Elsevier Editorial System(tm) for Marine Geology
Manuscript Draft

Manuscript Number:

Title: Dense shelf water cascades in the Cap de Creus and Palamós submarine canyons during winters 2007 and 2008

Article Type: Research Paper

Keywords: Sediment Transport; Submarine Canyons; Continental Margin; Western Mediterranean

Corresponding Author: Mrs Marta Ribó, Ph.D

Corresponding Author's Institution: Institut de Ciencies del Mar, CSIC

First Author: Marta Ribó, Ph.D

Order of Authors: Marta Ribó, Ph.D; Pere Puig; Albert Palanques; Claudio Lo Iacono

Suggested Reviewers: Andrea Ogston
School of Oceanography, Box 357940. University of Washington. Seattle, WA 98195-7940
ogston@ocean.washington.edu

Henko De Stigter
NIOZ. P.O.Box 59, 1790 AB Den Burg, Texel, The Netherlands
stigter@nioz.nl

Leonardo Langone
ISMAR-CNR, Bologna Consiglio Nazionale delle Ricerche Istituto di Scienze Marine, Sede di Bologna via Gobetti 101, 40129 Bologna, Italy
leonardo.langone@bo.ismar.cnr.it

Xavier Durrieu de Madron
CEFREM, 52 Avenue Paul Alduy. Perpignan – 66860, France
demadron@univ-perp.fr

# Dense shelf water cascades in the Cap de Creus and Palamós submarine canyons during winters 2007 and 2008.

Ribó, M.[1], Puig, P.[1], Palanques, A.[1], Lo Iacono, C.[2]

[1] Institut de Ciències del Mar, CSIC, Passeig Marítim de la Barceloneta 37-49, E-08003 Barcelona, Spain.

[2] Unitat de Tecnologia Marina, CSIC, Passeig Marítim de la Barceloneta 37-49, E-08003 Barcelona, Spain.

## Abstract

The Cap de Creus and the Palamós submarine canyon heads were instrumented during two consecutive winters to study their respective role in the dynamics of the sediment transport on the north-western Mediterranean Sea. Several events of dense shelf-water cascading (DSWC) were identified at both canyons and compared among them. DSWC events were characterized by abrupt drops of temperature and increases of current speeds, and with peaks of high suspended-sediment concentrations (SSC). Concentrations up to 170 mg $l^{-1}$ were recorded in both studied winters at the Cap de Creus Canyon coinciding with the first DSWC event concurrent with an eastern storm. Overall the amount of sediment transported during the DSWC events was one order of magnitude greater at the Cap de Creus Canyon than at the Palamós Canyon. Results from this study have identified the presence of DSWC events also in the Palamós Canyon head, south of the Gulf of Lions (GoL), and corroborated previous findings that

the Cap de Creus Canyon is the main pathway for DSWC and the associated sediment transport from the GoL down to the deeper regions of the north-western Mediterranean.

*Keywords: Sediment Transport, Submarine Canyons, Continental Margin, Western Mediterranean*

## 1. Introduction

Submarine canyons can be described as deep, steep-sided valleys of up to hundred of meters deep, cutting into the continental shelf and/or slope. Submarine canyons incised in continental margins are considered to be preferential pathways for the exchange of water and sediment particles between the coastal area and the open sea (Shepard, 1972). The usual dendritic shape of canyons increases the effective length of the shelf-break and hence the scope for across-margin exchanges and the rapid bathymetric changes may affect the regional circulation. (Huthnance, 1995; Skliris *et al.*, 2002). Hydrodynamics in submarine canyons depend upon several forcing conditions in the region such as general circulation, bottom morphology and atmospheric regime (Hickey, 1995; Puig *et al.*, 2001; Xu *et al.*, 2002). In most of coastal regions, nearshore water is trapped on the shelf by the presence of energetic slope currents, which are in quasi-geostrophic balance and thus inhibit cross-shelf exchanges (Ardhuin *et al.*, 1999, Klinck, 1996). Canyons, by intersecting the path of these currents, induce a new dynamic balance that is not geostrophic, leading to significant motions across the slope, while the steep canyon topography generates intense vertical motion (Skliris, 2004).

The sedimentary dynamics in the north-western Mediterranean continental margin has been continuously studied during the last decades in the framework of many research projects. The earlier studies using moored sediment traps demonstrated that river floods and storms enhanced particle fluxes inside submarine canyons and on the continental slope (e.g. Monaco *et al.*, 1990; Puig and Palanques, 1998), and for a long time, these processes were considered the major contemporary mechanisms able to transport sediment from the shelf towards deeper environments. However, recent studies conducted in the frame of the EuroSTRATAFORM project, during which seven submarine canyons from the Gulf of Lions (GoL) were instrumented simultaneously, also recognized the importance of the formation of dense shelf waters, and their subsequent downslope cascading, in exporting shelf particles towards deep-sea regions (see Palanques *et al.* (2006a) and Canals *et al.* (2006) for details). Since then, particularly active cascading events, occurring alone or combined with storm events, have been monitored in the (GoL) during the 2003-2006 period (Durrieu de Madron *et al.*, 2008; Puig *et al.*, 2008; Sanchez-Vidal *et al.*, 2009).

The strongest off-shelf sediment transport associated to DSWC events tend to occur during eastern storms, and sediment transfer is enhanced towards the western part of the GoL because of its down-flow location and the abrupt narrowing of the shelf, being particularly intense through the Cap de Creus submarine canyon. Observations indicate that net sediment fluxes in the Cap de Creus Canyon are 1 to 2 orders of magnitude higher than in all the other canyons of the GoL (Palanques *et al.*, 2006a). There is also satisfactory agreement between 3D sediment transport modeling and data observations. During wintertime, the storm-induced downwelling interact with DSWC that enhanced the near-bottom transport of sediment, advecting resuspended sediments towards deeper reaches of the westernmost canyons (Cap de Creus and Lacaze-Duthiers submarine canyons) (Ulses *et al*., 2008a, b). Modeling results also indicate that shelf waters are transferred south from the GoL, towards the Catalan margin, and suggest the presence of DSWC events during anomalous cold winters in the Palamós and Blanes submarine canyons (Ulses *et al*., 2008b). The analysis of daily deep-sea shrimp landings along the Catalan coast also corroborates this fact (Company *et al*., 2008) although direct observations of DSWC events in such submarine canyons have not been conducted.

The Palamós submarine canyon (also named La Fonera Canyon or Llafranc Canyon) is one of the most prominent topographic features in the NE Spanish margin (Serra, 1981). It was intensively studied in the context of the multidisciplinary project CANYONS (Palanques *et al*., 2005), although moored time series were not obtained during winter conditions, when DSWC events tend to occur. The CANYONS field experiment took place from March to November 2001 and involved measurements of downward fluxes and composition of particulate matter by means of sediment traps (Martín *et al*., 2006), as well as horizontal suspended particle fluxes through coupled turbidity and current meter measurements (Martín *et al*., 2007). During this 8-month experiment, net sediment transport at the Palamós canyon head was directed persistently up-canyon, suggesting retention of particles in the upper canyon reaches. Downward particle fluxes at the canyon head were almost constant throughout the experiment until November 2001, at the end of the observational period, when the off-shelf sediment transport associated to major storm overfilled the sediment trap. This transport event also overfilled the near-bottom sediment trap located within the Palamós canyon axis at 1200 m depth and caused significant increases of downward particle fluxes in all the other moored traps placed near the bottom or at intermediate depths (Martín *et al*., 2006). Suspended sediment concentrations at the canyon head during this off-shelf transport event reached ~10 mg $l^{-1}$ (Palanques *et al.*, 2006b), but associated near-bottom current velocities were low, suggesting the detachment of particles at the shelf break which passively settled into the canyon (Martín *et al*., 2006).

As it has been pointed out before, the Cap de Creus submarine canyon has been intensively studied during the past years and it has been identified as a major transport conduit in the northwestern Mediterranean during storms and DSWC events. On the contrary, almost no information exists about the sediment transport processes operating within the Palamós submarine canyon during wintertime. Therefore, the aim of this study is to determine the presence of DSWC events at the Palamós canyon head during winter conditions, and to compare these events with the contemporary ones occurring in the Cap de Creus canyon head.

## 2. Study area

The Cap de Creus and the Palamós submarine canyons are located in the northwestern Mediterranean, at the northern Catalan continental margin (Fig. 1). The general water circulation in this area is governed by a baroclinic current that follows the continental slope from NE to SW in quasi-geostrophic equilibrium with a shelf/slope density front established between coastal and open sea saline waters (Font *et al*., 1998). This slope current is referred as the Northern Current (Millot, 1999) and in this area flows mainly towards the southwest (Font *et al*, 1998). The circulation exhibits a seasonal variability with significant spatial mesoscale variability which plays a decisive role in exchange process between shelf and oceanic waters (Font *et al*., 1995; La Violette *et al*., 1990; López García *et al*., 1994). The absence of significant tidal motions and of a prevailing wind field makes the internal dynamics of the currents and its interaction with topography as the permanent source of variability in the area (Alvarez *et al*., 1996).

