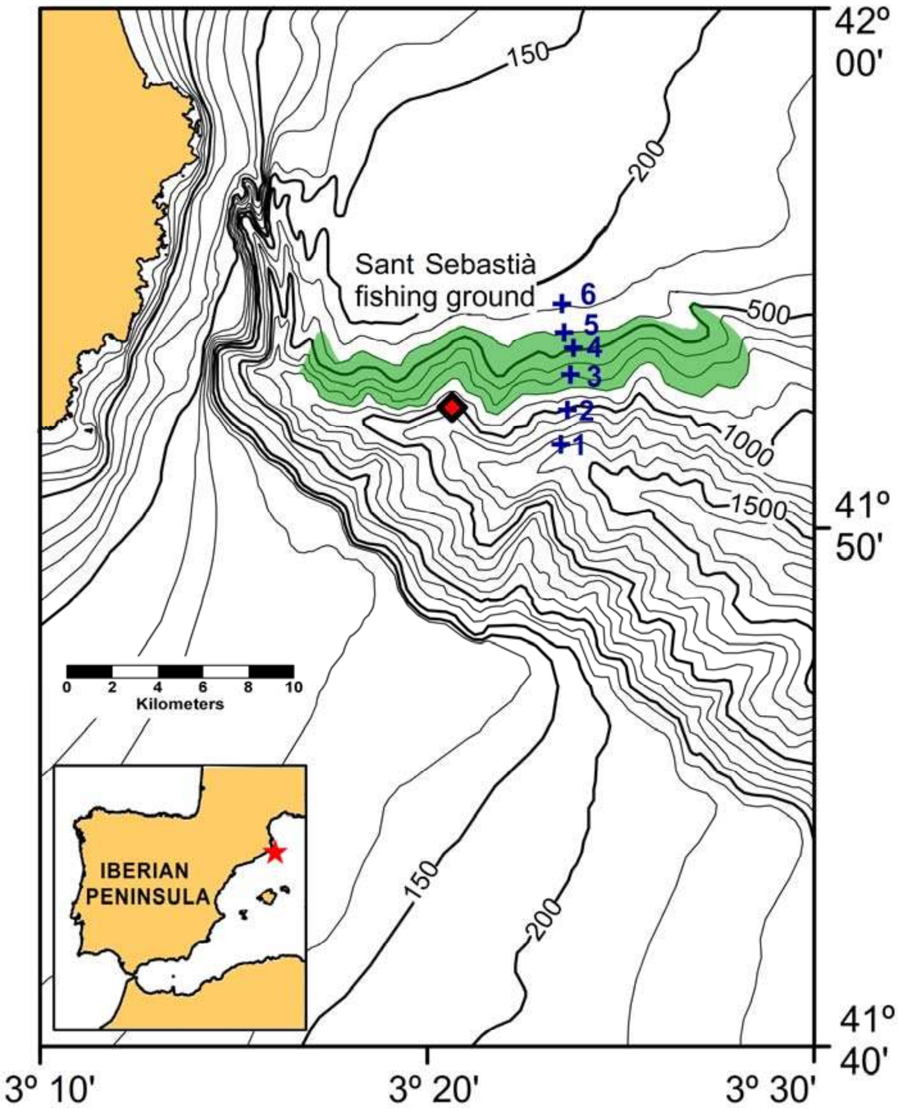
