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Impact of dense shelf water cascading on the transfer of organic matter to the deep western Mediterranean basin

A. Sanchez-Vidal,[1] C. Pasqual,[2] P. Kerhervé,[1] A. Calafat,[2] S. Heussner,[1] A. Palanques,[3] X. Durrieu de Madron,[1] M. Canals,[2] and P. Puig[3]

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[1] During winter 2005–2006, particle fluxes and near-bottom currents were measured in and around the Lacaze-Duthiers and Cap de Creus submarine canyons (western Gulf of Lion). Current anomalies show the occurrence of a major dense shelf water cascading event down to the slope, the latest recorded up to date in the area. Concomitant increased total mass fluxes highlight the ability of cascading waters to transport large amounts of coarse sediment and organic matter, which is predominantly of terrestrial origin. In addition, results reveal that the current regime and associated grain size sorting is the responsible for a geochemical gradient of settling organic particles along the slope. **Citation:** Sanchez-Vidal, A., C. Pasqual, P. Kerhervé, A. Calafat, S. Heussner, A. Palanques, X. Durrieu de Madron, M. Canals, and P. Puig (2008), Impact of dense shelf water cascading on the transfer of organic matter to the deep western Mediterranean basin, *Geophys. Res. Lett.*, *35*, L05605, doi:10.1029/2007GL032825.

1. Introduction

[2] Continental margins, at the interface between land and open ocean, are the most important regions within the ocean in terms of terrigenous input and biological production, which generate areas of high deposition of particulate matter. Physical processes occurring at and near the shelf edge are capable of efficiently exporting matter to the deep environment. Recent observations from the Gulf of Lion highlighted the importance of dense shelf water cascading (DSWC) in exporting large amounts of water and sediment to the deep-sea environment [*Canals et al.*, 2006]. The occurrence of DSWC relates to meteorological and hydrological forcing. Winter heat losses and evaporation caused by cold, dry and persistent northerly winds induce cooling and mixing of shelf waters over the Gulf of Lion. These waters eventually get dense enough to sink, overflow the shelf edge and cascade down-slope [*Béthoux et al.*, 2002]. On the western half of the shelf, the preferential cyclonic wind-induced circulation and the narrowing of the southern end of the shelf cause flow convergence and acceleration (Figure 1a), which provide a mechanism for shelf sediment erosion due to high effective shear stress [*Palanques et al.*, 2006; *Bourrin*, 2007]. The dense water plume, which overflows the shelf edge and cascades at high velocities (up to 80 cm s^{-1}) down the upper course of the westernmost submarine canyons, has the ability to entrain and transport coarse sediments and abrade the seafloor [*Canals et al.*, 2006].

[3] This energetic hydrodynamic regime, which affects the turbidity, the sediment grain size and the supply of organic material is likely to have important consequences on ecosystem functioning. The better understanding of physical and biogeochemical processes that control canyon ecosystems is one of the aims of the HERMES project (Hotspot Ecosystem Research on the Margins of European Seas) [*Weaver et al.*, 2004]. The knowledge of the biotic and abiotic drivers of canyon ecosystems and the qualitative assessment of particulate organic matter fluxes is, therefore, essential to characterize the environmental variables regulating diversity and faunal distributions. In this study, and with the aim of providing the input terms for a better understanding of ecosystem functioning, we investigate the “immediate” effect of DSWC on quality and distribution of organic carbon transported down-slope.

2. Data and Methods

[4] Current, temperature and particle fluxes were measured in winter 2005–06 along the axis of the Lacaze-Duthiers Canyon at 300, 1000 and 1500 m depth, the Cap de Creus Canyon at 1000, 1500 and 1900 m depth, and on the adjacent southern open slope at 1000 and 1900 m depth (Figure 1) in order to follow the path of the dense water plume along and across the slope. Particulate fluxes were measured with sequential PPS3 Technicap sediment traps at 30 m above the bottom, and current and temperature were measured with Aanderaa RCM9/11 current meters at 5 m above the bottom. Sampling intervals were set at 15 days for traps and 20 minutes for current meters. Due to overflowing of one sampling cup in January 2006, and entrance of material to the following cup during the rotation of the carrousel, pairs of consecutive flux and geochemical data have been mass weighted getting a 1-month resolution. Sediment trap sample processing is described in detail by *Heussner et al.* [1990]. Organic carbon (OC) and nitrogen content were measured in 25% HCl treated samples on a Thermo NA 2100 elemental analyzer, with uncertainties lower than 0.1% as determined from replicates of the certified estuarine sediment MESS-1. The stable isotopic composition of OC ($\delta^{13}C_{OC}$) was measured in decarbonated samples using an Eurovector elemental analyzer coupled to a GVI-Isoprime mass spectrometer, with uncertainties lower than 0.2‰ as determined from routine replicate measurements of the IAEA reference sample CH-3. Grain size