The Cap de Creus Canyon belongs to a complex network of submarine canyons cutting the western Gulf of Lions continental shelf and slope, which converges into the larger Sète Canyon (Berné *et al*., 1999). It is the south westernmost submarine canyon in the Gulf of Lions margin, before the constriction of the Cap de Creus promontory, and its detailed geomorphological aspects has been recently described in Lastras *et al*., (2007). The Palamós Canyon is located 20 km south from the Cap de Creus Canyon, and it is roughly oriented along a north-south direction and when its axis reaches approximately 800 m water it is oriented in WNW-ESE direction and gradually broadens towards the open sea. The steep canyon walls are indented by numerous tributaries (i.e. gullies) (Martín *et al*., 2006). The head of both submarine canyons reaches the continental shelf-edge by the 90 m depth contour, and its western canyon rim is about 2–3 km away from the coastline.

## 3. Materials and methods

### *3.1 Canyon seafloor morphology*

Multibeam bathymetry data from the Cap de Creus canyon head (Fig. 2a) was acquired using Fugro's M/V Geo Prospector, equipped with a hull-mounted Kongsberg Simrad EM300 30kHz system (1° x 1° configuration). Data was processed and binned at a cell size slightly larger than the beam-to-beam spacing for each area. Multibeam bathymetry data from the Palamós canyon head (Fig. 2b) was collected with the SEABEAM 1050D Multibeam Echosounder dual frequency (50 and 180 KHz) mounted on the R/V Garcia del Cid, which allows to collects bathymetric data in both shallow and medium depth waters over a wide swath in excess of 150 degrees. Multibeam data was corrected for heading, depth, pitch, heave and roll. The post-processing was produced with the HIPS system, a submarine mapping software developed by CARIS. Once the data was corrected for water column sound velocity variations and eventually cleaned with a ping graphical editor, gridding of the filtered soundings was carried out to obtain the final Digital Terrain Model (DTM). A 10m and a 25m bathymetric grid were produced for Cap de Creus and Palamós submarine canyons respectively, and visualization of bathymetric data was conducted using Golden Software Surfer. Multibeam bathymetric maps were used to locate the instrumented moorings deployed to characterize sediment transport processes along both submarine canyons.

### *3.2 Instrumented moorings*

The observational work during this study consisted of a series of field measurements carried out with two near-bottom instrumented moorings deployed at the Cap de Creus Canyon (3°19.3’; 42°23.4’) at 315 m water depth (Fig. 2a) and at the Palamós canyon head (3°14.9’; 41°56.1’) at 325 m depth (Fig. 2b). These moorings were equipped with an Aanderaa RCM 9 current meter with temperature, pressure, conductivity and two turbidity sensors of 0-20 and 0-500 FTU, placed at 5 m above the sea floor. Time series were collected from October 2006 to April 2007, and also from November 2007 to June 2008, covering two consecutive winters, and the sampling interval of the current meters was set to 30 min. Turbidity data recorded in FTU (Formazin Turbidity Units) were converted into suspended sediment concentrations (SSC) following the methods described in Guillén *et al*. (2000). Instantaneous sediment fluxes were obtained by multiplying the current speed by the SSC, and progressive cumulative fluxes were calculated for N-S and E-W components. In order to obtain the across- and along-canyon sediment fluxes, a rotation of the coordinates system was done using as reference the canyon axis orientation obtained from the multibeam bathymetries (Fig.2). In the case of the Cap de Creus Canyon, a clockwise rotation of 50º was applied, and about 55º in the Palamós Canyon. Time-integrated cumulative across- and along-canyon sediment transport was calculated at the head of both canyons. Averaged over time, these give the net across- and along-canyon sediment fluxes. From the resultant vector of those flux components, the estimated magnitude and direction of the sediment net fluxes were obtained.

*3.3 External data*

Daily river discharges in the study area were supplied by the "Agència Catalana de l'Aigua" and the "DDE Aude/HYDRO-MEDD/DE" (French ministry of environment and sustainable development). The Têt River was selected as the most representative river discharging north from the Cap de Creus Canyon, and the Fluvià River also as the most representative river north from the Palamós Canyon, since their watersheds are not affected by major dams (Fig. 1).

Wave data during the study period was also analyzed. Data of the Leucate coastal buoy, located at 40 m depth (Fig. 1), was provided by the Centre d'Études Techniques Maritimes Et Fluviales (Ministère de l'Ecologie, de l'Energie, du Développement durable et de la Mer. Forniture de données extradites de la base de données CANDHIS). Interruptions in the Leucate buoy time series were filled with data from the wind-wave model WAVEWATCH III. Data of the Palamós coastal buoy, located at 90 m depth (Fig. 1), was provided by "Puertos del Estado" (Ministerio de Fomento). Since there were important interruptions in the buoy time series, data from a WANA point (daily wave forecast output from the fourth generation WAve Model, WAM) was also used.

## 4. Results

### *4.1 Forcing conditions*

Time series of river discharges and significant wave height, from October 2006 to July 2008, are shown in Figure 3. The Têt and the Fluvià Rivers discharges reflected the most important flash floods from the Pyrenees' watershed rivers discharging onto the southwestern GoL and the northern Catalan shelf during the study periods. Both River discharges were relative low during all the time period, usually below 5 $m^3 s^{-1}$. On the 14th of April 2007, a maximum of 56.2 $m^3 s^{-1}$ was registered at the Têt River discharge, concurrent with an increase of 76.3 $m^3 s^{-1}$, just after a previous increase of 18.8 $m^3 s^{-1}$ at the Fluvià River discharge. A second peak was recorded also at both rivers on the 26th of May 2008. The Têt River and the Fluvià River discharges reached values of 52 $m^3 s^{-1}$ and 59.84 $m^3 s^{-1}$ respectively. Maximum significant wave heights (Hs) at the Leucate (Fig. 3c) and Palamós (Fig. 3d) wave buoys reached ~5 m and maximum period peaks (not shown) were around 10 s. Several moderate eastern and northern storm events with significant wave heights of > 4 m occurred, and some of these storms were identified (highlighted with arrows in Fig. 3c and Fig. 3d) as the ones that triggered or enhanced DSWC events into the studied submarine canyons.

*4.2 Time series Cap de Creus 2006 – 2007*

Time series of temperature, current speed, SSC, sediment flux and cumulative transport along and across-canyon of the Cap de Creus Canyon during the first study period are shown in Figure 4a. Temperature time series maintained relatively constant value of 13.3 °C from November 2006 to late January 2007. During this interval, current speed increased several times, reaching values of > 50 cm s$^{-1}$. These increases were caused by several northern and eastern storms affecting the study area (Fig. 3c), without causing any significant peak in SSC and sediment fluxes at the canyon head. Between the 28th and 31st of January 2007 and between the 4th and 9th of February 2007 the first two DSWC events of winter 2007 were recorded. In both events temperature decreased abruptly to values of 12.2 ºC and current speed increased simultaneously reaching values of > 60 cm s$^{-1}$ and of > 70 cm s$^{-1}$, respectively. SSC remained low in both events, 6.4 mg l$^{-1}$ and 5.7 mg l$^{-1}$, and also low sediment fluxes were recorded, 4.2 g m$^{-2}$ s$^{-1}$ and 1.7 g m$^{-2}$ s$^{-1}$, respectively. Between the 16th and the 19th of February 2007 another DSWC event was recorded. In this occasion, the DSWC event was enhanced by an eastern storm (Fig. 3c). Temperature decreased to values < 12.4 ºC and current speed increased up to > 70 cm s$^{-1}$, coinciding with a SSC peak of 173.1 mg l$^{-1}$ and a sediment flux peak of 113.2 g m$^{-2}$ d$^{-1}$. This event caused an important cumulative sediment transport towards NNE direction (0.8 T m$^{2}$) and down-canyon (2.7 T m$^{-2}$). On 26th of March 2007 a long DSWC event occurred and temperature decreased to 12.2 ºC, current speed increased to > 60 cm s$^{-1}$, and SSC and sediment fluxes decreased to 20 mg l$^{-1}$ and 5 g m$^{-2}$ s$^{-1}$, respectively. Cumulative transport slightly increased towards NNE (0.2 T m$^{-2}$), and down-canyon (0.8 T m$^{-2}$). This long episode ended on mid April 2007. On the

16th of April, an eastern storm took place and temperature decreased to 12.8 ºC and current speed increased to 50 cm $s^{-1}$ but low SSC (2 mg $l^{-1}$) and sediment transport (> 1 g $m^{-2}$ $s^{-1}$) were recorded. Net flux and direction during this time period accounted for a net flux of 0.3 g $m^2$ $s^{-1}$ towards the south-east (117º), in a down-canyon direction.

*4.3 Time series Cap de Creus 2007 – 2008*

In winter 2008 (Fig. 4b), the first DSWC event affecting the Cap de Creus canyon head was detected between the 19th and the 25th of December 2007. Temperature decreased from 13.4 °C to 12.5 °C, at the same time as the current speed increased from values ~ 10 cm $s^{-1}$ to > 80 cm $s^{-1}$. SSC and sediment fluxes values reached during this event were ~ 12 mg $l^{-1}$ and ~ 5 g $m^2$ $s^{-1}$, respectively. Cumulative sediment of 0.3 T $m^{-2}$ was transported towards NNE, and of 1.7 T $m^{-2}$ down-canyon. Afterwards, between the 2nd and the 6th of January 2008 a second DSWC event, enhanced by an eastern storm took place (Fig. 3c). Temperature recorded a minimum of 12ºC, current speed reached a peak of 86.8 cm $s^{-1}$ and the SSC reached a maximum of 175.3 mg $l^{-1}$ causing an instantaneous sediment flux of 125.9 g $m^{-2}$ $d^{-1}$. Cumulative transport calculated across and along canyon reached 1.2 T $m^{-2}$ towards NNE direction and > 5.5 T $m^{-2}$ downcanyon. After this DSWC, from mid January to late March 2008, temperature showed a decreasing trend with some small drops that coincided with moderate increases of current speed (reaching values of 40 cm $s^{-1}$) while SSC, sediment fluxes and cumulative transport maintained relatively constant values. From 2nd April to 27th May 2008, temperature and current speed time series showed high variability with several small peaks of SSC and sediment fluxes. This high frequency variability affecting the current regime and water properties can be attributed to inertial (~18 h) fluctuations, as seen in the time series spectral analysis (not shown). During this period, current speed maintained slightly higher values and contributed to increase sediment fluxes. Overall, in this second deployment, the net flux was 0.5 g $m^2$ $s^{-1}$ towards down-canyon (124º) direction.