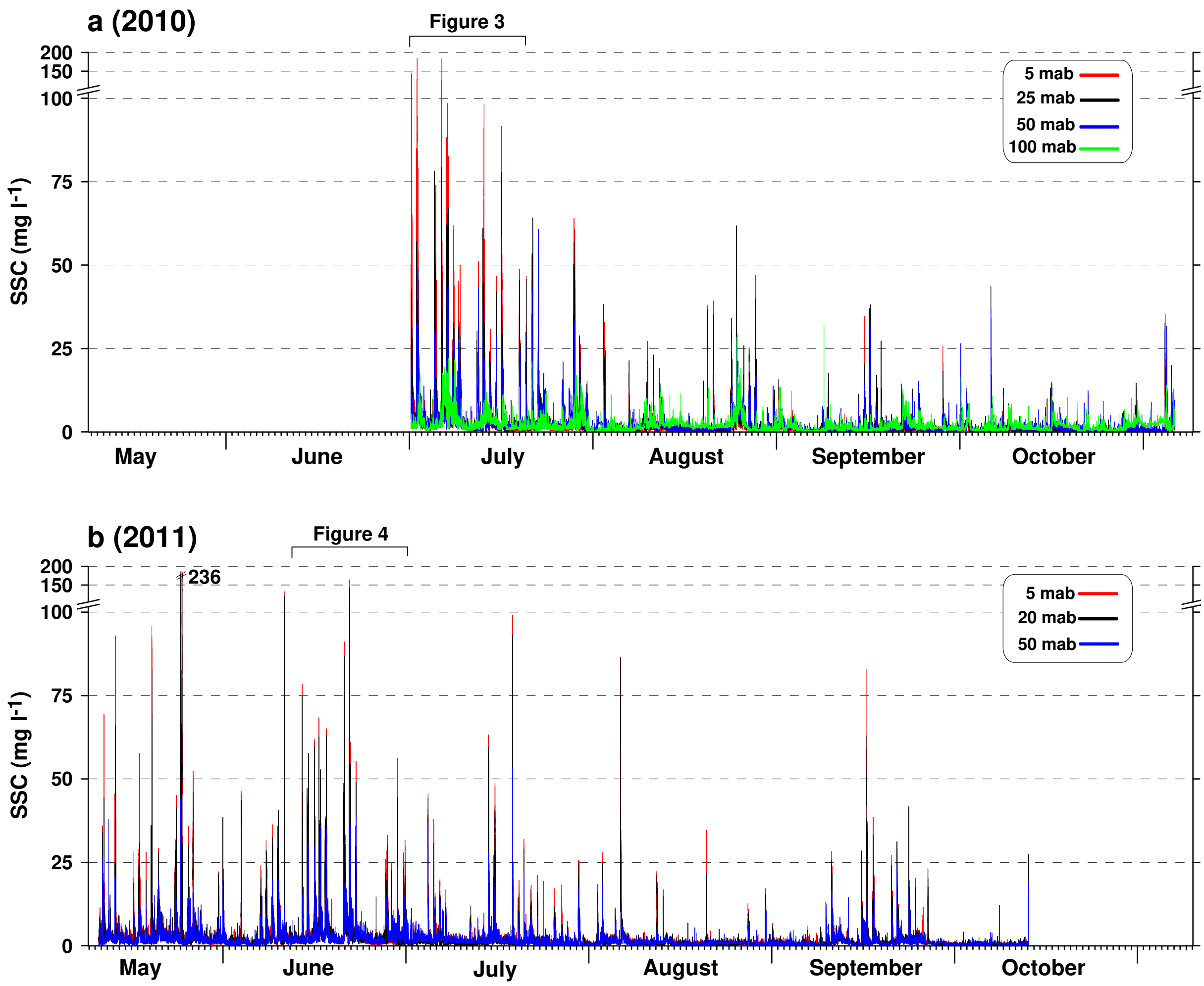

