Interactions between open-sea convection and shelf cascading dense waters in the formation of the Western Mediterranean Deep Water

Pere Puig [1], Albert Palanques [1], Jordi Font [1], Jordi Salat [1], Mikel Latasa [2] and Renate Scharek [2]

[1] *Institut de Ciències del Mar, CSIC, Barcelona, Spain*
[2] *Centro Oceanográfico de Gijón, IEO, Spain*

Abstract

Sea-atmosphere interactions play an important role on the oceanographic processes at various spatial and temporal scales. In the Mediterranean Sea, several regions are key spots of intense air-sea interactions which affect considerably the heat and water budgets. An example of this is the wintertime formation of dense water through interaction with the atmosphere, and further sinking by convection or cascading. The Gulf of Lions is one of the regions in the Mediterranean where massive dense water formation occurs because of cooling and evaporation of surface waters during winter-time. Concurrent with the well known open-sea convection process over the MEDOC region, coastal surface waters over the wide shelf of the Gulf of Lions also become denser than the underlying waters and cascade downslope until reaching their equilibrium depth. Through this climate-driven phenomenon, dense shelf waters carrying large quantities of particles in suspension are rapidly advected hundreds of meters deep, mainly through submarine canyons. Recent observations within the frame of several research initiatives conducted in the north-western Mediterranean indicate that major dense shelf water cascades from the Gulf of Lions have a direct effect on the Western Mediterranean Deep Water (WMDW) thermohaline properties and are responsible for the formation of a thick and persistent bottom nepheloid layer (BNL) that spreads throughout the western Mediterranean basin and scales in thickness with the WMDW anomaly created during sever winters like those of 1999 and 2005.

Introduction

Dense shelf water cascading (DSWC) is a global climate-driven oceanographic phenomenon common not only on high latitude continental margins, but also on mid latitude and tropical margins (Ivanov *et al*., 2004). DSWC is a specific type of buoyancy-driven current, in which dense water formed by cooling, evaporation or freezing in the surface layer over the continental shelf descends down the continental slope to a greater depth. The general DSWC concept was formulated by Fritjof Nansen (1906), who made the first direct measurements over the Rockall Bank in the North Atlantic Ocean (Nansen, 1913). The term “cascading” was introduced later by Cooper and Vaux (1949), but the same phenomenon is also referred as “shelf/slope convection”.

Cascades of DSW can last for several weeks and the associated strong currents can induce erosion and resuspension of surface sediments in the outer shelf/upper slope and generate bottom nepheloid layers (i.e. layers of water that contains significant amounts of suspended sediment). Such layers can be detached at intermediate levels when the mixture of water and particles reach their equilibrium depth, or if the density is large enough, evolve into a thick bottom nepheloid layer that can reach the lower continental slope and basin (Figure 1). This cascading mechanism contrasts with the typical offshore convection, since only the latter brings dense "blue water" free of particles to the basin.

