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Impact of open sea deep convection on sediment remobilization in the western Mediterranean

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[1] The northwestern Mediterranean is known to be a privileged area of deep water formation via dense shelf water cascading and offshore convection. The impact of the former in the sedimentary dynamics of the deep basin has been highlighted in recent years, while open sea convection has been solely studied from a hydrological perspective. Particle fluxes and hydrodynamics were monitored at the DYFAMED site (Ligurian Sea, western Mediterranean) at 200, 1000 m and near the seafloor (2350 m depth) during winter 2005–2006. From February to April 2006, and in coincidence with an unusual episode of deep water formation, a notable intensification of currents was observed in the entire water column and near-bottom particle flux increased up to two orders of magnitude. These observations suggest that offshore convection must be taken into account together with cascading as a major driving force for sedimentary dynamics in the deep western Mediterranean. **Citation:** Martín, J., J.-C. Miquel, and A. Khripounoff (2010), Impact of open sea deep convection on sediment remobilization in the western Mediterranean, *Geophys. Res. Lett.*, *37*, L13604, doi:10.1029/2010GL043704.

1. Introduction

[2] The northwestern Mediterranean is the most intensively studied region of deep water formation (DWF), where this process occurs through two variants: dense shelf water cascading [*Canals et al.*, 2006] and open sea deep convection [*MEDOC Group*, 1970]. During the last years, the role of shelf water cascading in the sedimentary dynamics of the deep northwestern Mediterranean basin has received a well-deserved attention [e.g., *Canals et al.*, 2006; *Puig et al.*, 2009]. Offshore deep convection on the other hand, though surveyed for a longer time, has been mainly considered from a hydrological perspective [*MEDOC Group*, 1970; *Marshall and Schott*, 1999] while its potential sedimentary role has not been documented to date.

[3] The main open-sea convective area of the northwestern Mediterranean is located in front of the Gulf of Lions and known as the MEDOC area (Figure 1). The Ligurian Sea, located eastward from the MEDOC area, has been traditionally considered an area of incomplete convection, where mixed layer depths (MLD) rarely exceed a few hundred meters and intermediate waters, rather than deep ones, are formed in winter [*Sparnocchia et al.*, 1995]. However, during winter 2005–2006, the main convective area shifted from the MEDOC area to the Ligurian subbasin and a major DWF episode ensued with far-reaching hydrological consequences for the western Mediterranean [*Smith et al.*, 2008; *Schroeder et al.*, 2008].

[4] Since 1988, the DYFAMED mooring line is located in the Ligurian Sea at 43°25′N, 7°52′E (Figure 1) over a bottom depth of 2350 m. The mooring sustains two sediment traps and current meters at permanent depths of 200 and 1000 m. Very opportunely, a set of a sediment trap and a current meter was present close to the bottom during 2005–2006 [*Khripounoff et al.*, 2009], which has allowed us to observe the dynamics of the DWF episode through the water column down to the bottom. A notable increase of near-bottom currents and particle flux was noticed by *Khripounoff et al.* [2009] from February to April 2006. Although the study area is under the potential influence of sediment gravity flows owing to its connection to the Var Canyon system, *Khripounoff et al.* [2009] proved that this event was not associated to gravity flows. In this work we show that the dramatic increase of near-bottom particle flux in the Ligurian Sea during winter-spring 2006 was associated to the exceptional DWF event that took place during this period.

2. Data and Methodology

[5] The sediment traps used in this study were Technicap PPS5/2, which consist of a conical collector with a baffled aperture of 1 m^2 and a programmable carrousel equipped with 24 sampling bottles. Traps were located at the DYFAMED site (Figure 1) at 200, 1000 m depth and 20 meters above the bottom (mab) over a total water depth of 2350 m. In order to prevent grazing from zooplankton and bacterial respiration, sampling bottles were filled prior to deployment with a buffered 2–3% (v/v) formaldehyde solution. Upon recovery from the sea, a common protocol was applied to all trap samples, including in this order: removal of zooplankton, desalting of samples with Milli-Q water, and freeze-drying. Bulk mass flux was then calculated from dry mass. Particulate organic carbon (POC, as % of dry weight) in the near-bottom trap samples was measured with a LecoWR12 analyzer after decalcification with 2N HCl.