*4.4 Time series Palamós submarine canyon 2006 – 2007*

Time series of temperature, current speed, SSC, sediment fluxes and cumulative sediment transport along and across the Palamós canyon head during the first study period are shown in Figure 5a. Only temperature and current speed records are shown for all the period, since intense fouling of the turbidity sensor did not allow to calculate SSC, sediment flux and cumulative transport during the end of the recording period. From November 2006 to mid-February 2007, temperature, current speed and SSC at the study site, showed variable, but almost constant values. During this period several eastern and northern storms took place (Fig. 3d) and small increases of temperature, SSC and sediment fluxes were recorded, accounting for a moderate continuous progressive cumulative transport during this period towards the SSW and down-canyon. Between the 16$^{th}$ and 19$^{th}$ of February 2007, first temperature slightly increased from 13.2 to 13.4 ºC and immediately afterwards decreased to 12.6 ºC while current speed increased from 10 to > 40 cm $s^{-1}$. This DSWC event was concurrent with an eastern storm, during which SSC within the canyon increased up to > 6 mg $l^{-1}$, and instantaneous sediment fluxes reached > 2.4 g $m^{-2}$ $s^{-1}$. Cumulative transport across-canyon changed direction, being first directed towards NNE and then towards SSW. Along-canyon cumulative transport was always down-canyon accounting for ~ 0.2 T $m^{-2}$. Some days after this event, the turbidity sensor started to be affected by fouling and the SSC record became useless. Nonetheless, temperature and current speed time series showed the effects of several DSWC associated with storms events, several of them concurrent with the ones registered at the Cap de Creus Canyon. A northern storm occurred between the 8th and the 11th of March 2007, causing an increase of temperature from 13.2 ºC to 13.5 ºC and maximum current speeds of > 50 cm $s^{-1}$. Between the 21st and the 23rd of March 2007, concurrent with an eastern storm (Fig. 3d), temperature decreased to 12.6 ºC, and current speed also increased up to > 50 cm $s^{-1}$, indicating another DSWC event. The 28th of March temperature started to decrease again to values ~ 12.6 ºC and current speed increased to ~ 40 cm $s^{-1}$ until the 7th of April 2007, indicating a long DSWC event, also recorded at the Cap de Creus Canyon (Fig. 4a). Finally, on the 16th of April 2007, temperature slightly increased, and current speed increased to > 45 cm $s^{-1}$, due to another eastern storm. The net flux during this first study period was of 0.097 g $m^2$ $s^{-1}$ towards down-canyon (145º).

*4.5 Time series Palamós submarine canyon 2007 – 2008*

At the beginning of the second study period several eastern and northern storms occurred, which caused temperature fluctuations and small increases of current speed and SSC (Fig. 5b). Between the 2nd and 6th of January 2008, due to an eastern storm, temperature increased significantly and reached a maximum of 13.8 °C and rapidly decreased to < 13 ºC during the same day. During this storm that enhanced a DSWC event, peaks of current speed (44.6 cm $s^{-1}$), SSC (5.7 mg $l^{-1}$) and sediment flux (1.45 g $m^{-2}$ $d^{-1}$) were recorded. Cumulative transport across canyon was initially towards NNE and then turned towards the SSW, while cumulative flux along-canyon was down-canyon and reached 0.1 T $m^{-2}$. This DSWC event was concurrent with the one recorded at the Cap de Creus Canyon on early January 2008 (Fig. 4b). Afterwards all values recovered and maintained the previous baseline until the 6th of March 2008 when another DSWC event was registered. Temperature decreased to values of < 12.6 ºC, current speed increased to ~ 40 cm $s^{-1}$, and SSC and sediment flux increased up to 5.69 mg $l^{-1}$ and 2.12 g $m^{-2}$ $s^{-1}$, respectively. Cumulative transport across-canyon was almost nil, while the down-canyon component accounted for ~ 0.1 T $m^{-2}$. This DSWC event was enhanced by a northern storm (Fig. 3d) and was only detected at the Palamós canyon head (no DSWC event was recorded at the Cap de Creus Canyon during the same day) (see Figure 8 in Discussion for details). Several minor storm events caused small temperature decreases and current speed increases. From mid April to early May 2008, high variability in temperature and current speed records was observed with ~ 18 h fluctuations related to inertial motions, as it has been registered in the Cap de Creus (Fig. 4b). Afterwards all parameters progressively recovered the previous baseline values until the mooring recovery, only showing two isolated drops in temperature associated to minor eastern storms. Cumulative transport during this second half of the record was towards the NNE and slightly up-canyon. The net flux during this second deployment was of 0.0069 g $m^{2}$ $s^{-1}$ (towards 112º).

## 5. Discussion

### *5.1 Sediment dynamics events*

In this study, several sediment transport events were identified in the Cap de Creus and Palamós canyon heads during winter 2007 and 2008. No relation between these events and nearby river discharges was found, and in both canyons, most of the sediment transport occurred during DSWC events enhanced or triggered by storms. Such behaviour was already documented for the Cap de Creus submarine canyon in previous similar studies conducted in the GoL (e.g. Palanques *et al*., 2006a, 2008; Ogston *et al*., 2008). Now, this new data set provides further insight of the off-shelf transport processed on this continental margin, as it also addressed the transport through the Palamós canyon head.

Several authors observed in the GoL submarine canyons asymmetries in the sediment transport from the shelf, mostly controlled by the shelf morphology and also by the morphology of the canyon head and adjacent coast. As Ongston *et al.* (2008) indicated, these characteristics play a large role in determining how much impact dense-water cascading and other downslope flows can have on the removal of shelf sediment in the GoL. However, both the Cap de Creus and Palamós submarine canyons are located in regions with a narrow and steep shelf and close to a coastal promontory, but differ considerably in the magnitude and frequency of DSWC and the associated sediment transport events. The observed sediment fluxes in the Palamós Canyon are much lower than the ones in the Cap de Creus Canyon and comparable to the ones recorded in the central canyons of the GoL, particularly in the Aude Canyon (Palanques *et al.*; 2006a), which are characterized by a broad and relatively flat shelf.

### *5.2 Comparison between the Cap de Creus and the Palamós submarine canyons*

Recorded DSWC events during winter 2007 and 2008 were more intense in the Cap de Creus and Palamós Canyons, accounting for faster down-canyon current velocities (> 60 cm $s^{-1}$ versus > 40 cm $s^{-1}$, respectively), larger drops in temperature (~ 1ºC versus ~ 0.5 ºC) and higher SSC peaks (> 170 mg $l^{-1}$ versus ~ 6 mg $l^{-1}$). Consequently, cumulative transport during the two consecutive winters was one order of magnitude greater at the Cap de Creus Canyon than at the Palamós Canyon (13.2 T $m^{-2}$ versus 0.4 T $m^{-2}$, respectively). These differences agree with the idea that the Cap de Creus Canyon is the main pathway of most of the off-shelf sediment transport in the northwestern Mediterranean during DSWC events (Palanques *et al*., 2006a). During both study periods all storm events could be considered moderate storms, with maximum wave heights < 5 m. Storm duration was arbitrarily defined as the time when the wave height started to increase. Nonetheless there were three storm events that particularly enhanced DSWC events generating large sediment fluxes in both submarine canyons. These events are here analyzed in detail:

*5.2.1 February 2007 eastern storm with shelf water cascading*

The DSWC event recorded on mid February 2007 affected both canyons and was enhanced by an eastern storm occurred between the 16th and the 19th of February 2007. Figure 6 shows the time series of wave data from the Leucate and Palamós wave buoys, and also the time series of temperature, current speed and SSC. Significant wave height reached values of 4.39 m at the Leucate buoy and values of 3 m at the Palamós buoy, and wave mean direction was between 90º and 100º, indicating an eastern storm. At the beginning of the storm, temperature at the Cap de Creus canyon head decreased irregularly 1ºC (from 13.4 to 12.4 ºC) concordant with irregular current speed increases.

Temperature maintained low values for almost two days, concordant with high current speed values and relatively low SSC. Towards the end of the event, SSC increased progressively until reaching a peak of 173.1 mg $l^{-1}$. Afterwards turbidity decreased abruptly, at the time that temperature recovered previous values and current speed dropped to ~10 cm $s^{-1}$. Therefore, most of the suspended sediment was transported down-canyon in few hours during the latter stages of this DSWC.