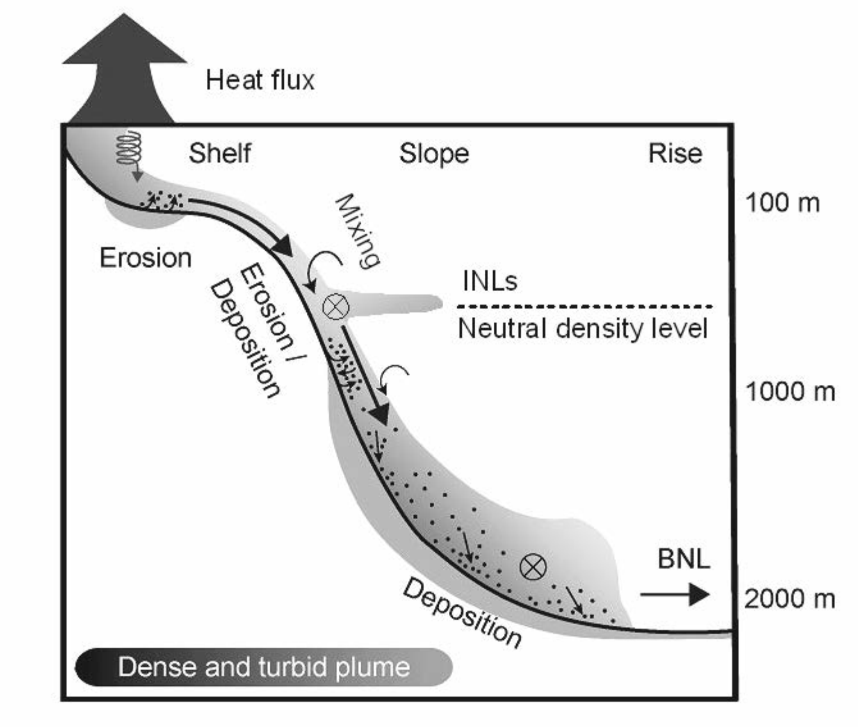

Figure 1. Schematic diagram of the DSWC mechanism illustrating the formation of intermediate nepheloid layers (INLs), when water and particle detachments occur at the neutral density levels, and of a thick bottom nepheloid layer (BNL) when dense shelf waters reach the basin [adapted from Fohrmann *et al.* (1998)].

Winter heat losses and evaporation induced by persistent, cold and dry northerly winds affecting the Gulf of Lions cause densification and mixing of coastal waters. Despite the buoyancy gain induced by freshwater inputs, once denser than surrounding waters, surface waters over the shelf sink, overflow the shelf edge, and cascade downslope until they reach their equilibrium depth, which changes from year to year (Millot, 1990; Durrieu de Madron *et al*., 2005). The first evidence of DSWC in the Gulf of Lions was found in 1953 by Bougis and Ruivo (1954), who identified the formation of dense waters along the southwestern shelf and their cascading into the Lacaze-Duthiers submarine canyon. Further DSWC events in the same area were also observed in 1969 by Fieux (1974) and in 1971 by Person (1974), who traced dense shelf waters down to 800 and 350 m depth, respectively. Further evidence was gained during winter 1995 by Lapouyade and Durrieu de Madron (2001) at the same location; they observed a cascade at its final stage with a large tongue of cold water escaping the shelf and reaching its neutral density level around 170 m depth. More recently, a fine spatial resolution hydrographic survey performed in 2004 along the axis of the Cap Creus Canyon (Durrieu de Madron *et al*., 2005) showed a cold and less salty filament, attached to the seabed, down to 350 m. The section exhibits a transitional case, as the leading edge has not reached the neutral density level, between 400 and 500 m. In both cases, the advection of turbid shelf waters produces a turbidity maximum associated to the dense water tongue.

In all cases, temperature is the sole driver of cascading. At the initial stages, when dense waters escape the shelf and spread around the shelf break depth (150-200 m), they contribute to the formation of the Winter Intermediate Water (WIW), with typical properties T = 12.5°C, S = 38.0 (Dufau-Julliand *et al.*, 2004). In the case when dense shelf waters cascade to deeper levels, they eventually mix with the warmer and saltier Levantine Intermediate Water (LIW) layer (T = 13.2°C, S = 38.5) that extends between 200 and 1,000 m depth or eventually with the underlying WMDW.

The monitoring of temperature, current and downward particle fluxes conducted since 1993 in the lower part of the Planier and Lacaze-Duthiers submarine canyons by the "Centre de Formation et de Recherche sur l'Environnement Marin" of Perpignan (CEFREM) revealed an inter-annual variation of the DSWC intensity in the Gulf of Lions (see Heussner *et al.*, 2006 and Canals *et al.*, 2006 for details). Based on these time series Béthoux *et al.* (2002) inferred that during the abnormally cold 1999 winter, the intense shelf cascading episode traced at 1,000 m on the continental slope, with down-slope velocities up to 60 cm s^{-1}, contributed to the renewal of the bottom waters of the western Mediterranean basin. Previous severe winters with anomalous dense water formation (i.e. those with major cascading events reaching the basin) were identified by these authors after the analysis of historical hydrographic data and presumably took place in winter 1971, 1980 and 1988, therefore occurring at subdecadal intervals.