[6] Rotor current meters Aanderaa RCM-7 and RCM-8 were fixed 5 m below (200, 1000 m) and 10 m above (near-bottom) the traps to record current speed and direction, as well as water temperature, at 2 h and 30 min intervals at midwaters and near-bottom respectively.

[7] Hydrographical vertical profiles were provided by the French Service d'Observation DYFAMED maintained by the Observatoire Océanologique de Villefranche-sur-Mer (www.obs-vlfr.fr/sodyf). MLD was calculated from hydro-

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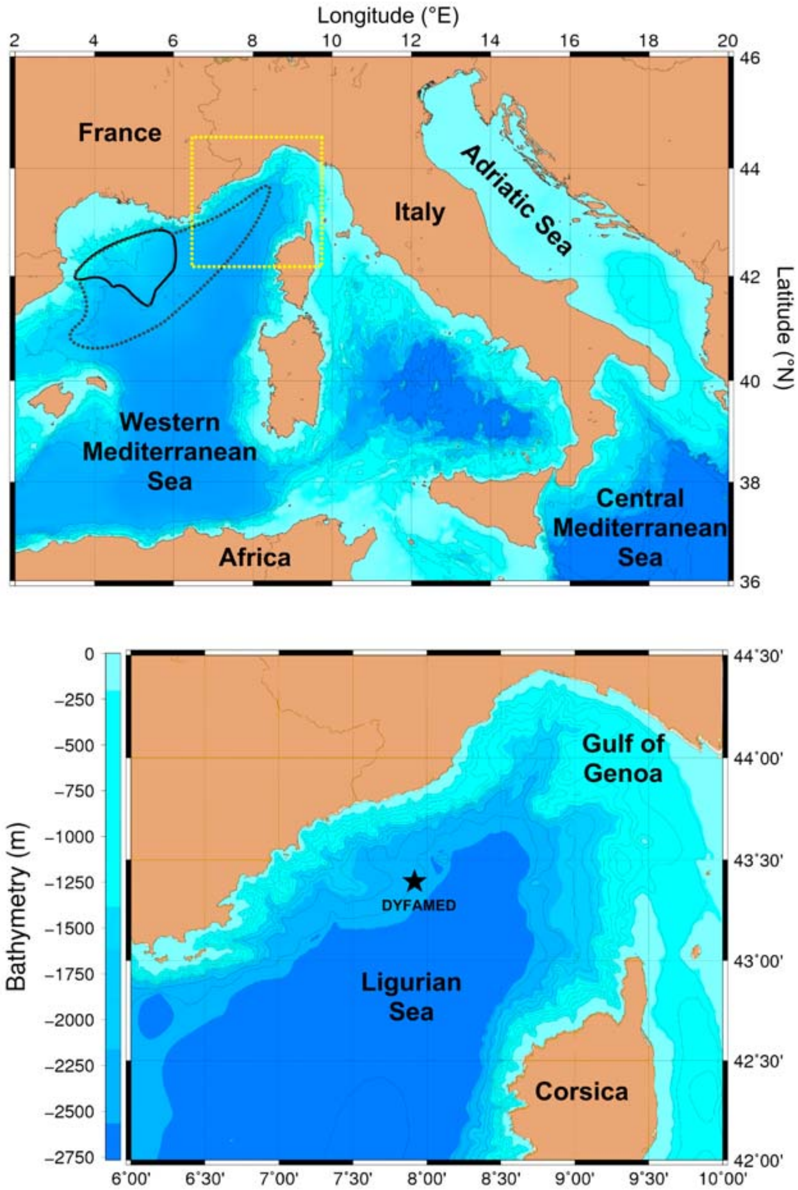

Figure 1. (top) Partial map of the Mediterranean Sea and study area (square). The main area of open-sea convection is marked with a bold line. An extended area where convection is considered to occur to a lesser vertical extent and/or frequency, including the eastern Catalan and western Ligurian basins, is indicated with dotted line. (bottom) Enlarged map of the Ligurian Sea showing the location of the DYFAMED site.

graphical data as the depth were an increase in potential density of 0.03 kg m^{-3} is reached with respect to 10 m depth [*de Boyer Montégut et al.*, 2004].