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[1] CEFREM, UMR-5110 CNRS-Université de Perpignan, Perpignan, France.

[2] GRC Geociències Marines, Facultat de Geologia, Universitat de Barcelona, Barcelona, Spain.

[3] Institut de Ciències del Mar, CSIC, Barcelona, Spain.

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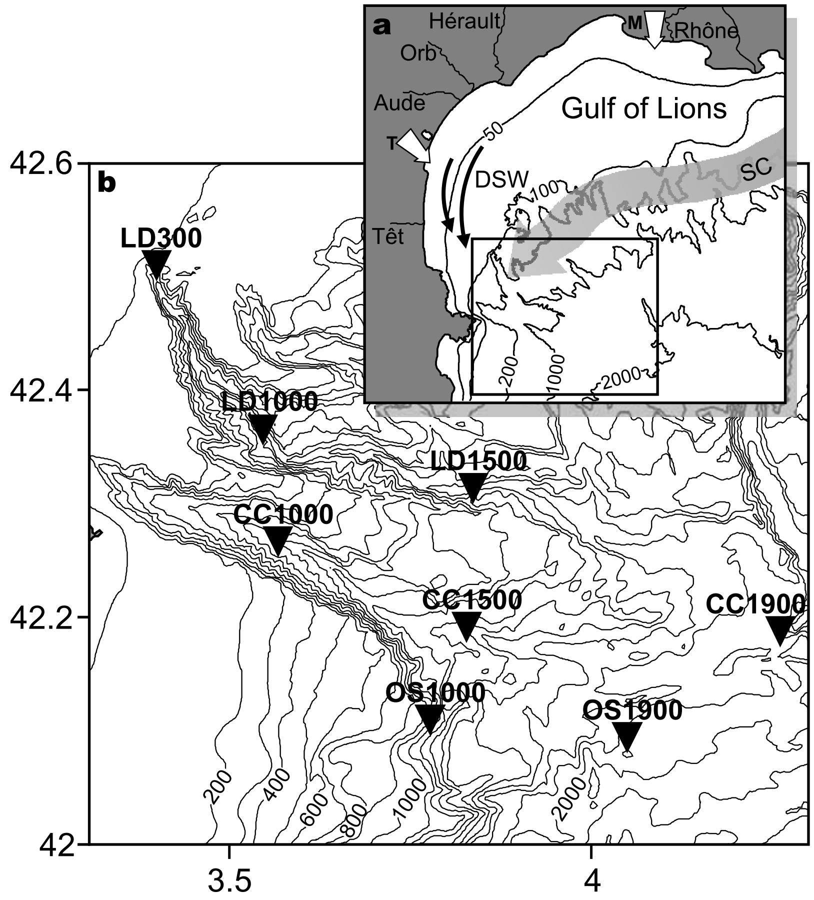

Figure 1. (a) General bathymetric map of the Gulf of Lion with main river systems. Arrows show Tramontane (T) and Mistral (M) winds (white), direction of the mean slope circulation (SC, grey), and Dense Shelf Water circulation (DSW, black). (b) Location of the mooring lines within Lacaze-Duthiers Canyon (LD), Cap de Creus Canyon (CC) and the southern open slope (OS) (number in station labels correspond to water depths).

distribution was analyzed with a Coulter LS 230 Laser Particle Size Analyzer after organic matter oxidation with 10% H_2O_2.