At the Palamós Canyon, sediment transport was quite different during this event (Fig. 6). Once the storm started, temperature slightly increased (0.2 ºC) and current speed and SSC maintained low values. At the peak of the storm, on the 18th of February current speed started to increase and reached values of > 40 cm $s^{-1}$, and an isolated peak of SSC, up to 6 mg $l^{-1}$, was recorded. This turbidity peak was caused either by local resuspension within the canyon or by the advection of shelf resuspended sediments towards the canyon caused by the storm-induced downwelling. Few hours later, SSC increased again (reaching 4 mg $l^{-1}$), along with warm temperature and current speed maximums (> 40 cm $s^{-1}$ and 13.4 ºC, respectively). At the end of the storm event, temperature decreased rapidly concurrent with another increase of current speed and SSC, indicating the occurrence of a mild DSWC event at the canyon head. It has to be noticed that the arrival of this DSWC event into the Palamós Canyon occurred almost 3 days later than the one recorded in the Cap de Creus Canyon. Few hours later, current speed dropped to values ~10 cm $s^{-1}$, but waters within the canyon head maintained low temperatures and relatively high SSC values for several days. Temperature and SSC records recovered previous values the 25th February (not shown) 6 days after the end of the storm.

### *5.2.2 January 2008 eastern storm with shelf water cascading*

The early January 2008 DSWC event was also enhanced by an eastern storm that affected both Cap de Creus and Palamós canyons between the 2nd and 6th of January (Fig. 7). Significant wave heights reached maximum values of 4.9 m at the Leucate buoy and of 4.2 m at the Palamós buoy, and mean wave direction was between 70º and 100º. At the beginning of the storm, temperature at the Cap de Creus canyon head, abruptly decreased from 13.6 to 12.2 ºC, and irregularly maintained low values, with some sudden drops, until the 5th of January when it started to recover. During this time interval, current speed increased to values of > 70 cm $s^{-1}$ and also turbidity increased progressively. Approximately 2 days after the beginning of the storm and DSWC event, SSC reached maximums of 175.3 mg $l^{-1}$ (Fig. 7). Afterwards turbidity and current speed started to decrease concurrent with a progressive temperature increase. The DSWC event finished coinciding with the end of the storm, the 6th of February, when temperature, current speed and SSC recovered previous baseline values.

In the Palamós Canyon, this storm also produced a downwelling and posterior DSWC event, following the same pattern as in the February 2007 event. At the beginning of the storm, temperature at the Palamós Canyon increased (from 13.4 to 13.8 ºC) coinciding with current speed increases of ~50 cm $s^{-1}$ and subtle peaks of SSC. During the storm peak nearby the Palamós Canyon, temperature decreased concurrent with a second current speed increase (up to 40 cm $s^{-1}$) coinciding with a SSC maximum of 5.7 mg $l^{-1}$ (Fig. 7). The arrival of this DSWC event into the Palamós canyon head occurred 2 days after the one recorded in the Cap de Creus Canyon. Current speed and SSC associated to this DSWC event maintained relatively high values for more than two days, as long as the water temperature within the canyon was low.

*5.2.3 March 2008 northern storm with shelf water cascading*

A long and moderate northern storm, between the 4th and the 8th of March 2008, also enhanced a DSWC event. Time series of significant wave height, temperature, current speed and turbidity are shown in Figure 8. Significant wave height was only 1.9 at the Leucate buoy and 3.3 m at the Palamós buoy, and mean wave direction was north (360º and 0º) in both buoys. At Cap de Creus Canyon, during the 5th of March, temperature slightly decreased (0.3 ºC), current speed irregularly increased (up to 40 cm $s^{-1}$), and turbidity showed just a subtle increase (2 mg $l^{-1}$) indicating small transport event at the canyon head. Conversely, at the Palamós Canyon, during the storm peak, temperature decreased ~ 1 ºC, current speed increased to > 40 cm $s^{-1}$, and SSC reached a maximum value of 5.6 mg $l^{-1}$. During this northern storm, no downwelling of warmer shelf waters was registered at the Palamós Canyon, providing a different pattern of sediment transport at the canyon head observed during eastern storms.

The amount of sediment transported through the Cap de Creus Canyon was insignificant compared with the other DSWC events previously analyzed. This could be because although even northerly winds in the GoL facilitate dense water formation during wintertime, only small waves are generated on the inner shelf, due to the short fetch (Estournel *et al*., 2003), and low amounts of sediment can be resuspended and transported toward the GoL submarine canyons. Furthermore, dense water flows southwardly dodging the Cap de Creus promontory, arriving to the Catalan margin. As numerical models predict (Ulses *et al*., 2008b), dense water from the GoL as well as water formed in the Gulf of Roses, can reach the Palamós canyon head advecting shelf sediment resuspended by the higher waves developed in the Palamós area.

*5.3 High concentrated sediment transport events*

Sediment fluxes in the canyon heads of the GoL are closely related to local hydrology and atmospheric events (Bonin *et al.*, 2008). As it has been already mentioned, during winters 2007 and 2008 the highest concentrated sediment transport was recorded in the Cap de Creus Canyon during DSWC events enhanced by the first moderate eastern storm of the winter season. The first observational evidence of a strong winter eastern storm ($H_s$=7 m) associated with moderated DSWC that generated a major sediment transport event through the GoL submarine canyons and particularly through the Cap de Creus Canyon was recorded in February 2004 (Palanques *et al.*, 2006, 2008). Such transport event was even detected at the north western Mediterranean basin by increasing downward particle fluxes in a moored sediment trap deployed at 2350 m deep (Palanques *et al.*, 2009). Maximum SSC reached at the Cap de Creus canyon head during this event was unknown (i.e. 0-20 FTU turbidity sensor reached its limit during 10 hours) and it was reported as SSC > 68 mg $l^{-1}$. Palanques et al. (2008) observed that during the initial stages of the February 2004 event, SSC slightly increased and such signal was attributed to sediment resuspended either at the canyon head and/or on the outer shelf near the canyon head during the peak of the storm. The strong SSC peak (> 68 mg $l^{-1}$) was observed 27 hours after the beginning of the storm and lasted for 10 hours. Such high concentrations were interpreted as produced by shelf-to-canyon advection of the sediment resuspended during the storm at inner shelf locations. Few hours later, a third SSC peak was observed, which was attributed to the settling of suspended particles through the water column (Palanques et al., 2008). Comparing this event with the ones analyzed here at the Cap de Creus canyon for winter 2007 and 2008, we observe that the same sediment transport pattern also occurred during the first long-lasting DSWC event concurrent with the first moderate storm of the winter season (Figs. 6 and 7). It has to be noted, that these transport events occurred after several months without significant storms during which the continental shelf was presumably covered by easily resuspendable sediments. Palanques *et al*. (2008) suggested that such a large sediment transport event should occur linked to major storms ($H_s$ >7 m) with a recurrence period of several years. However, this new data suggest that even storms with $H_s$ between 4 and 5 m associated with moderate DSWC events, can also generate high suspended sediment concentrations and fluxes, being more frequent than previously thought. This idea agrees with Ogston *et al*. (2008) that found that even a minor storm event can induce significant off-shelf and downslope sediment transport if occurs during a period of dense-water cascading.

## 6. Conclusions

Analysis of contemporary measurement conducted at the Cap de Creus and Palamós submarine canyon heads during winter 2007 and 2008 have supported the following conclusions:

1) New observations indicate that DSWC events also take place at the Palamós Canyon being concurrent with the ones occurring at the Cap de Creus Canyon. This confirms what numerical models simulated, that the Palamós Canyon also contributes to the down-slope flow of dense shelf water.
2) In both submarine canyons, the major suspended sediment transport was during DSWC events enhanced by moderate eastern storms. At the Palamós Canyon

northern storms can also enhance DSWC without any significant effect at the Cap de Creus Canyon.

3) Different sediment transport patterns were observed between both canyons. During eastern storms, DSWC events were immediately observed in the Cap de Creus Canyon, while in the Palamós Canyon, downwelling always precede DSWC. Conversely, during northern storms, small cascading was detected in the Cap de Creus Canyon and DSWC without downwelling was recorded at the Palamós Canyon.
4) High-concentrated transport events (reaching >170 mg $l^{-1}$) were observed during both winters only in the Cap de Creus Canyon coinciding with the first long-lasting DSWC event concurrent with a moderate eastern storm.
5) The amount of sediment transported during DSWC events is one order of magnitude grater at the Cap de Creus Canyon than at the Palamós Canyon, corroborating that the maximum off-shelf sediment transport in the northwestern Mediterranean during DSWC events occur at the southwestern end of the Gulf of Lions, through the Cap de Creus Canyon.

**Acknowledgment**

This research was supported by the Spanish national project CASCADES (Ref. CTM2008-01334-E/MAR) and the European research project HERMIONE (ref. 226354). We thank the captain and the crew of the R/V "Garcia del Cid", the R/V "Sarmiento de Gamboa" and the fishing boat "Felipe" for their kind assistance during the mooring operations. We are grateful to the UTM technicians Pablo Rodriguez, Javier Prades and Jose "Pou" Pozo for providing assistance during the mutibeam bathymetry acquisition and to Susana Díez for her advices during the processing of the bathymetric data.

## References

Alvarez, A., Tintoré, J., & Sabatés, A. 1996. Flow modification and shelf-slope exchange induced by a submarine canyon off the Northeast Spanish coast. *Journal of Geophysical Research*, 101(C5), 12043–12055.

Ardhuin, F., Pinot, J. M., & Tintoré, J. 1999. Numerical study of the circulation in a steep canyon off the Catalan coast (western Mediterranean). *Journal of Geophysical Research*, 104(C5), 11115–11135.

Berné, S., Loubrieu, B., the CALMAR ship board party. 1999. Canyons and recent sedimentary processes on the Western Gulf of Lions margin. *C. R. Acad. Sci., Ser. IIa: Sci. Terre Planets* 328: 471–477.