3. Results and Discussion

[8] Figure 2 outlines the temporal evolution of potential density (σ_θ) at the DYFAMED site from autumn 2005 to late summer 2006, and also the historical trends of MLD and current speed at the site. The progressive vector diagrams calculated from the three current meters are displayed in Figure 3. Figure 4 presents time series of current speed and temperature at the three sampling depths, and mass flux measured by sediment traps.

[9] After the classical work by *MEDOC Group* [1970], open sea convection is described as a sequence of three progressive phases: preconditioning, violent mixing and sinking+spreading. Preconditioning often involves persistent, cold and dry winds that promote weakening of the vertical stability through buoyancy losses in the surface. Other circumstances that contribute to reduce vertical stability, and that are met at the NW Mediterranean, are a general cyclonic circulation and the presence of subsurface salty and warm waters. It has been claimed that, since weather conditions were not particularly severe in winter 2005–2006, other preconditioning factors, as the presence of saltier, warmer, and shallower-than-normal intermediate waters [*Smith et al.*, 2008] or persistent drought during the preceding years [*Marty and Chiaverini*, 2010] were responsible for the 2006 Ligurian DWF event.

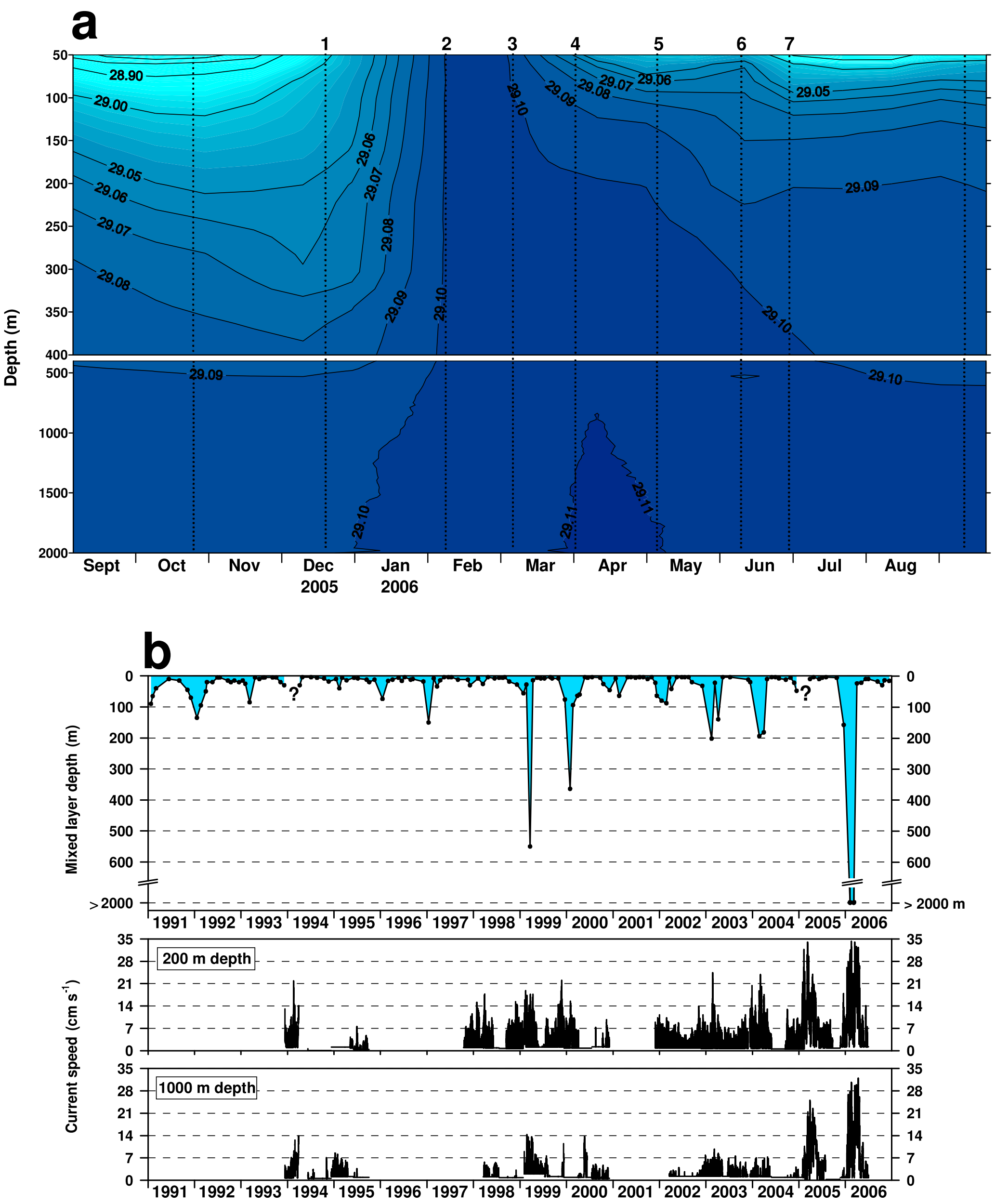