42º
00'
41º
50'
41º
40'
3º 10'
3º 20'
3º 30'
150
200
500
1000
1500
Sant Sebastià
fishing ground
6
5
4
3
2
1
0
2
4
6
8
10
Kilometers
IBERIAN
PENINSULA

Figure 2



a (2010)
Figure 3
200
150
100
75
50
25
0
SSC (mg l-1)
5 mab
25 mab
50 mab
100 mab
May
June
July
August
September
October
b (2011)
Figure 4
236
200
150
100
75
50
25
0
SSC (mg l-1)
5 mab
20 mab
50 mab
May
June
July
August
September
October

Figure 3

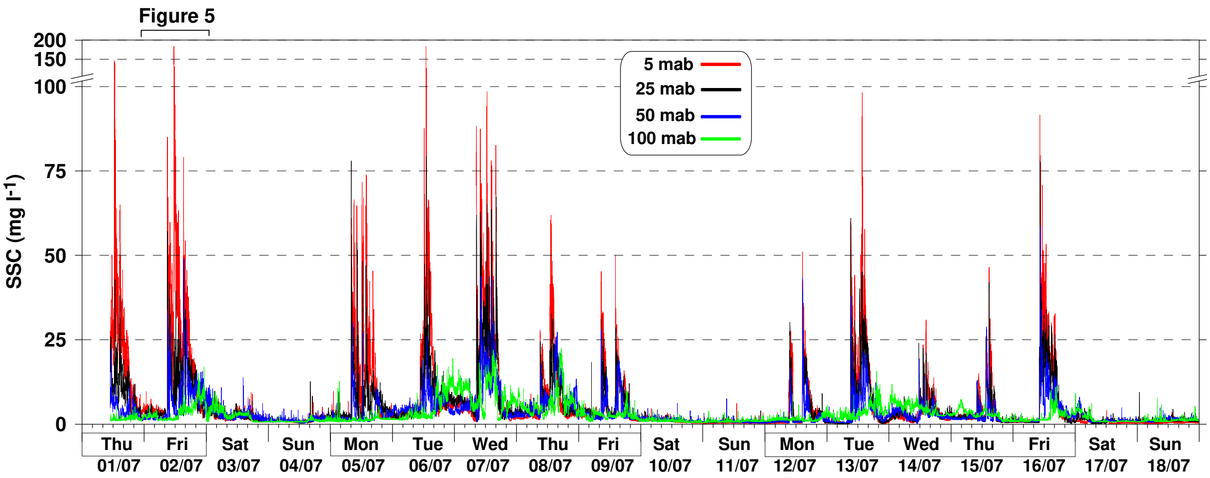


Figure 5
200
150
100
75
50
25
0
SSC (mg l-1)
5 mab
25 mab
50 mab
100 mab
Thu 01/07
Fri 02/07
Sat 03/07
Sun 04/07
Mon 05/07
Tue 06/07
Wed 07/07
Thu 08/07
Fri 09/07
Sat 10/07
Sun 11/07
Mon 12/07
Tue 13/07
Wed 14/07
Thu 15/07
Fri 16/07
Sat 17/07
Sun 18/07