Bonin, J., Heussner, S., Calafat, A., Fabres, J., Palanques, A., Durrieu de Madron, X., Canals, M., Puig, P., Avril, J., Delsaut, N. 2008. Comparison of horizontal and downward particle fluxes across canyon of the Gulf of Lions (NW Mediterranean): Meteorological and hydrodynamical forcing. *Continental Shelf Research*, 28: 1957-1970.

Canals, M., Puig, P., Durrieu de Madron, X., Heussner, S., Palanques, A., Fabres, J., 2006. Flushing and reshaping submarine canyons by dense shelf water cascading. *Nature*, 444: 354-357.

Centre d'Etudes Techniques Maritimes Et Fluviales. Leucate buoy data from the Base de données CANDHIS (http://www.cetmef.equipement.gouv.fr/)

Company, J.B., Puig P., Sardà, F., Palanques, A., Latasa, M., Scharek, R. 2008. Climate Influence on Deep Sea Populations. PLoS ONE 3(1):e1431. Doi:10.1371/journal.pone.0001431.

Durrieu de Madron, X., Zervakis, V., Theocharis, A., Georgopoulos, D. 2005. Comments on “Cascades of dense water around the world”. *Progress in Oceanography*, 64: 83-90.

Durrieu do Madron, X., Wiberg, P., Puig, P. 2008. Sediment dynamics in the Gulf of Lions: The impact of extreme events. Introduction special issue. *Continental Shelf Res*. 28: 1867–1876.

Estournel, C., Durrieu do Madron, X., Marsaleix, P., Auclair, F., Julliand, C., Vehil, R. 2003. Observations and modelisation of the winter coastal oceanic circulation in the Gulf of Lions under wind conditions influenced by the continental orography (FETCH experiment). *Journal of Geophysical Research* 108 (C3), 8059.

Font, J., Salat, J., Tintoré, J. 1988. Permanent features of the circulation in the Catalan Sea. *Oceanologica Acta*, 9: 51-57.

Font, J., García-Ladona, E., Górriz, E. G. 1995. The seasonality of mesoscale motion in the Northern Current of the western Mediterranean: Several years of evidence. *Oceanologica Acta*, 18: 207–219.

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. *Scientia Marina*, 64 (4): 427-435.

Guillén, J., Bourrin, F., Palanques, A., Durrieu de Madron, X., Puig, P., Buscail, R. 2006. Sediment dynamics during ‘wet’ and ‘dry’ storm events on the Têt inner shelf (SW Gulf of Lions). *Marine Geology* 234: 129-142

Hickey, B. M. 1995. Coastal submarine canyons. In P. Müller & D. Henderson (Eds.), Topographic effects in the ocean (pp. 95–110). *Manoa: School of Ocean and Earth Science and Technology*.

Huthnance, J.M. 1995. Circulation, exchange and water masses at the ocean margin: the role of physical processes at the shelf edge. *Progress in Oceanogrography*, 35: 353-431.

Ivanov, V.V., Shapiro, G.I., Huthnance, J.M., Aleynik, D.L., Golovin, P.N. 2004. Cascades of dense water around the world. *Progress in Oceanography*, 60: 47-98.

Klinck, J. M. 1996. Circulation near submarine canyons: A modelling study. *Journal of Geophysical Research*, 101, 1211–1223.

Lastras, G., Canals, M., Urgeles, R., Amblas, D., Ivanov, M., Droz, L., Dennielou, B., Fabrés, J., Schoolmeester, T., Akhmetzhanov, A., Orange, D., García-García, A. 2007. A walk down the Cap de Creus canyon, Northwestern Mediterranean Sea: Recent processes inferred from morphology and sediment bedforms. *Marine Geology*, 246: 176-192.

La Violette, P. E., Tintoré, J., Font, J. 1990. The surface circulation of the Balearic Sea. *Journal of Geophysical Research*, 95, 1559–1568.

López García, M. J., Millot, C., Font, J., García-Ladona, E. 1994. Surface circulation variability in the Balearic Basin. *Journal of Geophysical Research*, 99, 3285–3296.

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

Martín, J., Palanques, A., Puig, P. 2007. Near-bottom horizontal transfer of particulate matter in the Palamós submarine Canyon (NW Mediterranean). *Journal of Marine Research,* 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. *Marine Geology*, 252: 150-155.

Millot, C. 1999. Circulation in the western Mediterranean Sea. *Journal of Marine Systems*, 20: 423-442

Ogston, A., Drexler, T., Puig, P. 2008. Sediment delivery, resuspension, and transport in two contrasting canyon environments in the southwest Gulf of Lions. *Continental Shelf Research* 28: 2000–2016.

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., Pages, F., 2005. General patterns of circulation, sediment fluxes and ecology of the Palamós (La Fonera) submarine canyon, northwestern Mediterranean. *Progress in Oceanography*, 66 (2–4): 89– 119.

Palanques, A., Durrieu de Madron, X., Puig, P., Fabres, J., Guillén, J., Calafat, A., Canals, M. and. Bonnin. J. 2006a. Suspended sediment fluxes and transport processes in the Gulf of Lions submarine canyons: The role of storms and dense water cascading. *Marine Geology* 234:43–61.

Palanques, A., Martin, J., Puig, P., Guillén, J., Company, J.B., and Sarda, F. 2006b. Evidence of sediment gravity flows induced by trawling in the Palamós (Fonera) submarine canyon (northwestern Mediterranean). *Deep-Sea Research Part I* 53:201–214.

Palanques, A., Guillén, J., Puig, P., Durrieu de Madron, X. 2008. Storm-driven shelf-to-canyon suspended sediment transport at the southwestern Gulf of Lions. *Continental Shelf Research* 28:1947–1956.

Palanques, A., Puig, P., Latasa, M., Scharek, R., 2009. Deep sediment transport induced by storms and dense shelf-water cascading in the northwestern Mediterranean basin. *Deep-Sea Research Part I* 53:201–214.

Puertos del Estado. Consulta de datos históricos de oleaje. Boya de Palamós y punto WANA (www.puertos.es)

Puig, P., Palanques, A., 1998. Temporal variability and composition of settling particle fluxes on the Barcelona continental margin (northwestern Mediterranean). *Journal of Marine Research*, 56: 639–654.

Puig, P., Company, J.B., Sardà, F., Palanques, A. 2001. Responses of deep-water shrimp populations to intermediate nepheloid layer detachments on the Northwestern Mediterranean continental margin. *Deep-Sea Research Part I* 48:2195–2207.

Puig, P., Ogston, A.S., Mullenbach, B.L., Nittrouer, C.A., Sterneberg, R.W. 2003. Shelf-to-canyon sediment-transport processes on the Eel continental margin (northern California). *Marine Geology* 193: 129-149.

Puig, P.; Ogston, A. S.; Mullenbach, B. L.; Nittrouer, C. A.; Parsons, J. D.; Sternberg, R. W. 2004. Storm-induced sediment gravity flows at the head of the Eel submarine canyon, northern California margin. *Journal of Geophysical Research* 109 (C3), C03019.

Puig, P., A. Palanques, D.L. Orange, G. Lastras, and M. Canals. 2008. Dense shelf water cascades and sedimentary furrow formation in the Cap de Creus Canyon, northwestern Mediterranean Sea. *Continental Shelf Research* 28(15):2017–2030.

Serra, J. 1981. Els canyons submarins del marge continental Català. *Treb. Inst. Cat. Hist. Nat.*, 9, 53-57.

Shepard, F.P. 1972. Submarine canyons. *Earth-Science Review*, 8:1-12

Skliris, N., Lacroix, G., Djenidi, S. 2004. Effects of extreme meteorological conditions on coastal dynamics near a submarine canyon. *Continental Shelf Research* 24, 1033–1045.

Skliris, N., J.H. Hecq and S. Djenidi. 2002. Water fluxes at an ocean margin in the presence of a submarine canyon. *Journal of Marine Systems*, 32: 239–251.

Ulses C., Estournel C., Bonnin, J., Durrieu de Madron X., Marsaleix P. 2008a Impact of storms and dense water cascading on shelf-slope exchanges in the Gulf of Lion (NW Mediterranean). *Journal of Geophysical Research*. 113, C02010.

Ulses C., Estournel C., Puig P., Durrieu de Madron X., Marsaleix P. 2008b. Dense shelf water cascading in the northwestern Mediterranean during the cold winter 2005: Quantification of the export through the Gulf of Lion and the Catalan margin. *Geophysical Research Letters* 35, L07610.

Xu, J.P., M. Noble, S.L., Eittreim, L.K. Rosenfeld, F.B. Schwing and C.H. Pilskaln. 2002. Distribution and transport of suspended particulate matter in Monterey Canyon, California. *Marine Geology*, 193:129-149.

## Figure captions

**Figure 1.** Map of study area in the north-western Mediterranean basin showing the location of the areas covered by the multibeam bathymetry at the Cap de Creus Canyon and Palamós Canyon. Circles indicate mooring positions and triangles indicate Leucate (north) and Palamós (south) wave buoys positions.

**Figure 2**. Multibeam bathymetric maps of Cap de Creus Canyon (a) and Palamós Canyon (b).

**Figure 3.** Temporal evolution of the Têt (a) and the Fluvià River discharges (b), significant wave height at the Leucate buoy (c) and at the Palamós buoy (d). Study time periods are indicated at the bottom of the figure. Storm events that triggered or enhanced DSWC events are highlighted with arrows and letters E (eastern storms) N (northern storms).