Figure 2. (a) Contour plots integrating potential density anomaly (σ_θ) at the DYFAMED station from autumn 2005 through summer 2006. Vertical dotted lines represent the dates and depths of measurements used to create the interpolated contours. Numbers on top of vertical lines will be recalled in Figures 3 and 4. (b) Time series of current speed at 200 and 1000 m depth and MLD at the site from 1991 to 2006. Question marks indicate winter periods where MLD could not be calculated due to missing or dubious data.

3.1. Observations

[10] The density vertical profiles at the DYFAMED site (Figure 2a) indicate that mixing of the water column down to at least 2000 m was achieved by the first days of February, but the mixing phase may have started by early- or mid-January 2006, judging from the notable intensification of current velocity and vorticity (Figure 3) that usually accompany the mixing phase [*Marshall and Schott*, 1999]. The sinking phase was apparently consummated by late March (as already suggested by *Smith et al.* [2008]), when the densest water was present at 2000 m depth (Figure 2a) and temperature increased at the seafloor (Figure 4). After the arrival of warm waters to the seafloor in March, near-bottom temperature decreased again but, instead of returning to the pre-mixing temperature range, remained 0.02–0.05°C higher, in agreement with observations of rapid and sharp warming of the Deep Western Mediterranean Water following the 2006 Ligurian DWF event [*Schroeder et al.*, 2008; *Marty and Chiaverini*, 2010].

[11] Previous to the mixing period (December 2005), the water flow at 200 m depth matched the SW direction characteristic of the main regional circulation [*Millot*, 1999], while currents at 1000 m and near the seabed were decoupled from the upper flow and from each other (Figure 3). From mid January, currents at the three levels

