Fast deep sinking in Mediterranean eddies

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[1] Large (up to 0.03 m s^{-1}) downward vertical water velocities (w) are observed using yearlong moored ADCP at ~2400 m in the deep Mediterranean Sea's Algerian basin. Once every 2–3 months, |w| rapidly increases to O(0.01 ± 0.002 m s^{-1}) before slowly decreasing during a few weeks, in association with the passage of mesoscale eddies formed nearby. These amplitudes of negative w are O(100) times larger than those commonly linked to mesoscale eddies near the surface (subduction), and O(10) times larger than settling velocities for marine snow. Our observations suggest that mesoscale eddies, which are important for biological productivity near the surface, can also convect nearly fresh material down to the bottom (~3000 m there) within a few days. **Citation:** van Haren, H., C. Millot, and I. Taupier-Letage (2006), Fast deep sinking in Mediterranean eddies, *Geophys. Res. Lett.*, *33*, L04606, doi:10.1029/2005GL025367.

1. Introduction

[2] In the ocean, vertical velocities (w) are usually very weak, typically O(10^{-5}–10^{-3} m s^{-1}), that is O(0.01–0.001) times horizontal current components (u, v). Exceptions of much larger w are reported from areas of dense-water formation [*Voorhis and Webb*, 1970; *Gascard*, 1973] known as chimneys (convection process). Even though the yearly mean negative w there is O(10^{-3} m s^{-1}), maxima up to 10^{-1} m s^{-1} are observed in the upper (<1000 m) part (at least) of relatively narrow and deep (both dimensions being O(10^3 m)) convection plumes [*Schott and Leaman*, 1991]. Because intense near-surface cooling lasts up to several days (wintertime gales' duration) and the horizontal advection speed is O(10^{-1} m s^{-1}), such convection displays a wildly fluctuating pattern with a typical time scale of several hours when observed at a fixed location. More persistent negative w are expected in meandering frontal areas (subduction process) associated with mesoscale eddies that are O(100 km) in diameter [*Allen et al.*, 2001]. However, values reported until now are restricted to the upper (<400 m) layer and are O(10^{-4} m s^{-1}). In contrast, our yearlong 75 kHz acoustic Doppler current profiler (ADCP) observations (mooring characteristics in Table 1) are from much larger depths (2000–2400 m) in an area (south-western Mediterranean Sea) not affected by any convection process. In the present paper we discuss relatively large vertical velocities and the consequences for vertical transport of biological material.

[3] Major processes in the study area (off Algeria) are linked to the dynamics of the Algerian Current that is 200–400 m thick. This current, which is relatively warm in winter, tends to flow alongslope counterclockwise and is baroclinically unstable, hence generating mainly mesoscale anticyclonic eddies that propagate downstream at a few km/day (i.e., a few 10^{-2} m s^{-1}). Several times per year, some eddies become relatively large (100–200 km in diameter; see Figure 1), being characterised by horizontal currents up to ~1 m s^{-1} in the surface layer (down to the pycnocline at ~200 m). However, these anticyclonic eddies also extend across the entire deeper layer (200–3000 m), with typical horizontal velocities up to ~0.05 m s^{-1} that are in phase and nearly constant down to the bottom [*Millot et al.*, 1997]. This very specific characteristic could be due to a pressure gradient (surface elevations O(10^{-1} m)) that is not fully compensated by a lowering of the interface [*Obaton et al.*, 2000].

[4] One consequence is that, due to their large size and deep extent, these eddies cannot propagate downstream embedded within their parent current through the Channel of Sardinia that is relatively narrow at depth (see isobaths in Figure 1); hence, they follow the deep (>2000 m) isobaths and proceed north before looping in the Algerian subbasin. This eddy's propagation speed of 5.5 ± 1.5 km/day during the period in Figure 1 was relatively large (compared to a 2–4 km/day usual speed) [*Obaton et al.*, 2000; *Millot and Taupier-Letage*, 2005].

[5] Another consequence is that, in the whole deeper layer within such an eddy, the measured current basically results from the superposition of the current induced by the (mesoscale, anticyclonic) eddy and the current induced by the (permanent, alongslope, counterclockwise, basin-scale) circulation. Even though the circulation-induced horizontal current has average amplitudes of 0.05–0.1 m s^{-1} in the study area at 2000–3000 m, it can be smaller there than the eddy-induced current, hence leading off Algeria and, in the southern part of an energetic eddy, to a resulting (measured) current reversing from eastward to westward, sometimes for months [*Millot and Taupier-Letage*, 2005].