3. Results and Discussion

[5] Strong negative near-bottom temperature anomalies and increased current speeds recorded by the moored instruments during HERMES revealed that a major DSWC event occurred in winter 2005–06 (Figures 2a and 2b and Table 1). Current speeds peaked (>70 cm s^{-1}) at the onset of the event (early January 2006) at the upper course of both canyons (Table 1), with current directions mainly oriented down-canyon. Concomitant velocity and temperature anomalies could be tracked along the continental slope mostly down to 1500 m (Figure 2a and Table 1). This intense DSWC event was the latest up to date recorded, and followed those that occurred in winters 1998–99 [*Béthoux et al.*, 2002] and 2004–05 [*Canals et al.*, 2006].

[6] Downward particle fluxes during December 2005 and January 2006 are shown in Table 1. Particle fluxes in December 2005 displayed an overall seaward decreasing trend, ranging from 12.85 g $m^{-2}d^{-1}$ at the 300 m station of the Lacaze-Duthiers Canyon to 0.03–0.05 g $m^{-2}d^{-1}$ at the 1900 m stations of the Cap de Creus Canyon and the southern open slope. The trend of decreasing particle flux with distance to the shelf edge is a rather common feature in the Gulf of Lion submarine canyons [*Heussner et al.*, 2006]. Most sediment particles collected by traps showed minor to negligible sand contents (Table 1). In January 2006, when the study area was impacted by the DSWC event, total mass fluxes increased simultaneously over the entire slope, with the exception of the head of the Lacaze-Duthiers Canyon. Maximum averaged fluxes up to 74.46 g $m^{-2}d^{-1}$ (Table 1) were recorded in the upper course of the Cap de Creus Canyon. At deeper stations, particle fluxes were 10 to 90 times higher than those measured during the preceding month. Sand content increased dramatically at all stations and peaked at 22.6% (Table 1), showing a first mode at 100–120 μm and a smaller secondary mode at 200–250 μm (Figure 2c). These compositions highlight the capacity of cascading currents to maintain a significant suspended load of fine and very fine sand. Indeed, in several occasions during the January 2006 period, current speeds at 5 m above the bottom exceeded the critical threshold for 100–120 μm and 200–250 μm sand suspended load transport (respectively 34–36 and 47–54 cm s^{-1} as calculated from the SEDTRANS model [*Li and Amos*, 2001]) (Figure 2).

[7] Following the increased abundance of the sand fraction at the upper course (300–1000 m) of both canyons, grain size distribution during the DSWC event reveals that

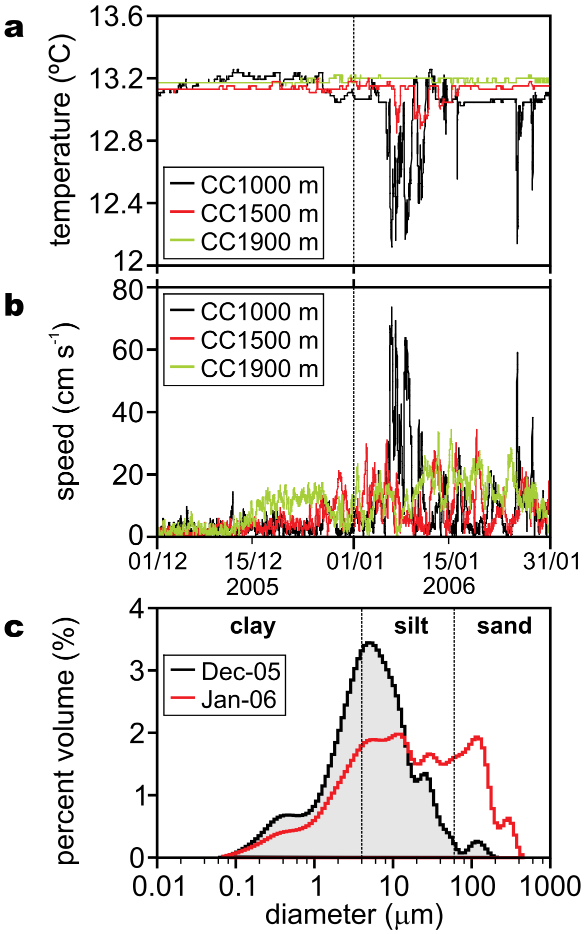

Figure 2. (a) Near-bottom in situ temperature (°C) and (b) near-bottom current speed time-series along the Cap de Creus canyon (stations CC1000, CC1500 and CC1900). (c) grain size distribution of settling particles at station CC1000 in December 2005 (black line) and January 2006 (red line).