Figure 4

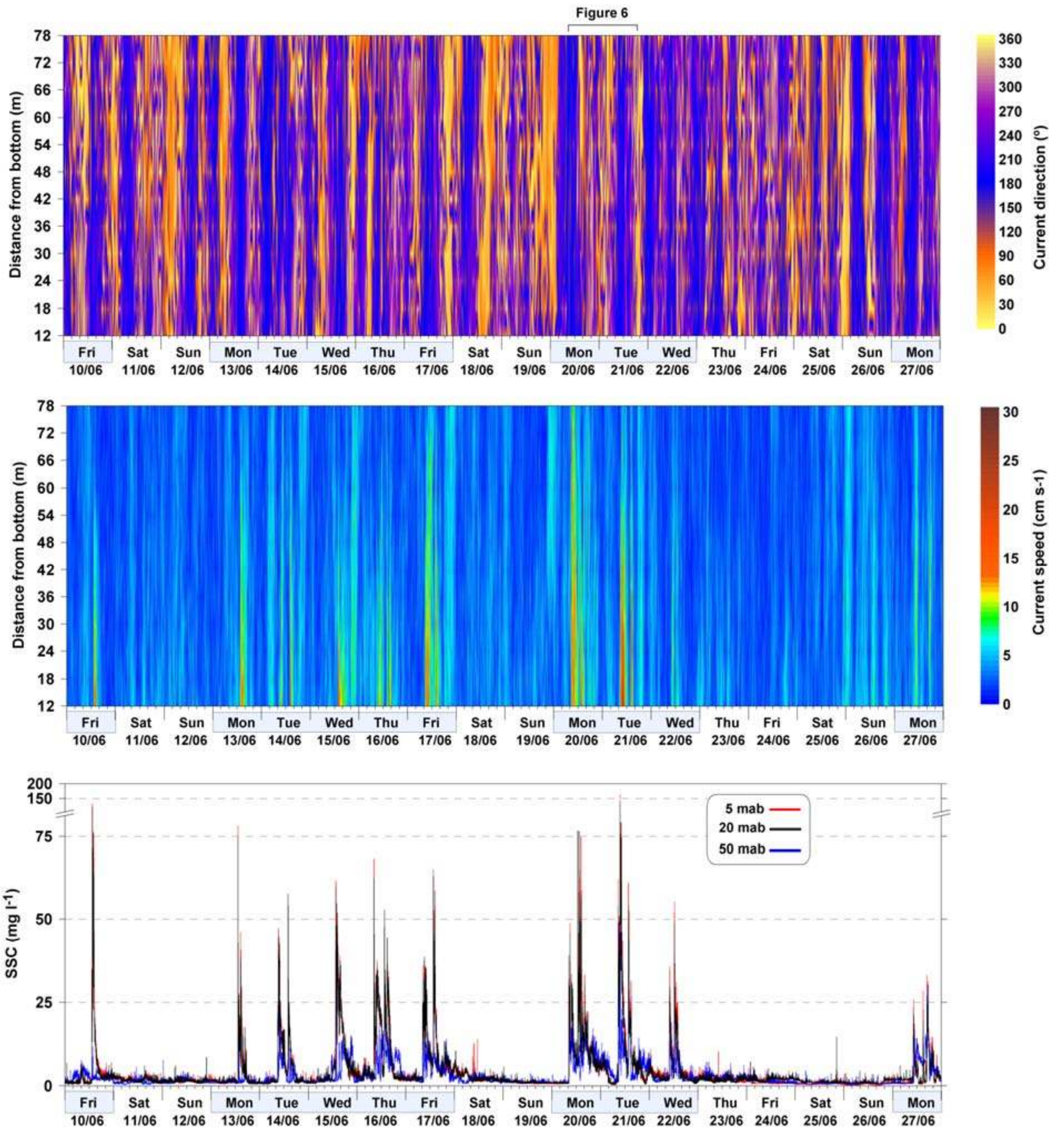
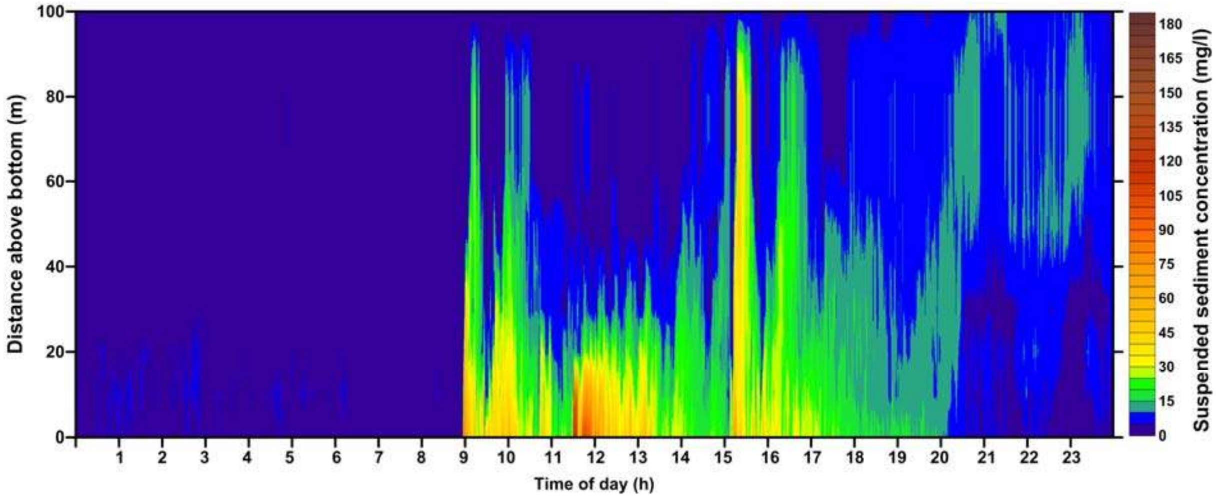