2. Data

[6] An upward looking 75 kHz, four-beam ADCP was moored with its head at ~2400 m southwest of Sardinia in the western basin of the Mediterranean Sea (mooring characteristics in Table 1). Due to unexplained reasons, the w signal showed a negative bias of $-4 \cdot 10^{-3}$ m s^{-1} throughout the measurement range, so that we corrected w to get a zero average over the entire period. This negative bias is very close to previously reported ($-3 \cdot 10^{-3}$ m s^{-1}) offset of upward-looking ADCP's [*Schott and Leaman*, 1991].

[7] This bias could have been due to variation of the attitude parameters (pitch, roll) that are measured with an accuracy of a few 0.1°. However, according to tilt sensor information the mooring did not move more than ~1.2 ±

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Table 1. 75 kHz Upward Looking ADCP Mooring Details

Property	Value
Latitude	38° 26.967′N
Longitude	007° 39.883′E
Water depth	2840 m
Deployment	03/10/2003
Recovery	08/09/2004
Beam spread	20°
Instrument depth	2428 m
First cell	2395 m
No. cells × cell size	60 × 8 m
Ensemble period	900 s
Std u, v	$1.1 \cdot 10^{-2}$ m s^{-1}/ensemble
Std w, err	$0.28 \cdot 10^{-2}$ m s^{-1}/ensemble

0.2° (or ~0.2 m in the vertical), so that for typical horizontal currents $|u_h| = (u^2 + v^2)^{1/2} = 0.05$ m s^{-1} a maximum bias in w of $1.2 \cdot 10^{-3}$ m s^{-1} is expected, only. Moreover, no correlation was found between records of tilt and w.

[8] The w-data (noise) quality is further verified using the additional 'error velocity (err)' parameter, defined as the difference between the two w computed from the two beam pairs multiplied by a scaling factor [*van Haren et al.*, 1994] for proper comparison with w. Heterogeneities in u, v, w between the slanted ADCP beams, for example caused by an object obstructing one or more beams, will affect w measurements when err → w. As $|w| > 10|err|$ is observed at 2350 m (Section 3), we conclude that w is significantly measured. As a result, good quality low-frequency (~daily averaged) w are expected to a relative accuracy of $\sim 3 \cdot 10^{-4}$ m s^{-1} (Table 1, in which error levels for 15 min periods are given), nearly two orders of magnitude less than the observed amplitudes.

[9] In addition to the current data, the ADCP's acoustic backscatter signal (I) is used, although only relative to the time mean $\langle\ \rangle$ at every depth level: $dI = I - \langle I \rangle$.

3. Results

[10] As we lack thermistor string observations, the passage of eddies is best observed in variations in horizontal currents. At all levels (8 m intervals) where we got ADCP data in the depth range 1900–2400 m, 11-month mean currents are directed toward NNW (along the isobaths) and have amplitudes of $4.5 \pm 1 \cdot 10^{-2}$ m s^{-1}. During the experiment, some moderately energetic eddies such as the one in Figure 1 propagated (toward NNW too) over the mooring, the eddy's center passing either to the west or to the east of it. In such a situation, an anticyclonic eddy induces a mesoscale current that is basically first eastward and then westward. Therefore, when an eddy is passing by, the measured current first deflects from NNW to N (eventually NE), then it comes back to NNW and deflects to NW (eventually W) before regaining the NNW direction. This deflection was observed (Figure 2), and always while eddies where passing by (as indicated by images (not shown) as the ones in Figure 1).

[11] Together with these features, it is clear from the three most energetic events displayed in Figure 2 that, a few days after the first (clockwise) deflection, w at all available levels (Figure 3) rapidly becomes significantly downward and its amplitude increases up to extremely large values $O(10^{-2}$ m $s^{-1})$ before going back to nearly zero values within a few weeks. As illustrated in Figure 1, such a few-weeks period