Further time series observations in the Gulf of Lions were conducted under the frame of the EuroSTRATAFORM project, during which seven submarine canyon heads were monitored simultaneously in winter 2004. These results revealed that the preferential cyclonic circulation of the coastal current and the narrowing of the shelf at the southwestern end of the Gulf cause most of the water and sediment transport during DSWC events to occur through the Cap de Creus submarine canyon (Palanques *et al.*, 2006). Since then, the occurrence and effects of dense shelf water cascades from the Gulf of Lions have been continuously monitored at the Cap de Creus submarine canyon head, as a complement to the two long-term mooring deployments in the Planier and Lacaze-Duthiers submarine canyons at 1,000 m depth. The subsequent major DSWC event recorded by those instrumented moorings occurred during the abnormally dry, windy and cold winter 2005, when cascading was exceptionally intense, lasting for more than three months. Under these circumstances, dense shelf waters propagated along and across the continental slope (Font *et al.*, 2007), reaching depths >2,000 m where they merged with dense waters formed off-shelf, in the MEDOC area, by a typical open-sea convection process (MEDOC group, 1970). The mixing of these two dense waters generated a thermohaline anomaly in the WMDW that spread throughout the entire north-western Mediterranean basin (López-Jurado *et al.*, 2005; Schroeder *et al.*, 2006). The following major DSWC event occurred in winter 2006, which could be also traced down to 1,900 m depth by a large network of instrumented moorings deployed in the south-western end of the Gulf of Lions margin under the frame of the HERMES project (Sánchez-Vidal *et al.*, 2008). This consecutive major DSWC event presumably contributed to the modification and spreading of the "new" WMDW generated after winter 2005 and 2006 characterized by Schroeder *et al.* (2008).

The aim of this contribution is to provide evidence of the contribution of DSWC to the changes in the WMDW after the strong winters 2005 and 2006, and to revisit the role that the winter 1999 DSWC event played in the thermohaline and turbidity anomalies in the WMDW, which resemble the 2005-2006 ones.

TIME SERIES OBSERVATIONS

As stated before, the occurrence and effects of dense shelf water cascades from the Gulf of Lions have been continuously monitored at the Cap de Creus submarine canyon head (300-500 m depth) since November 2003 under the frame of several research projects (Figure 2). This mooring has been maintained as a permanent observatory and is equipped with an Aanderaa RCM 9/11 doppler current meter with temperature, conductivity, pressure and turbidity sensors placed at 5 m above the bottom.