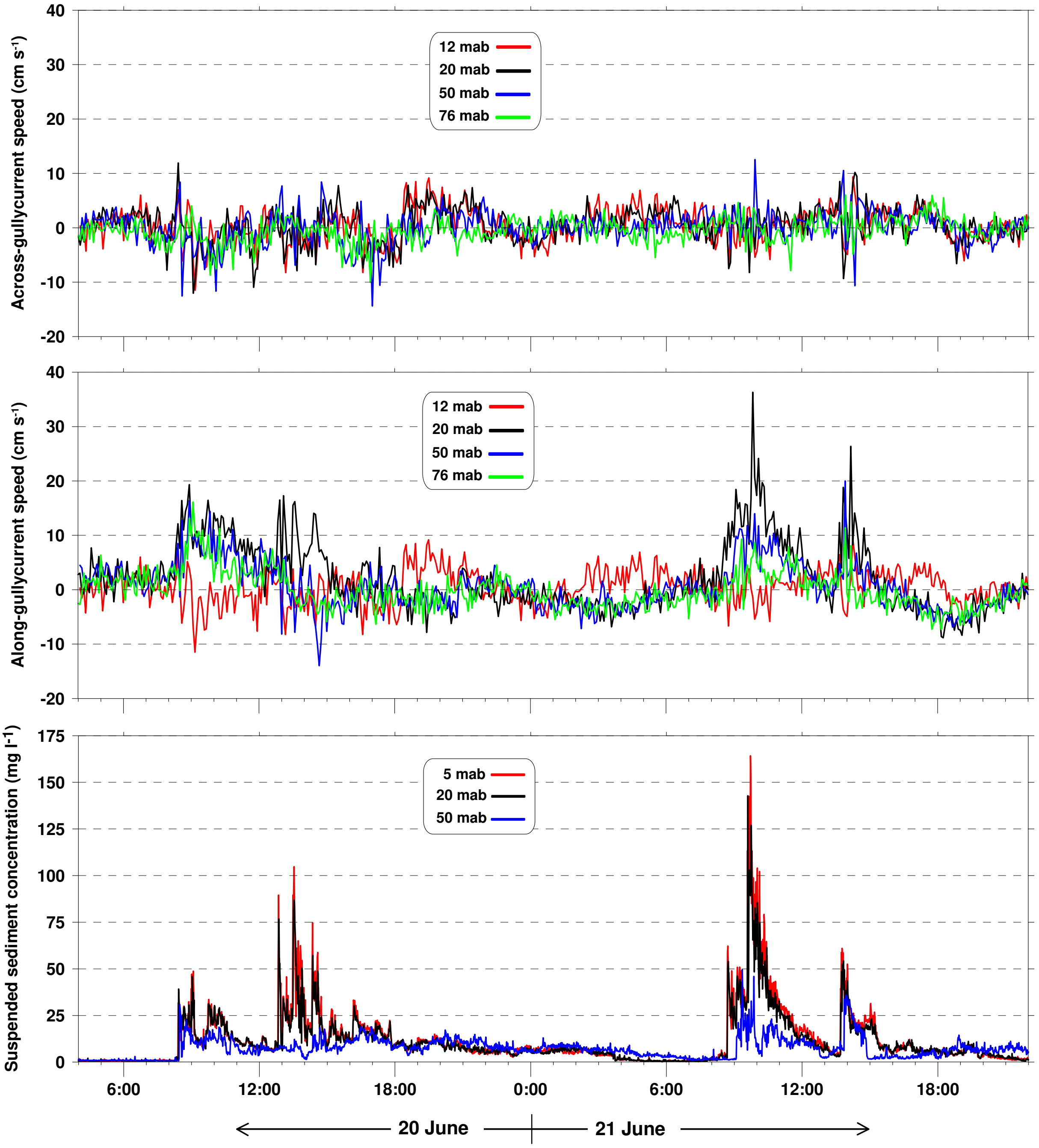
Figure 6
Distance from bottom (m)
Current direction (°)
Current speed (cm s-1)
SSC (mg l-1)
5 mab
20 mab
50 mab
Fri 10/06
Sat 11/06
Sun 12/06
Mon 13/06
Tue 14/06
Wed 15/06
Thu 16/06
Fri 17/06
Sat 18/06
Sun 19/06
Mon 20/06
Tue 21/06
Wed 22/06
Thu 23/06
Fri 24/06
Sat 25/06
Sun 26/06
Mon 27/06