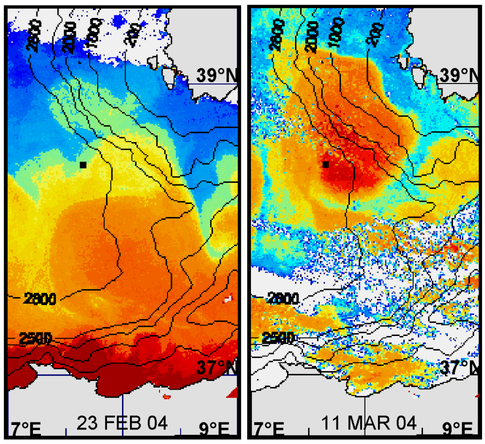

Figure 1. Sea-surface temperature from AVHRR radiometers housed on NOAA satellites on 23 Feb 2004 while the eddy was just reaching the mooring (solid square) and 11 Mar 2004 while it was centred north of it. The area displayed is SW of Sardinia (visible in the upper-right corner) and north of Algeria (coast visible at the bottom). Images are presented with different colour-coding for temperatures, enhancing the visualisation of the structures. Temperatures range from ~12°C (dark blue) to ~15°C (dark red).

roughly corresponds to the time an eddy is over the mooring. In addition to the fact that these values are O(100) times larger than the mesoscale subduction velocities in near-surface layers [*Allen et al.*, 2001], it must be emphasised that they are observed in the deep (2000–2400 m).

[12] Instead of the irregular variations commonly observed in dense-water formation areas [*Schott and Leaman*, 1991], we observe a dominant low-frequency w signal that even clearly stands out from raw data (Figure 3

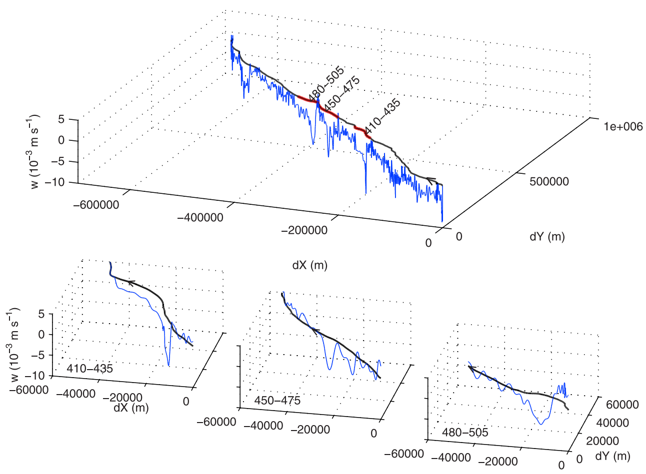

Figure 2. (top) 340-days ADCP record at 2372 m of low-pass filtered horizontal current progressive vector diagram (black), starting at arbitrary (0, 0), and the associated w (blue). (bottom) Periods of relatively large downward w (each starting at arbitrary origin) following a deflection of the horizontal current to the right. In these panels the low-pass filtered w is mean-corrected. The filter cut-off was at 0.7 cycles/day (about half the local inertial frequency).

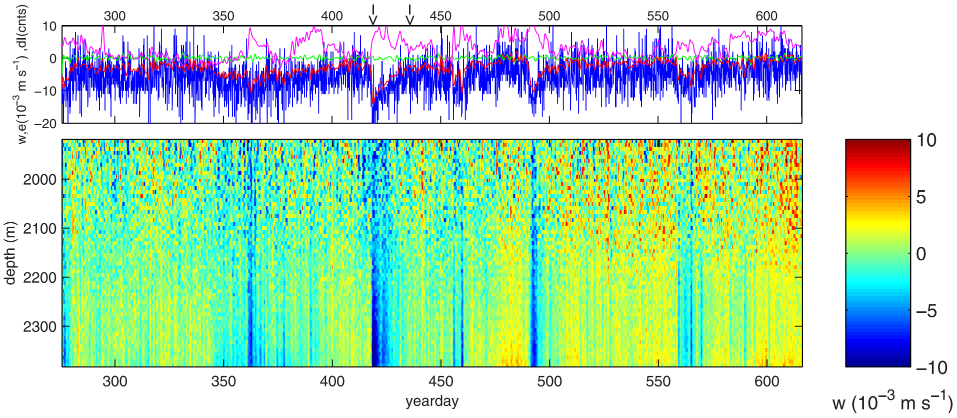

Figure 3. (top) Time series of ADCP data at 2372 m: raw w (blue), and low-pass filtered and vertically offset w (red), error velocity (green), relative backscatter (purple). The arrows indicate days of images in Figure 1. (bottom) Depth-time series of low-pass filtered and mean-corrected w. Time is in yeardays starting in 2003 (2004-days are >365).