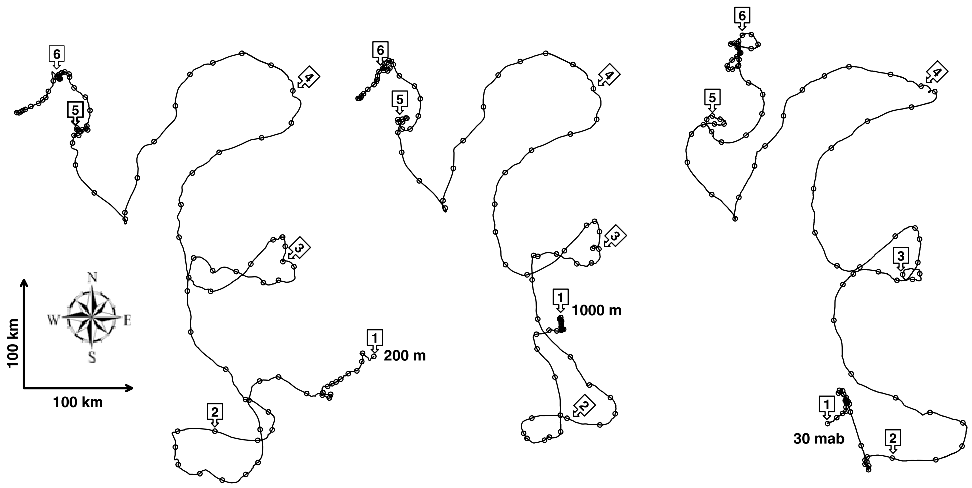

Figure 3. Progressive vector diagrams calculated from current meters deployed at the DYFAMED site at 200, 1000 m depth and 30 mab from 19 December 2005 to 2 July 2006. Arrows mark the dates of hydrological casts numbered in Figure 2a. Dots over the progressive vectors are spaced at intervals of 48 h.

tended to couple progressively and from March through May, both the direction and intensity of the currents were essentially mimicked from 200 m to the bottom at 2350 m, testifying to a very efficient transfer of energy and vorticity from the upper ocean to the seafloor. As a result, near-bottom currents were markedly intensified, particularly from February through April, reaching peaks up to 38.6 cm s^{-1} (Figure 4).

[12] In coincidence with the increase in current speed, the near-bottom sediment trap measured particle fluxes between one and more than two orders of magnitude above the average mass flux (20 mg m^{-2} d^{-1}) measured during similar deployments outside winter-spring 2006 [*Khripounoff et al.*, 2009]. A maximum flux of 9188 mg m^{-2} d^{-1} was measured during the last week of March. Up to this date, maximum mass flux at this benthic site was measured in spring 1996 (~570 mg m^{-2} d^{-1} at 4 mab) in association with currents ~20 cm s^{-1} at 12 mab [*Guidi-Guilvard et al.*, 2009].

3.2. Origin of the Near-Bottom Flux

[13] It is unlikely that the bulk of the flux measured by the near-bottom trap was the result of vertical settling from the upper ocean, since mass fluxes measured by the pelagic traps during this study were in the range 12.2–130.6 and 10.5–158.7 mg m^{-2} d^{-1} at 200 and 1000 m depth respectively. Also, time-weighted mean downward fluxes measured at the site from 1988 to 2005 are 94.9 and 87.4 mg m^{-2} d^{-1} (historical maxima 1228 and 893 mg m^{-2} d^{-1}) at 200 and 1000 m depth respectively, that is, two orders of magnitude lower than the near-bottom flux. It could be argued that the high current speeds could have led to underestimation of the settling flux measured by sediment traps. However, since all the traps were the same model and current intensities were similar at the 3 depths, hydrodynamic bias would also be similar in all the traps and hence it cannot explain the strong excess of near-bottom fluxes in comparison to the settling of pelagic particles.