Figure 5



Distance above bottom (m)
0
20
40
60
80
100
Time of day (h)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23
Suspended sediment concentration (mg/l)
0
15
30
45
60
75
90
105
120
135
150
165
180

Figure 6



Across-gullycurrent speed (cm s-1)
12 mab
20 mab
50 mab
76 mab
40
30
20
10
0
-10
-20
Along-gullycurrent speed (cm s-1)
12 mab
20 mab
50 mab
76 mab
40
30
20
10
0
-10
-20
Suspended sediment concentration (mg l-1)
5 mab
20 mab
50 mab
175
150
125
100
75
50
25
0
6:00
12:00
18:00
0:00
6:00
12:00
18:00
20 June
21 June

Figure 7

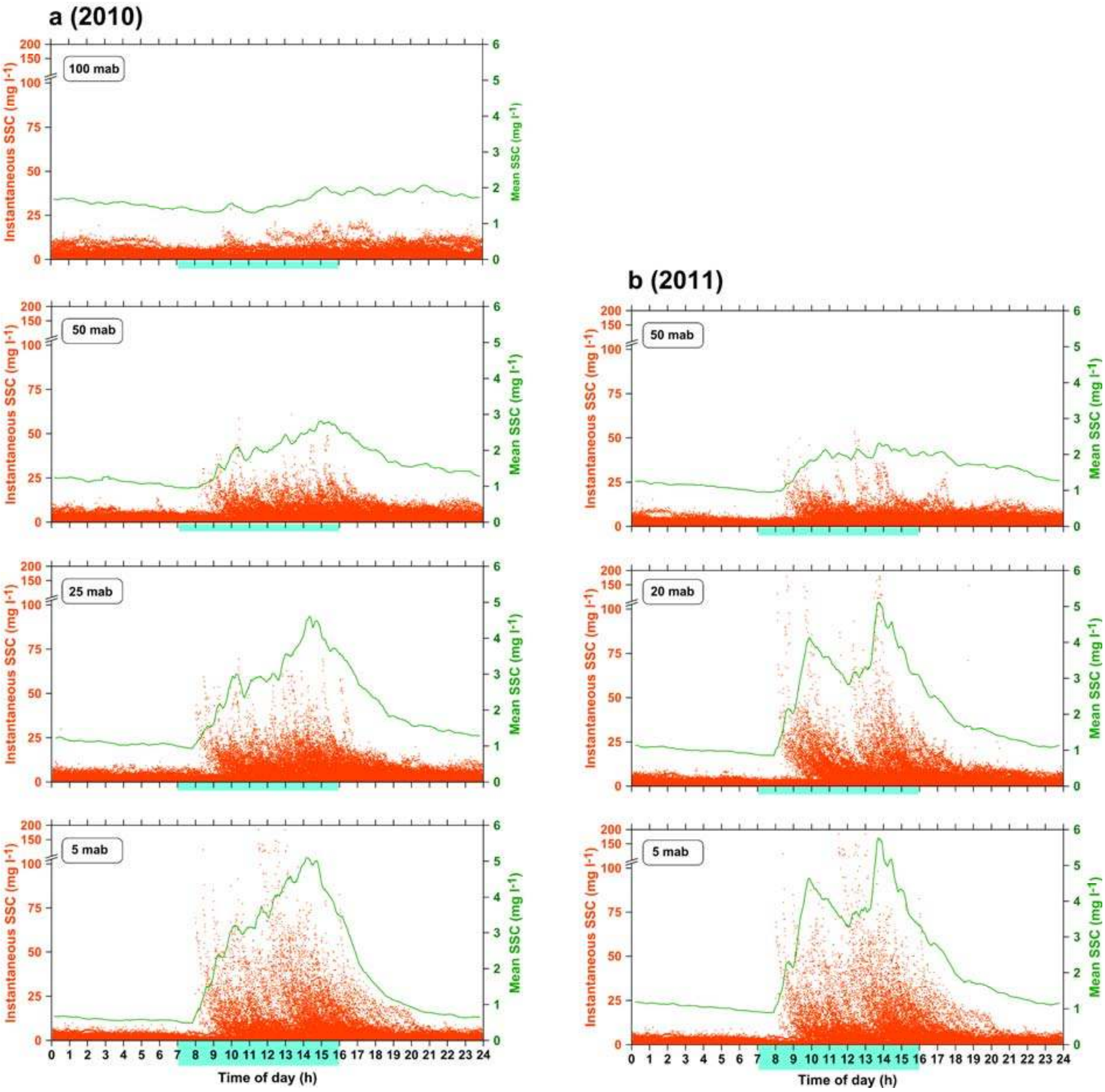
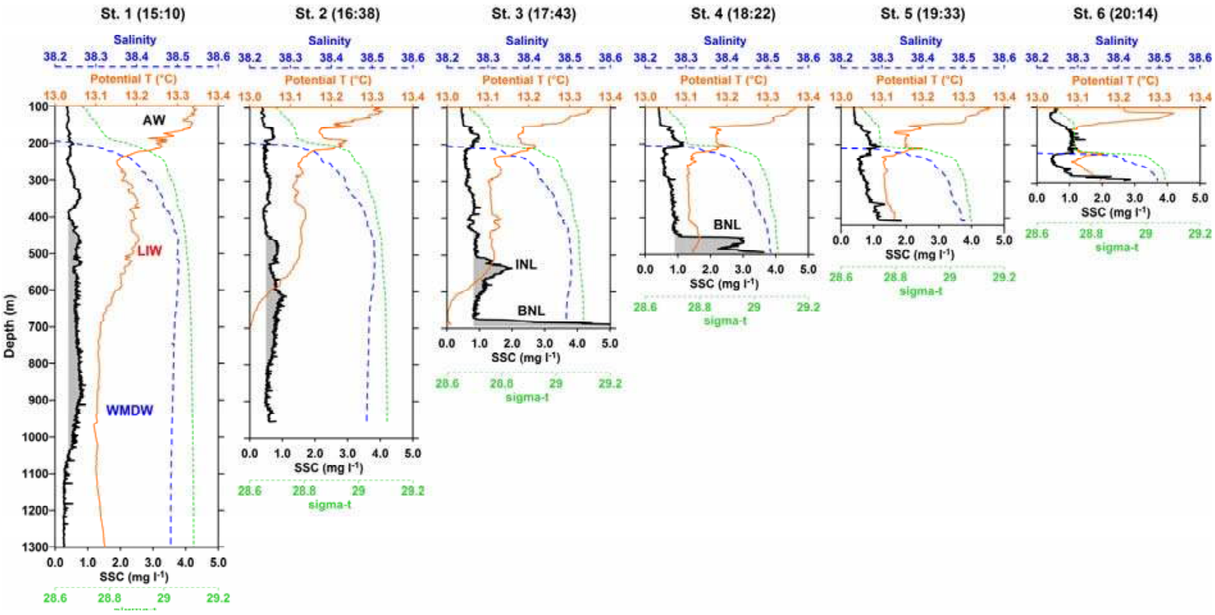

a (2010)
b (2011)
100 mab
50 mab
25 mab
20 mab
5 mab
Instantaneous SSC (mg l-1)
Mean SSC (mg l-1)
Time of day (h)

Figure 8


St. 1 (15:10)
St. 2 (16:38)
St. 3 (17:43)
St. 4 (18:22)
St. 5 (19:33)
St. 6 (20:14)
Salinity
38.2 38.3 38.4 38.5 38.6
Potential T (°C)
13.0 13.1 13.2 13.3 13.4
Depth (m)
100 200 300 400 500 600 700 800 900 1000 1100 1200 1300
SSC (mg l-1)
0.0 1.0 2.0 3.0 4.0 5.0
sigma-t
28.6 28.8 29 29.2
AW
LIW
WMDW
INL
BNL