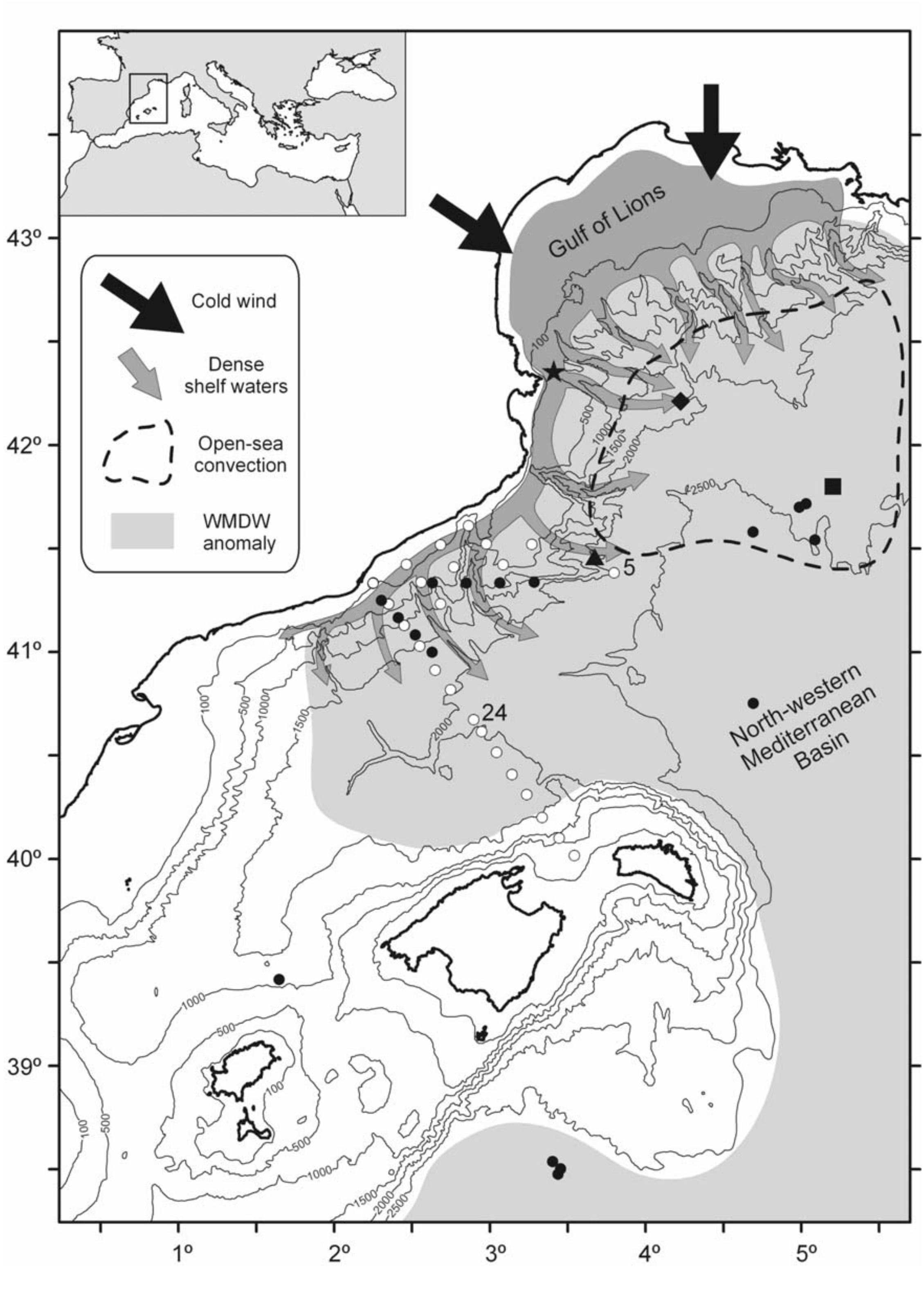

Figure 2. Bathymetric map of the north-western Mediterranean showing the pathway of the dense shelf water cascading mechanism extending from the Gulf of Lions along and across the Catalan continental slope, the open-sea convection region (MEDOC area) and the region affected by the thermohaline and turbidity anomaly observed in the WMDW during the 1999 and 2005 major cascading events. Black dots represent the CTD casts collected in winter 2005 and the white dots those collected in winter 1999. The location of the monitoring sites at the head (star) and mouth (diamond) of the Cap de Creus submarine canyon, at the basin (square) and at the Hydro Changes ICM location (triangle) is also shown.

Contemporary with the Cap de Creus time series observations, since October 2003 and as part of the HydroChanges (HC) pilot program launched by CIESM (<http://www.ciesm.org/marine/programs/hydrochanges.htm>; CIESM, 2002), the "Institut de Ciències del Mar of Barcelona" (ICM) has been maintaining an instrumented mooring in the lower Catalan continental slope (hereafter named HC-ICM), which has proved very valuable in identifying the interactions between open-sea convection and shelf cascading dense waters in the formation of the WMDW (see Font *et al*., 2007 for details). The HC-ICM mooring is located at 1,890 m depth, downstream from the Gulf of Lions margin and south of the Palamós submarine canyon (Figure 2). This location was chosen because it was previously used in 1993-94 for a study related to the spreading of the deep water formed in the NW Mediterranean (Send *et al.*, 1996), from where background information existed. The mooring is equipped with a SeaBird 37 model CTD recorder at 15 mab and an Aanderaa RCM 8 mechanical current meter at 11 mab, and since March 2007 an auxiliary Aanderaa RCM 11 doppler current meter equipped with a turbidity sensor has been installed on it.

Additionally, in the context of the research project EFLUBIO a moored instrumented array was installed in the North Balearic Basin at 2,350 m depth (5º 12'; 41º 48'; Figure 2) from November 2003 to April 2005. The array was equipped with an Aanderaa RCM 11 doppler current meter and a Technicap PPS 5/2 conical sediment trap with a 1 m^2 collecting area and 24 receiving cups. The current meter was placed 220 mab and the sediment trap 250 mab. The sediment trap collected 48 samples in the two consecutive deployments with a mooring turn-around in mid-September 2004. The trap collecting intervals ranged from 5 to 15 days, depending on the season, and the current meter sampling interval was set at 60 minutes.

In the same study area, and as part of the HERMES project, nine mooring lines were also deployed from October 2005 to October 2006 along the axes of the Lacaze-Duthiers and Cap de Creus submarine canyons at 300, 1,000, and 1,500 m depth, and on the adjacent southern open slope at 1,000 and 1,900 m depth. Each mooring was equipped with one sequential sampling (12 cups) PPS3 Technicap sediment trap (0.125 m^2 opening) at 30 mab and an Aanderaa RCM 9/11 doppler currentmeter with temperature, conductivity, pressure and turbidity sensors placed at 5 m above the bottom (mab). For the purpose of this contribution, only the time series from the mooring placed at 1,900 m depth along the Cap de Creus canyon axis (Figure 2) is used.