**Figure 4.** Time series of in situ temperature, currents and suspended sediment transport recorded at the Cap de Creus Canyon, for the time periods 2006-07 (a) and 2007-08 (b).

**Figure 5.** Time series of in situ temperature, currents and suspended sediment transport recorded at the Palamós Canyon, for the time periods 2006-07 (a) and 2007-08 (b).

**Figure 6**. Time series of significant wave height and wave direction registered at the Leucate and Palamós wave buoys. Time series of temperature, current speed and turbidity recorded at the Palamós and Cap de Creus submarine canyon heads, during the DSWC event enhanced by the eastern storm on mid February 2007.

**Figure 7**. Time series of significant wave height and wave direction registered at the Leucate and Palamós wave buoys. Time series of temperature, current speed and turbidity recorded at the Palamós and Cap de Creus submarine canyon heads, during the DSWC event enhanced by the eastern storm on early January 2008.

**Figure 8.** Time series of significant wave height and wave direction registered at the Leucate and Palamós wave buoys. Time series of temperature, current speed and

turbidity recorded at the Palamós and Cap de Creus submarine canyon heads, during the DSWC event enhanced by the eastern storm on early March 2008.

Figure 1.
Click here to download high resolution image

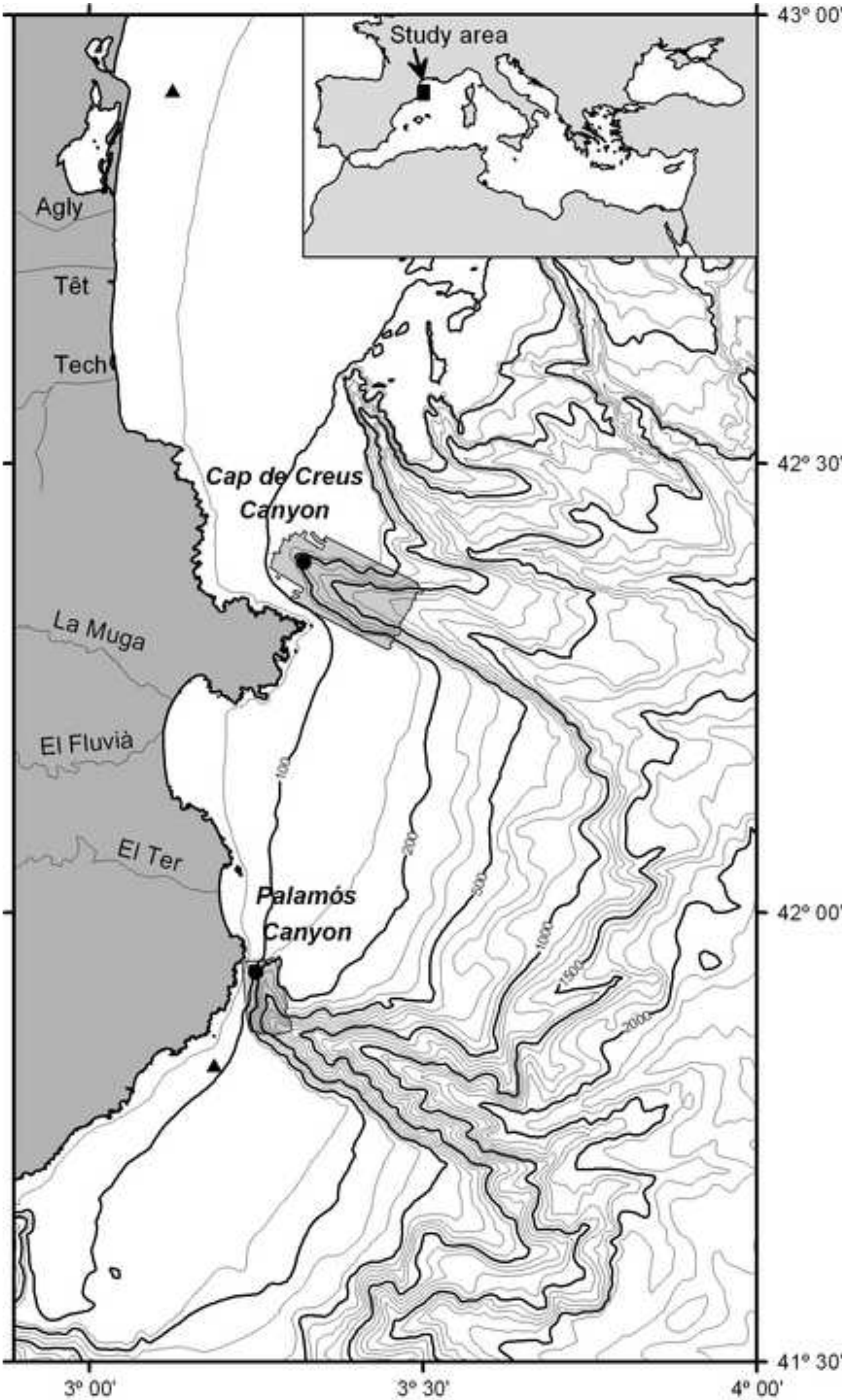