silt-sized particles (4–63 μm) reached their highest abundance at greater depths (1000–1500 m), including stations along the southern slope (Table 1). Inversely, clay-sized particles (<4 μm) reached their highest abundance at the deepest stations in both canyons as well as in the open slope. This grain size sorting is associated to the decreasing transport capacity of the DSW plume along its down canyon and slope propagation. The attenuation of current speeds with increasing depths (Table 1 and Figure 2b) caused selective deposition of particles along the canyon and beyond, on the southern slope, according to their size. The basinwards transport of suspended fine particles led to the formation of a 200–500 m thick turbid bottom nepheloid layer that was measured at depths in excess of 1500 m over the canyon and open slope in April 2006 (data not shown), similarly to the findings by *Canals et al.* [2006] and *López-Jurado et al.* [2005].

[8] Besides a clear impact of DSWC on sediment transport and downstream sorting, we investigate the effects of DSWC on the "quality" (as a measure of source) of settling organic matter. Generally, organic matter in continental margin environments can be assigned to different sources based on $\delta^{13}C_{OC}$ composition and N/C atomic ratios. These include marine algae ($\delta^{13}C_{OC}$ from -19 to -22‰, $N/C > 0.12$) and terrestrial organic matter, which in the study area may include soil-derived organic matter ($\delta^{13}C_{OC} < -25$‰, $N/C = 0.12–0.06$) and woody debris ($\delta^{13}C_{OC} < -25$‰, $N/C < 0.06$) from C-3 plants (see review by *Hedges et al.* [1997]). C-4 plants are not thought to contribute to the OC load of rivers discharging into the Gulf of Lion [*Kim et al.*, 2007]. However, other factors such as early diagensis can alter the organic matter signature of the original source. For example, selective preservation of refractory compounds, such as lignin, can decrease $\delta^{13}C_{OC}$ and N/C [*Lehmann et al.*, 2002], and addition of new microbial biomass increases N/C [*Holmes et al.*, 1999]. Table 2 shows particle composition and Figure 3 shows $\delta^{13}C_{OC}$ versus N/C ratio of

Table 1. Average Current Speed, Maximum Current Speed, Time Weighted Total Mass Flux and Flux Weighted Percentages of Clay, Silt, and Sand Recorded in December 2005 and January 2006[a]

Station and Depth	u, cm s^{-1}	u$_{max}$, cm s^{-1}	TMF, g m^{-2}d^{-1}	Clay (<4 μm), %	Silt (4-63 μm), %	Sand (>63 μm), %
			December 2005			
LD 300 m	6.7	38.1	12.85	40.1	48.4	11.6
LD 1000 m	3.9	14.4	2.54	41.7	54.7	3.6
LD 1500 m	N.D.	N.D.	0.05	N.D.	N.D.	abs.
CC 1000 m	3.3	14.4	2.48	44.6	53.2	2.2
CC 1500 m	4.1	21.1	0.09	N.D.	N.D.	abs.
CC 1900 m	6.8	17.6	0.05	N.D.	N.D.	abs.
OS 1000 m	7.2	27.0	0.27	N.D.	N.D.	abs.
OS 1900 m	5.5	24.3	0.03	N.D.	N.D.	abs.
			January 2006			
LD 300 m	29.5	72.7	3.43	34.8	48.2	17.1
LD 1000 m	5.8	21.1	30.84	36.2	57.2	6.6
LD 1500 m	N.D.	N.D.	1.34	39.7	52.1	8.2
CC 1000 m	12.8	73.6	74.46	26.8	50.6	22.6
CC 1500 m	10.3	34.3	5.36	35.6	60.4	4.0
CC 1900 m	14.5	34.3	0.69	38.6	52.5	8.9
OS 1000 m	18.6	54.6	18.74	33.5	57.0	9.6
OS 1900 m	12.3	31.7	3.00	37.5	57.7	4.8

[a] Here u is average current speed, u$_{max}$ is maximum current speed, TMF is time weighted total mass flux, N.D. means no data available due to malfunctioning of the current meter or lack of available sediment for grain size analysis; abs. means absence of sand in low flux samples as determined by visual inspection.