Figure 3 shows several time series obtained in the above-mentioned observational sites reflecting the changes in the thermohaline properties of the WMDW and the transfer of particles to the north-western Mediterranean basin. Data recorded during several consecutive winter deployments in the Cap de Creus submarine canyon head (300-500 m depth) have allowed monitoring and identifying the occurrence and magnitude of dense shelf water cascades from the Gulf of Lions (Figure 3a,b). Cascading events are easily recognizable since they are characterized by abrupt decreases in water temperature (below 12 ºC) associated with increases in current speed (up to 80 cm/s) and with increases of suspended sediment concentration (data not shown).

The time series of data recorded at the HC-ICM mooring indicated a clear difference between winters characterized by minor or major cascading events. The potential temperature (12.84-12.86 ºC) and salinity (38.45-38.46) values at 1,980 m depth in the lower Catalan continental slope (Figure 3c,d) were almost unchanged from October 2003 until the end of January 2005, indicating a stable water mass situation that corresponds to typical WMDW characteristics (θ 12.8-12.9, S 38.43-38.46, σ_θ 29.09-29.10), depending on the specific conditions that occurred during its formation in winter. However, from this last date, and simultaneously with the initiation of the major 2005 cascading event in the Cap de Creus Canyon, θ and S rapidly increased to 12.99 ºC and 38.50 respectively, and then for one month fluctuated between 12.90-12.95 ºC and around 38.49 (σ_θ = 29.11). Such increases were attributed by Font *et al.* (2007) to the arrival at the HC-ICM site of dense waters formed or pre-conditioned by the offshore convection process, which had a large contribution of an unusually warm and salty LIW/TDW. By early March 2005, potential temperature and salinity suddenly decreased by more than 0.2 ºC and 0.04, respectively, as a consequence of the arrival of colder and fresher dense shelf waters, which cascade from the Gulf of Lions to the lower Catalan continental slope (Font *et al.*, 2007). The signature of these dense shelf waters remained during one month in a range of low values (with peaks down to 12.51 ºC and

38.41, σ_θ = 29.14), lasting for almost as long as the continuous cascading was recorded within the Cap de Creus Canyon, and was followed by a period of gradual θ and S increase until reaching quite steady values of 12.88 ºC and 38.48 (σ_θ = 29.12) by mid June 2005. In late December 2005, potential temperature and salinity sharply increased by 0.06 ºC and 0.01 respectively, presumably as a consequence of the arrival of newly formed dense waters by winter offshore convection, and afterward, θ and S fluctuated between 12.82-12.95 ºC and 38.47-38.49 until mid March 2006. At that time, a sudden drop of 0.16 ºC and 0.04 took place, associated to the arrival of dense shelf waters to the HC-ICM site exported during the major 2006 cascading event. Similar to what occurred in the preceding year, the signature of the dense shelf waters could be detected at 1,890 m depth for more than a month, with minimum values of 12.66 and 38.43 (σ_θ = 29.13). Progressively, θ and S values reached the same "new" (i.e. after 2005) steady values of 12.88 and 38.48 (σ_θ = 29.12) by mid May 2006, although both variables showed after that date a subtle but persistent increasing trend with periodic fluctuations of several days. The HC-ICM mooring was recovered (and reinstalled again) in early March 2007 without showing any evidence of thermohaline changes in the WMDW associated to the several minor cascades that occurred in winter 2007.