[14] Hence, most of the particle flux collected by the near-bottom trap was presumably resuspended from the seafloor. The question remains as to which degree the particle flux was fed by in situ resuspension or by material resuspended from other locations affected by convection-induced resuspension and advected into the study area. Sediment focusing towards the DYFAMED site has been invoked in the past to account for mass and element imbalances between water column and sedimentary fluxes [*Martín et al.*, 2009]. A suggestion for an allochthonous contribution to the flux measured in winter-spring 2006 lies on the relatively high POC measured in the 20 mab trap. POC was between 0.9 and 1.5% during the highest flux pulses, while it has been recurrently found to be <0.6% in the topmost underlying sediments [*Martín et al.*, 2009; A. Khripounoff et al., unpublished results, 2010]. It is also noteworthy that the absolute maximum of near-bottom mass flux was not coincident with maximum current speed, but with maximum temperatures (Figure 4), suggesting the climax of the sinking+spreading phase and probably implying lateral particle inputs carried with the dense water as it spreads through the basin. It is plausible that the resuspensive effect of convection-induced turbulence proceeds from shallower to deeper areas as the mixing and sinking phases evolve, thus forming a bottom nepheloid layer fed with easily resuspensible particles from the continental slope that are dragged offshore within the newly formed deep water. Additionally, it has been claimed that the previous winter (2004–2005), cascading in the Gulf of Lions produced a bottom nepheloid layer that filled the entire western Mediterranean basin [*Puig et al.*, 2009]. This nepheloid layer may have provided the deep basin with important amounts of unconsolidated sediments that were subsequently resuspended by open sea convection the next year.

3.3. Extension and Recurrence of Deep Convection in the Ligurian Sea

[15] There is evidence that the episode of convection-induced enhancement of particulate flux described in this work affected substantial extensions of the Ligurian basin. Near-bottom currents and particle fluxes in the ranges presented here were observed simultaneously in several points on the adjacent continental slope [*Khripounoff et al.*, 2009]. Also at the ANTARES site, located in the western limit of the Ligurian basin (42°50′N; 6°10′E, 2400 m depth),