Table 2. Flux Weighted OC Concentration, N/C Atomic Ratio, $\delta^{13}C_{OC}$, and Contributions of Marine and Terrestrial OC of Settling Particles in December 2005 and January 2006[a]

Station and Depth	OC, %	N/C atomic	$\delta^{13}C_{OC}$, ‰	OC_{TER}, %	OC_{MAR}, %
			December 2005		
LD 300 m	1.7	0.09	−22.95	47	53
LD 1000 m	1.7	0.09	−22.66	43	57
LD 1500 m	4.5	0.11	−23.37	54	46
CC 1000 m	2.0	0.08	−23.16	51	49
CC 1500 m	3.7	0.10	−22.39	38	62
CC 1900 m	4.7	0.09	−22.93	47	53
OS 1000 m	2.6	0.12	−22.76	44	56
OS 1900 m	4.9	0.08	−23.24	52	48
			January 2006		
LD 300 m	1.5	0.09	−23.55	57	43
LD 1000 m	1.3	0.11	−23.69	60	40
LD 1500 m	1.6	0.12	−23.52	57	43
CC 1000 m	0.9	0.09	−24.68	76	24
CC 1500 m	1.5	0.10	−23.52	57	43
CC 1900 m	1.5	0.10	−23.53	57	43
OS 1000 m	1.2	0.09	−23.98	65	35
OS 1900 m	1.2	0.12	−24.22	69	31

[a] Marine OC (OC_{MAR}) and terrestrial OC (OC_{TER}) have been estimated following a simple binary mixing model assuming marine $\delta^{13}C_{OC}$ = −20.1‰ [*Harmelin-Vivien et al.*, 2008] and terrestrial $\delta^{13}C_{OC}$ = −26.5‰ [*Kim et al.*, 2007] endmembers.

settling particles and OC sources for the western Gulf of Lion. Settling particles plot within the mixing region of terrestrial organic matter and marine algae, suggesting their OC may be a mixture of these sources. However, while particles settling in December 2005 displayed $\delta^{13}C_{OC}$ relatively closer to marine algae (−23.37 to −22.66‰) and enriched OC content (1.7 to 4.9%), those settling in January 2006 showed the influx of terrestrially derived OC, as shown by depleted $\delta^{13}C_{OC}$ (−24.68 to −23.52‰) and OC content (0.9 to 1.5%). In addition, along-canyon changes in OC content, N/C ratio and $\delta^{13}C_{OC}$ during the DSWC event reflected compositional differences among the organic matter associated with the different grain size fractions. The lowest $\delta^{13}C_{OC}$ and percent OC values were measured at the upper course of the Cap de Creus canyon where the highest current velocities, mass flux and sand abundance were recorded. $\delta^{13}C_{OC}$ and percent OC values increased down-canyon together with fining settling particle size (Table 1), and N/C atomic ratios showed a concomitant increase from 0.09 to 0.12 (Table 2). These observations suggest that the current-induced grain size sorting is the responsible for a geochemical gradient of settling organic particles along the Cap de Creus canyon.

[9] Marine and terrestrial OC estimated following a simple binary mixing model show that the influence of the energetic DSWC event yielded a contribution of terrestrial OC ranging from 57 to 76% (Table 2). Since none of the rivers from the Gulf of Lion drainage basin were flooding during January 2006, it is likely that this enhanced terrestrial contribution originates from resuspension of previously deposited riverine material. Indeed, the Gulf of Lions continental shelf stores sediment supplied by rivers and biological production [*Heussner et al.*, 2006; *Palanques et al.*, 2006]. $\delta^{13}C$ and N/C values of settling particles in January 2006 reflect the mixed origin of particles available for resuspension and transport, which may include, in different proportions, both marine and terrestrial OC stored on the shelf and canyon floor sediments (Figure 3). The relative importance of resuspended terrestrial OC from the shelf to particle flux is more evident at the material arriving at the upper course of the Cap de Creus canyon, as shown by its low $\delta^{13}C$ and N/C values (Figure 3). Furthermore, visual inspection of settling material at this location revealed the presence of large fragments of *Posidonia oceanica* (coastal marine phanerogam, 0–40 m depth) seagrass leaves, which suggests that shelf sediments resuspended by the DSW flow reached the upper course of the canyon. In fact, recent studies have shown that fluvial materials deposited during high river discharge events can be remobilized and deposited as secondary (and successive) flood deposits during storm [*Guillén et al.*, 2006] and DSWC [*Bourrin.*, 2007] events. Therefore, it appears that in absence of a synchronous river flood, DSWC led to a delayed transport event of a mixture of erodible sediment stored on the shelf and canyon floor sediments along the canyon axis.