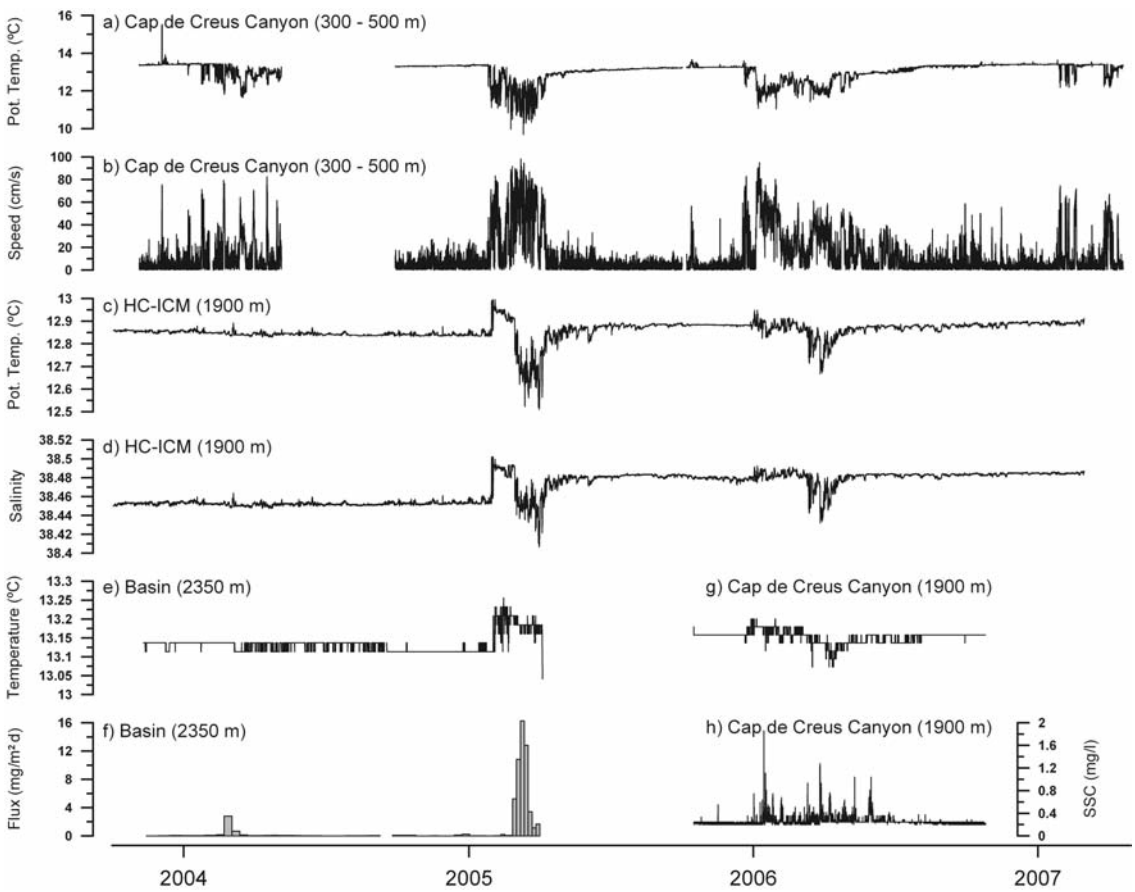

Figure 3. Time series observations from the north-western Mediterranean showing: a) potential temperature and b) current speed at the head of the Cap de Creus submarine canyon; c) potential temperature and d) salinity recorded at the HC-ICM site; e) *in situ* temperature and f) total mass fluxes collected at the basin site; and g) *in situ* temperature and h) suspended sediment concentrations recorded at the Cap de Creus canyon mouth.

At the basin site (2,400 m depth, 220 mab), *in situ* temperature recorded at 220 mab from November 2003 to February 2005 showed a similar temporal evolution pattern. It maintained a relatively constant value of 13.11-13.13 ºC and increased to 13.20-13.23 ºC between early February and early March 2005. Afterwards it decreased by about 0.05ºC, to 13.16-13.18 ºC, until early

April 2005, when a sudden drop to 13.04 ºC occurred just before the mooring recovery (Figure 3e). Based on these multiple observations on the effects of the major 2005 DSWC event, we can state that dense shelf waters head began to flow uninterruptedly down-slope along the Cap de Creus canyon towards greater depths on 24 February 2005. Five days later, DSWC mixed with offshore convection waters reached the ICM-HC site, producing a temperature drop of 0.2 ºC. This drop was smaller (0.05 ºC) at the basin site and occurred seven days later, indicating that the arriving of dense shelf waters to the basin was more mixed with offshore convection waters than at the Catalan deep slope. The arrival of DSWC at the basin site produced a particle flux increase of 2-3 orders of magnitude (up to 16.27 g/m^2d) from late February 2005 until at least the end of the deployment on early April 2005 (Figure 3f), indicating that this deep DSWC event transported a large particle load to the basin (Palanques *et al*., 2009).

At the Cap de Creus canyon mouth (1,900 m depth), during winter 2006, *in situ* temperature also exhibited the same temporal evolution recorded at the HC-ICM site (Figure 3g). It showed quasi steady values around 13.16 ºC from mid October to late December 2005, and afterwards it progressively increased to 13.20 ºC. By mid January 2006, a drop to 13.11 ºC (event also noticed in the HC-ICM record) coincided with a sharp peak of suspended sediment concentration (SSC) (Figure 3h). From that date onwards, temperature decreased progressively to 13.07 ºC until mid April 2006 (with an isolated drop by mid March 2006) and SSC displayed high values until late June 2006 at the time that *in situ* temperature progressively increased and stabilized again at values around 13.16 ºC.