Figure 2.
Click here to download high resolution image

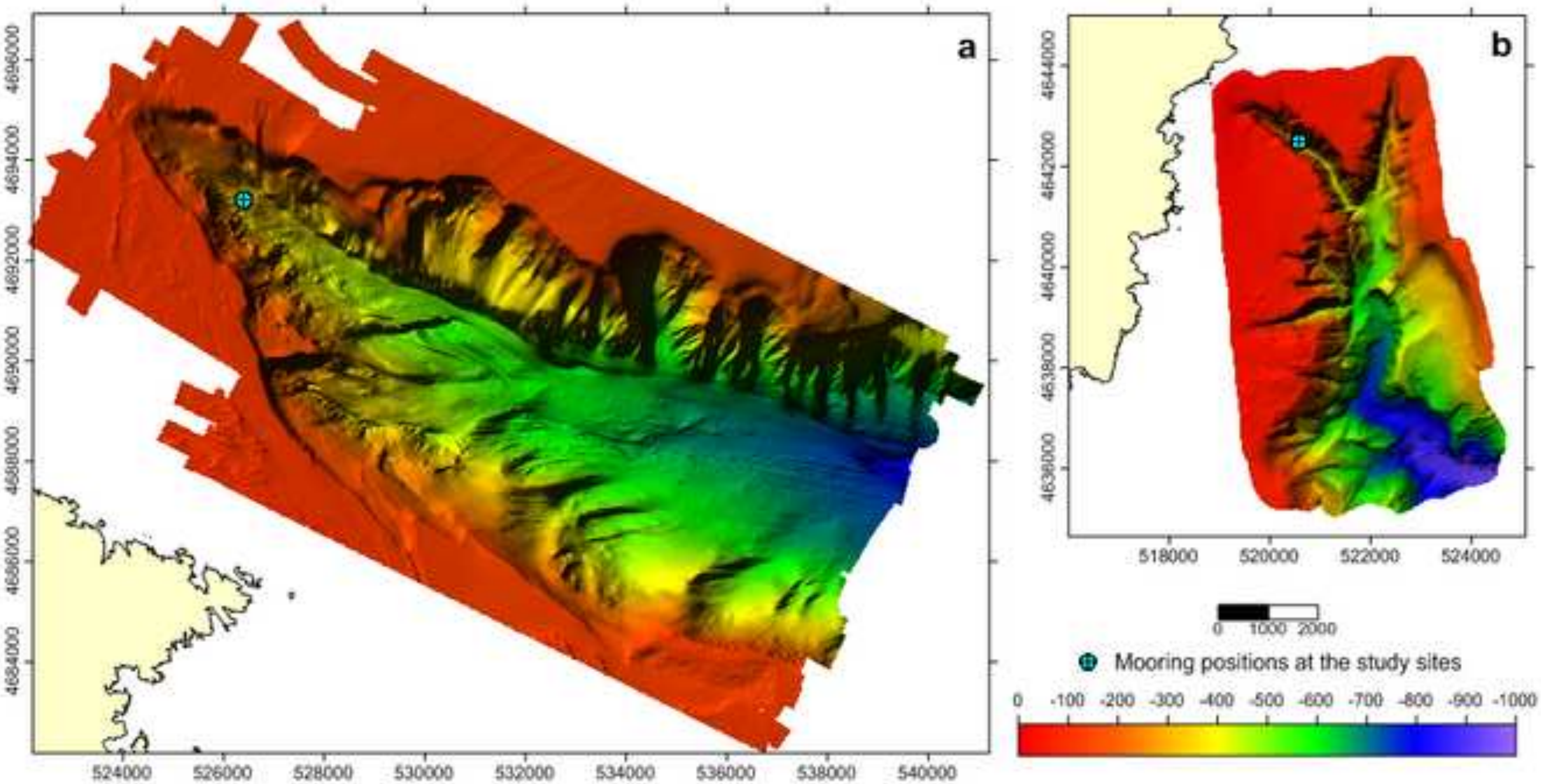

Figure 3.
Click here to download high resolution image

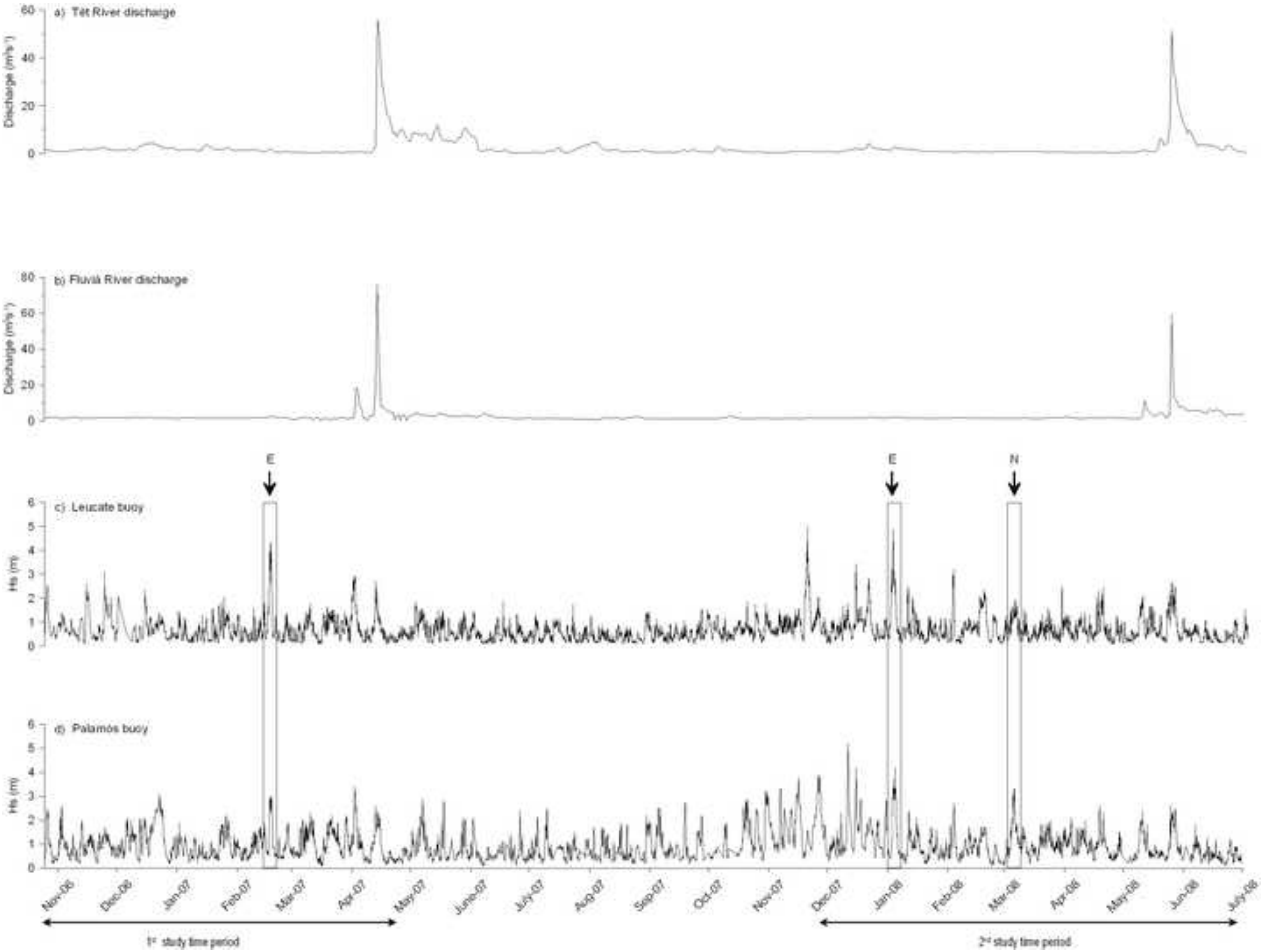

**Figure 4.**
**Click here to download high resolution image**

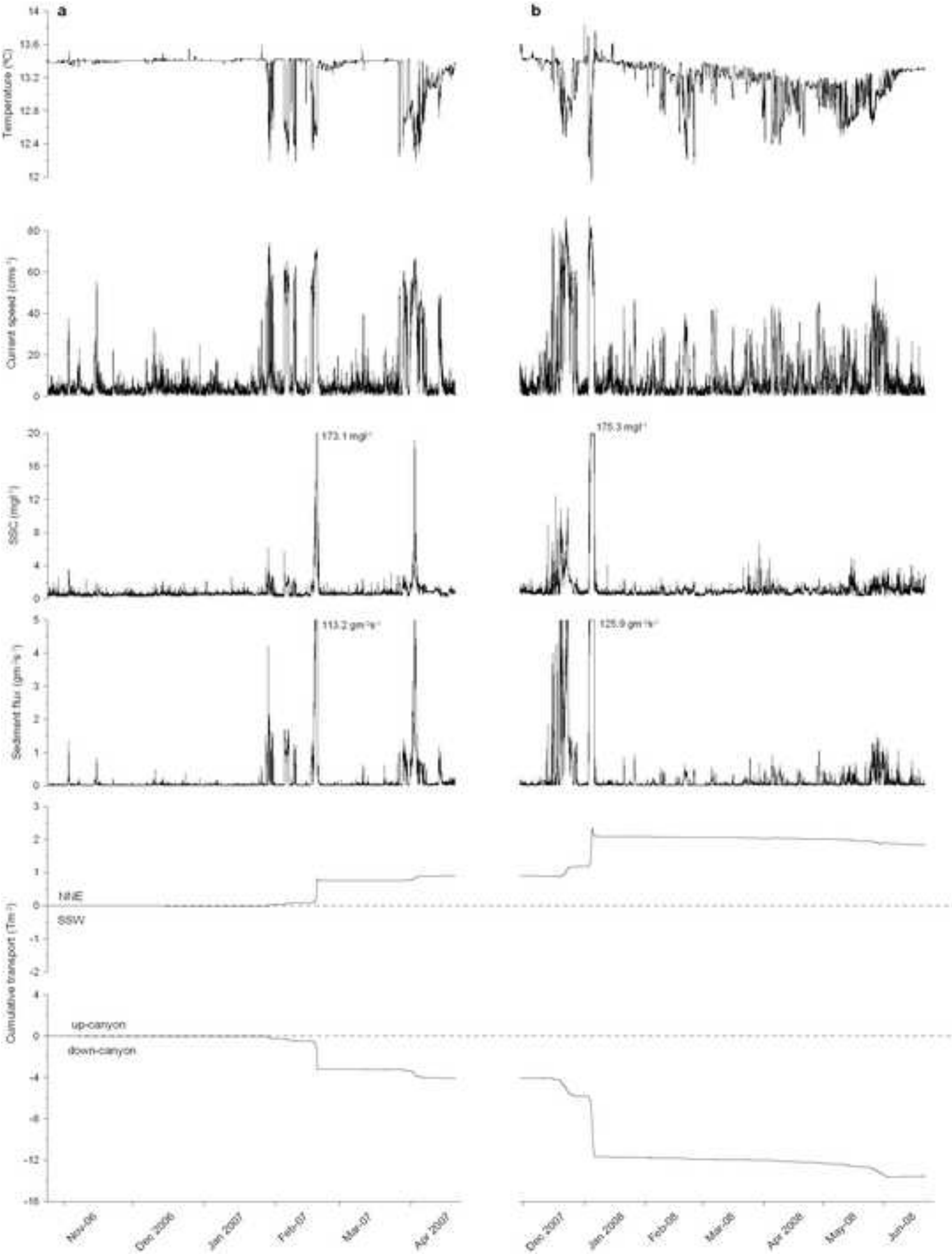

**Figure 5.**
**Click here to download high resolution image**

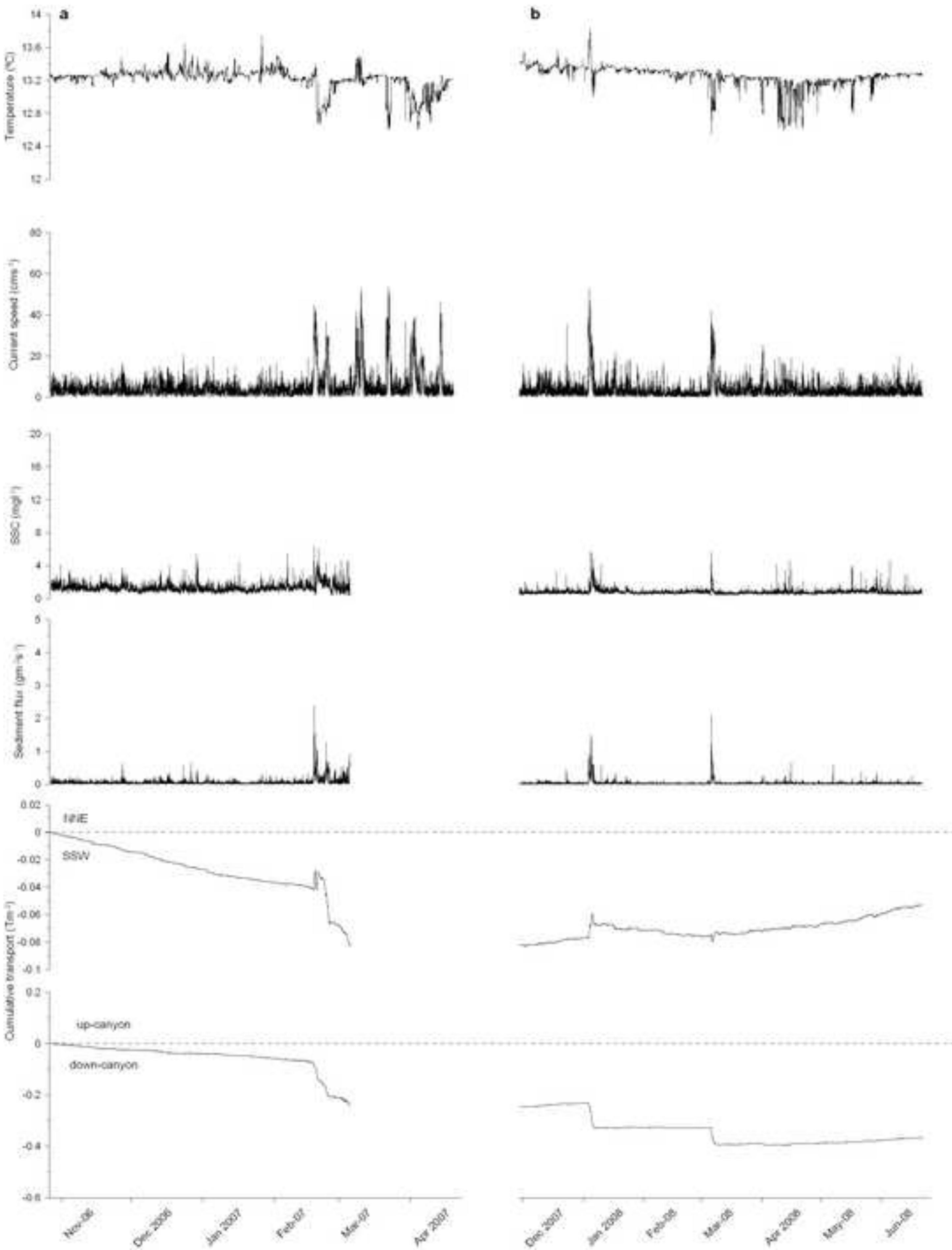

**Figure 6.**

**Click here to download high resolution image**

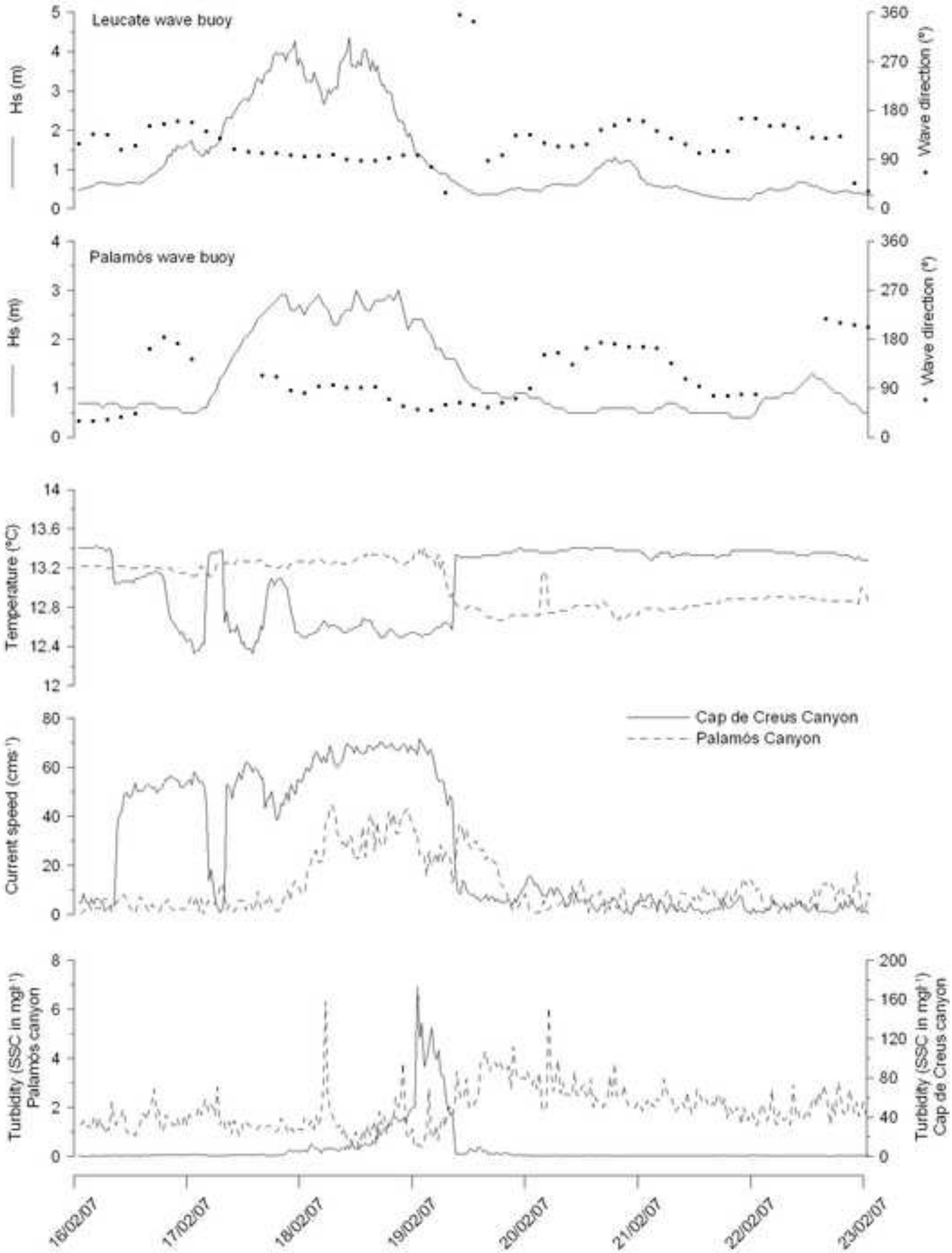

Figure 7.
**Click here to download high resolution image**

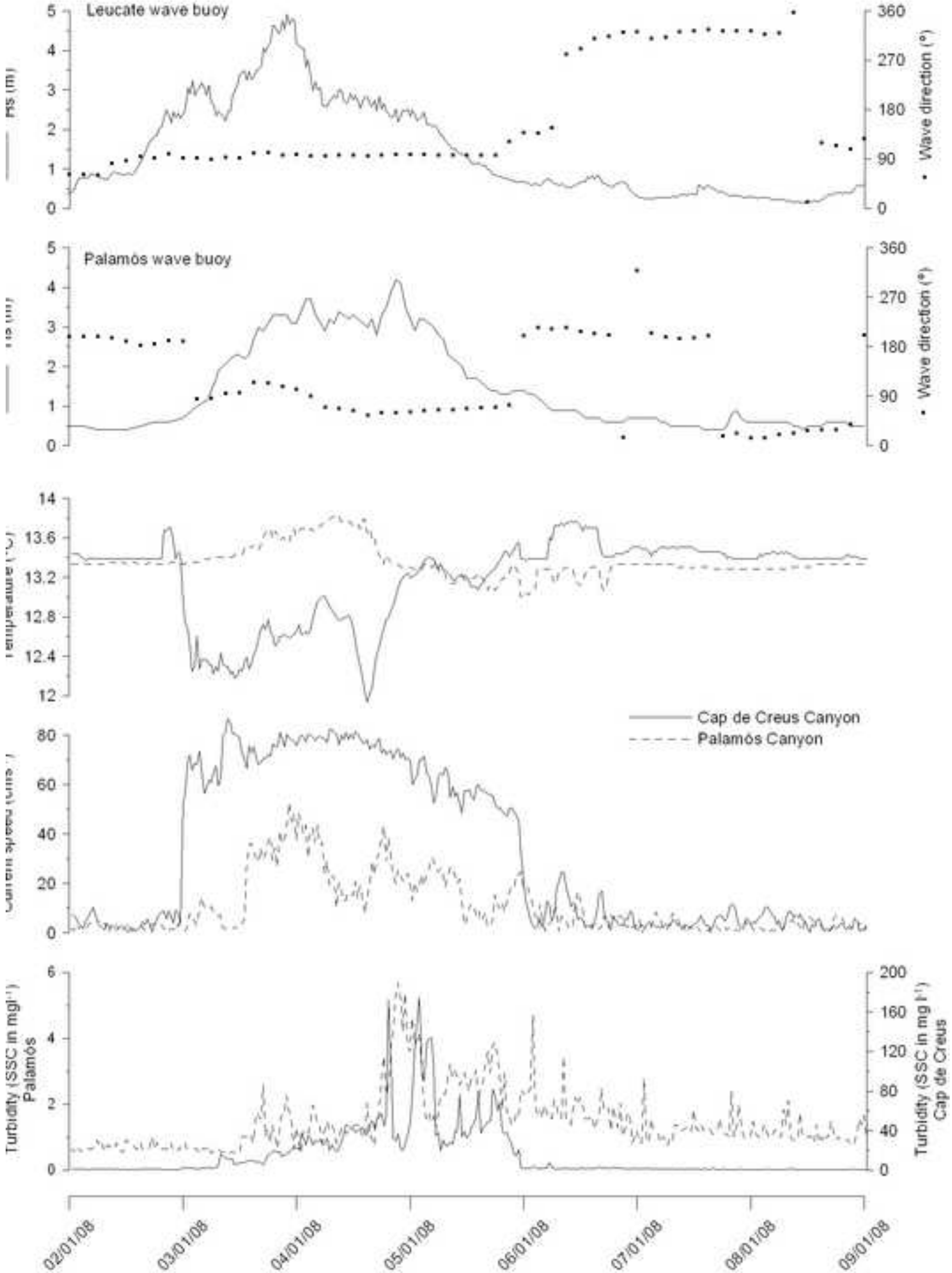

**Figure 8.**
**Click here to download high resolution image**