4. Concluding Remarks

[10] Our findings to date show that DSWC has a significant impact in the amount and origin of settling organic particles. The magnitude of the DSWC-related fluxes to the seabed illustrates the capacity of the strong cascading currents to erode and maintain a significant suspended load of particles, carrying massive amounts of material several

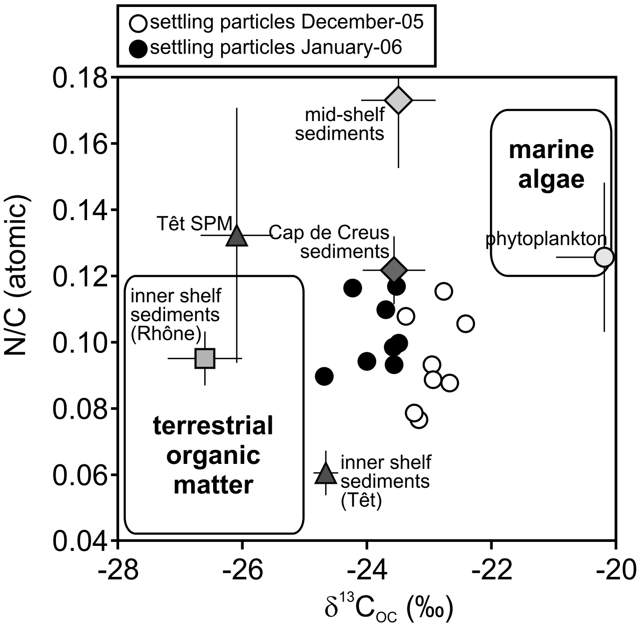

Figure 3. Plot of $\delta^{13}C_{OC}$ versus N/C atomic ratio in settling particles in December 2005 (open circles) and January 2006 (closed circles). Local OC sources are also displayed. Averaged data of Rhône prodelta, mid-shelf and Cap de Creus canyon sediments (October 2004 and April 2005) are from *Tesi et al.* [2007]; data of Têt river suspended particulate matter (SPM) and prodelta sediments (November 2005) are from *Kim et al.* [2007]; and phytoplankton data (May and October 2004) are from *Harmelin-Vivien et al.* [2008].

tents of kilometres off the shelf in few days. The Cap de Creus canyon represents a preferential pathway for coarse particles and terrestrial OC resuspended from shelf and canyon floor, with the terrestrial signal progressively decreasing along the path of cascading waters due to reducing transport capacity of the DSW plume. The different components of the benthic fauna and bacterial assemblages may respond distinctly to DSWC events, depending on the ecology and feeding habits of the inhabiting species along the slope. For example, while some benthic communities may be negatively affected due to catastrophic sand and terrestrial OC deposition, other communities with the ability to use this specific carbon source, such as deposit-feeding polychaetes [*Darnaude et al.*, 2004] may benefit from this pulse of OC. DSWC is thus likely to have profound implications for food availability for along-canyon and deep-basin benthic ecosystems. In addition, the larger than expected fraction of terrestrial OC exported off-shelf should be considered in global biogeochemical models, and quantification of these fluxes in other DSWC margins worldwide merits consideration to constrain the carbon budget of the global ocean.

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A. Calafat, M. Canals, and C. Pasqual, GRC Geociències Marines, Facultat de Geologia, Universitat de Barcelona, E-08028 Barcelona, Spain.

X. Durrieu de Madron, S. Heussner, P. Kerhervé, and A. Sanchez-Vidal, CEFREM, UMR-5110 CNRS-Université de Perpignan, 52 av. P. Alduy, F-66860, Perpignan, France. (anna.sanchez@univ-perp.fr)

A. Palanques and P. Puig, Institut de Ciències del Mar, CSIC, Pg Marítim de la Barceloneta 37-49, E-08003 Barcelona, Spain.