CTD PROFILES

The sequence of changes recorded by these time series observations could be observed in numerous CTD casts collected immediately after the 2005 dense water formation period. During the EFLUBIO-2 cruise conducted from mid March to early April 2005 (see CTD casts position in Figure 2), the signal of the 2005 DSWC event and the formation of a thick BNL associated to the dense water plume spreading off the Gulf of Lions could be mapped and traced as far south as Barcelona.

Figure 4 shows the vertical profiles of SSC and σ_θ of a hydrographical transect across the Barcelona continental margin, from 300 m down to 1,700 m depth. On these profiles (as well as in others not shown) a thick BNL that scales in thickness with a dense water plume can be observed at all depths. This BNL becomes thicker with depth although the maximum concentrations reached close to the seafloor are similar and reach values around 0.6 mg/l (three times higher that the typical background levels).

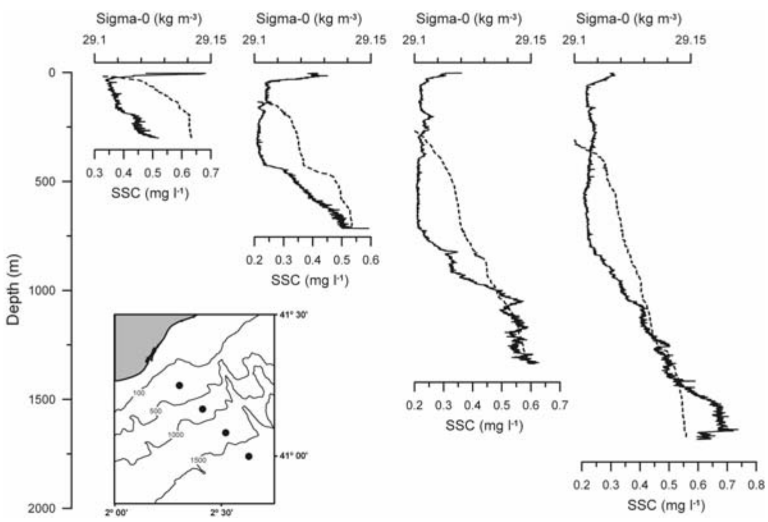

Figure 4. Vertical profiles of suspended sediment concentration (SSC) and σ_θ from a hydrographical transect conducted across the Barcelona continental margin, from 300 m down to 1,700 m depth on 24 March 2005. The inset map shows the detailed location of the CTD casts (see Figure 2 for a general situation).

These observations corroborate the results obtained by the deployed instruments and clearly illustrate the capacity of the major DSWC events in the Gulf of Lions to spread along and across the north-western Mediterranean margin and to carry large amounts of particles in suspension, along with dense shelf waters, towards the basing.

This BNL has been observed in deeper profiles collected during the same cruise (Figure 2), not only associated with the dense shelf waters, but with the positive thermohaline anomaly in the WMDW that spread throughout the entire north-western Mediterranean basin (López-Jurado *et al*., 2005; Schroeder *et al*., 2006).

THE 1999 EVENT

As stated before, the previous anomalous winter that affected the north-western Mediterranean and caused a major cascading event was in 1999. To asses the extent to which the CTD observations collected after the 2005 DSWC were unique or shared some similarities with the 1999 DSWC, data from the HIVERN-99 oceanographic cruise were re-examined. This cruise took place from late February to mid March 1999 (see CTD casts position in Figure 2) during which several deep CTDs and a detailed transect from Barcelona to Mallorca was conducted. To illustrate the interactions between open-sea convection and shelf cascading dense waters in the formation of the WMDW during winter 1999, the θ, S and SSC vertical profiles from two CTD casts have been plotted in Figure 5.

The CTD cast conducted closer to the Gulf of Lions (cast # 5) clearly captured the formation of dense waters by open sea convection since the θ and S vertical profiles were almost constant through the water column (12.89 ºC and 38.44) and free of particles in suspension. However, the near-bottom layer was occupied by a 600 m thick colder, fresher and more turbid water mass that corresponded to the arrival of dense shelf waters to the basin (see inset in Figure 5).