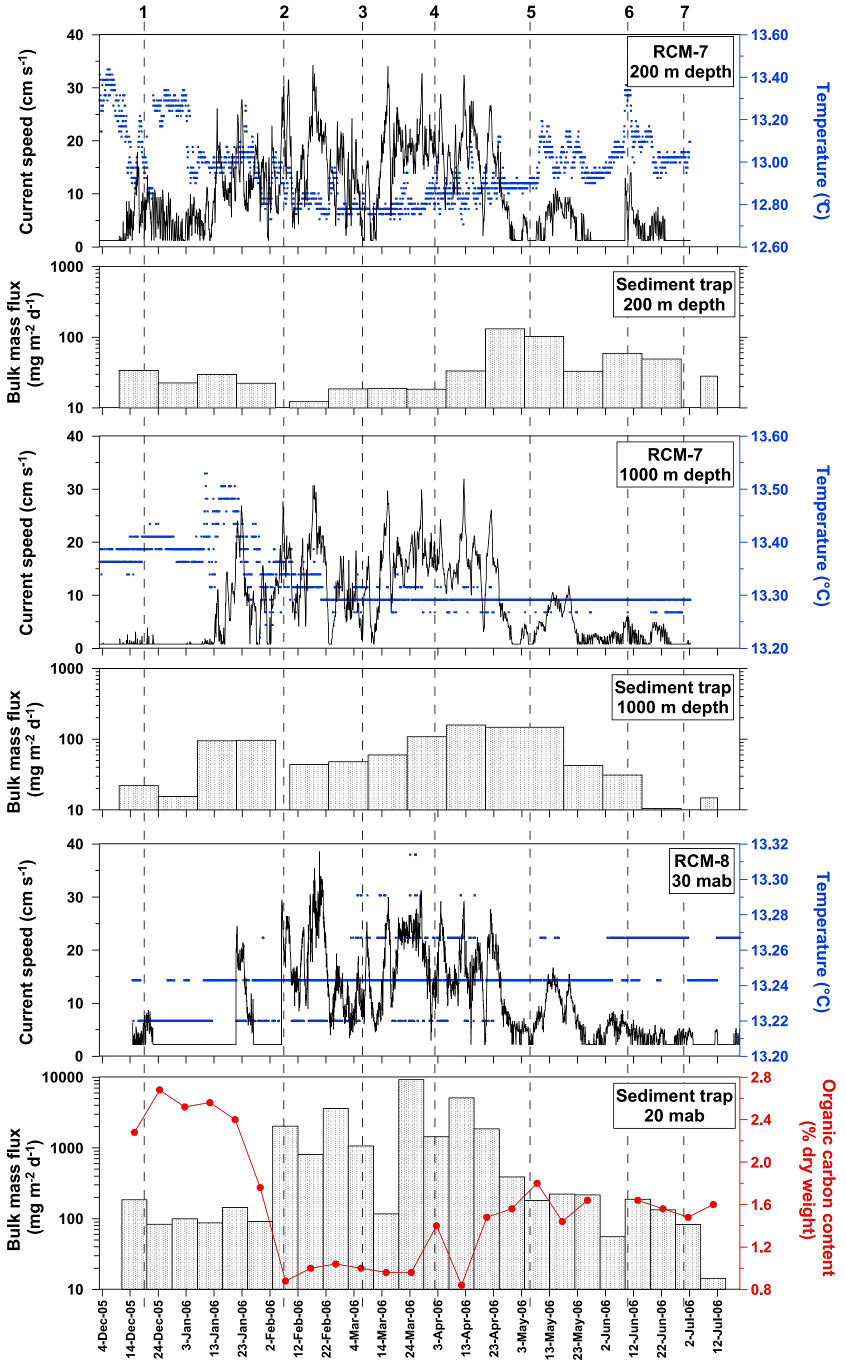

Figure 4. Time series of current speed (lines), temperature (dots), and particulate mass flux (bars), measured at the DYFAMED site from December 2005 through summer 2006. POC measured in the near-bottom trap (lines and dots) also shown. Total water depth is 2350 m. Vertical dashed lines correspond to the dates outlined in Figures 2a and 3. Note the logarithmic scale for mass flux.

increases of horizontal current speed and suspended matter loads of one order of magnitude were observed near the seafloor during the same period [*Aguilar et al.*, 2010].

[16] An important open question is the frequency with which episodes like the 2006 DWF can occur in the Ligurian Sea. Convective cells reaching depths up to 1200 m and 800 m have been described in the Ligurian Sea for February 1969 and February 1991 respectively [*Sparnocchia et al.*, 1995; *Buongiorno and Salusti*, 2000]. From 1992, the monthly observations at the DYFAMED site (Figure 2b) have documented shallower vertical mixings, until 2006. Deep convection during the first months of 2006 was stronger than any other previous year, not only for extending to more than 2000 m but also from the fact that this unusual situation was present along two consecutive monthly hydrological cruises (February and March 2006, Figure 2). Also, currents measured at 200 and 1000 m depth during winter-spring 2006 were stronger than ever in the available current meter time series (Figure 2b). A relevant episode of open sea convection, whose vertical extension is presently unknown to

us, occurred also during the previous winter 2004–2005. According to *Smith et al.* [2008] and *Marty and Chiaverini* [2010], convection during winter 2004–2005 in the Ligurian Sea, though remarkable, was less intense than in the following winter. Nonetheless, it is worth to note that horizontal current speeds at 200 and 1000 m depth during winter-spring 2005 were unusually strong and only comparable to the currents measured in 2006 (Figure 2b).

3.4. Consequences and Prospects

[17] In comparison to shallower subaquatic environments frequently disturbed by the action of tides, wind waves and storms, the deep sea is in general a physically stable environment. Therefore, processes able to resuspend and relocate deep sediments in a basin-wide scale become very relevant in a number of issues such as sedimentary dynamics, elemental cycling or benthic ecology. In the particular setting of the Ligurian Sea at the depths studied, water column mixing down to the seabed and the associated sediment resuspension/transport may be a novel or very infrequent process, based on the apparent uniqueness of the Ligurian 2006 DWF in the published literature.

[18] This study also suggests that open-sea convection should be considered, together with dense-shelf water cascading, as a major driving force for deep sedimentary dynamics in the MEDOC area, and eventually in other DWF regions of the global ocean.

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