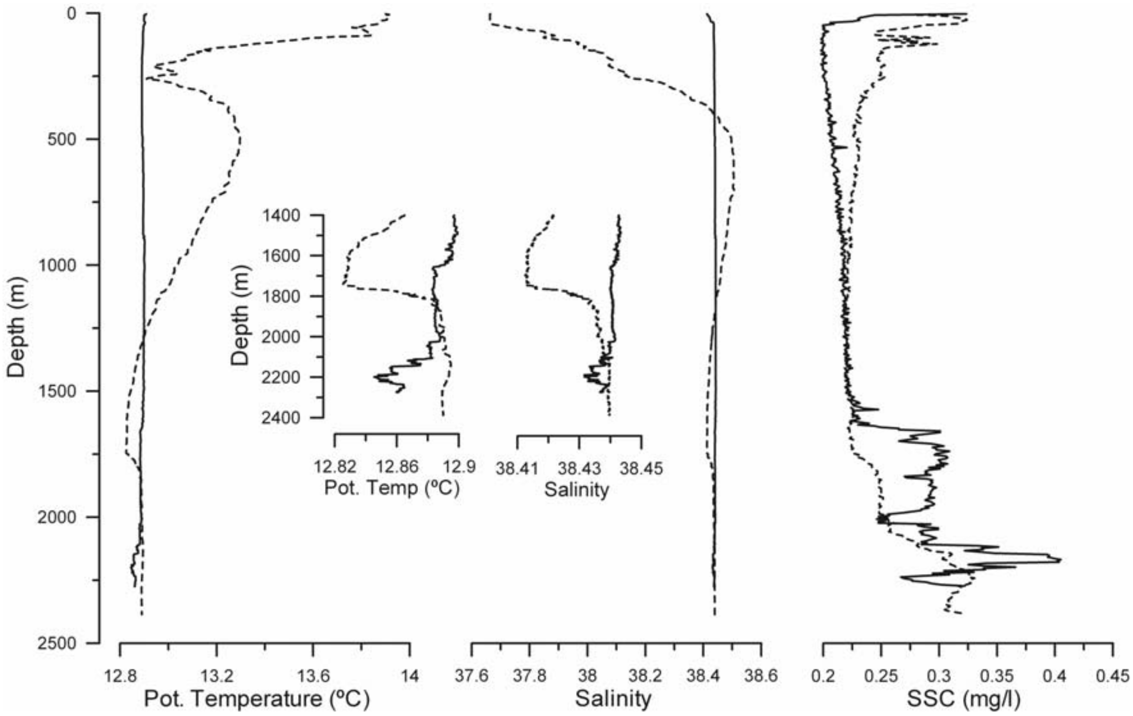

Figure 5. Vertical profiles of potential temperature, salinity and suspended sediment concentration from two deep CTD casts collected in the north-western Mediterranean on 21 February 1999 (cast # 5, solid line) and on 25 February 1999 (cast # 24, dashed line) illustrating the interaction between the cascading and convection dense waters generated during winter 1999. See Figure 2 for CTD positions.

Contrary to what was observed in winter 2005, the hydrographic transect from Barcelona to Mallorca did not show the formation of a thick BNL associated to the spreading of dense shelf waters towards the south, probably because of a limited extension of the dense water plume escaping from the Gulf of Lions at the time of the cruise. Nonetheless, the deepest profile in the middle of the Valencia valley (cast # 24) did show a well developed BNL (600 m thick) that scaled in thickness with a positive thermohaline anomaly similar to that observed in 2005 (Figure 5).

The comparison between these two deep CTD casts conducted in winter 1999 provide further evidence that the arrival of suspended particles to the basin during anomalous winters is associated to the occurrence of deep DSWC events, while the positive thermohaline anomaly is caused by the open sea convection process, since the high anomalous θ and S values for the WMDW in cast # 24 fall in the range of the dense convection waters observed in cast # 5 (i.e. 12.89 ºC and 38.44). Therefore, it seems that the mixing of the two dense water masses is responsible for the thermohaline (mainly convection) and turbidity (solely cascading) anomaly observed after winter 1999, as well after winters 2005 and 2006 (see Salat *et al.*, this volume for further details).

Acknowledgements: this research was supported by the EuroSTRATAFORM Program funded by the ONR (contract N00014-04-1-0379) and by the EC 5th FP (project EVK3-2002-00079). Additional support was obtained from the HERMES Project funded by the EC 6th FP (contract GOCE-CT-2005-511234) and by the project EFLUBIO funded by the Spanish Ministry of Education and Science (Ref: REN2002-04151-C02-01/MAR). The HC-ICM mooring turnaround was also supported by the Spanish Ministry of Education and Science (Ref: CTM2007-28881-E).