(top)). Six periods of low-frequency large downward w are recognized in the 340-day time series. Their distribution is more or less evenly distributed over the year, so that there is no seasonal variation, consistently with what occurs for the generation of the mesoscale eddies [*Millot and Taupier-Letage*, 2005]. Such characteristics resemble those described for near-surface subduction at the edges of an eddy and are not associated with convection. Most of these periods appear highly asymmetrical with time: first a sharp decrease is observed, with w attaining its minimum value (down to $-3.1 \cdot 10^{-2}$ m s^{-1} at 2370 m, day 418) within <12 hours, followed by a much slower relaxation to reduced amplitudes over typically 5–15 days. The mean bias-corrected w between days 418–423 at 2370 m is $-0.85 \cdot 10^{-2}$ m s^{-1}.

[13] These periodically large downward w are found in phase throughout the whole 480-m range, also in the noisy data range far from the ADCP (Figure 3 (bottom)). However, at large distances from the instrument (<2200 m), the low dI in these deep layers induces some expected additional bias. With time, and especially in the depth range 2200–2400 m where mean echo intensity was generally larger than instrumental noise, large downward w are always associated with increases in dI (Figure 3 (top); note that dI is occasionally large when |w| is not enhanced). This correspondence clearly suggests that these periods of intense subduction are associated with a relatively large amount of suspended material, hence that the subduction originates far above these deep layers.

4. Discussion

[14] Our observed large negative w O(10^{-2} m s^{-1}) are not due to instrumental errors following the lack of correspondence with tilt or err. The w are also unlikely to be associated with the estimated sinking of (aggregated) particles, which are O(10^{-3} m s^{-1}) for marine snow [*Lampitt et al.*, 1993] and $0.5–2 \cdot 10^{-3}$ m s^{-1} for diatoms [*Passow*, 1991], the fastest sinking phytoplankton species. We are also unaware of any coordinated zooplanktonic migration that persists for days at such great depths ($\gg$500 m, the common migration limit). As a result, we conclude that sinking particles are not explaining the observed w.

[15] The present observations were made in a deep layer that is homogeneous between ~1900–2840 m (the sea floor) [*van Haren and Millot*, 2004], for which we assume that the observed w are uniform (no stratified turbulence) as indeed is observed in the upper half of this range. As a result, using corrected w observed at 2370 m, w(2370), a particle released at 2000 m on day 418 will arrive at the sea floor within ~0.5 day. From the weakly stratified layers above we have no observations of w. However, it seems not unreasonable to assume continuity of the low-frequency (sub-inertial) motions across the transition between stratified and homogenous layers. Thus, still using corrected w(2370) and speculating to give orders of magnitude, particles released at the surface in the position of the edge of the eddy passing the mooring on day 418 will reach the sea floor within ~1.5 days, while those released at the surface above the mooring on days 455 and 490 will reach the bottom within ~3.5 days and ~7.5 days, respectively.

[16] The above (extrapolated) observation suggests the possibility of a supply of nearly fresh plankton material to deep layers. Such supply will not only be fresh but also abundant, because mesoscale eddies can show, locally, primary production rates larger than their environment that is attributed to favourable nutrient supply to the surface from the deep [*Williams and Follows*, 1998; *Fielding et al.*, 2001]. It could also explain episodic large downward particle fluxes of contaminant polycyclic aromatic hydrocarbons (PAH) that were recently inferred from sediment trap samples at 250 and 2850 m, in the same area [*Bouloubassi et al.*, 2006]. For some unexpected PAH-fluxes in summer sinking rates were estimated larger than 10^{-3} m s^{-1} for the 30 days averages, which is O(0.1–1) times our direct observations for shorter periods, but not small.

[17] Considering the systematic occurrence of mesoscale eddies in the southern Mediterranean Sea, and in most places of the global ocean as well, such a near-bottom supply will be repeatedly occurring. Finally, in case a barotropic forcing, such as the one hypothesised for the Algerian eddies [*Obaton et al.*, 2000], is the dominant forcing in other places, it is not surprising that the supply there should be found down to the sea floor too, whatever the value of vertically invariant w. Therefore, future modelling of production rates should include the presently

observed vertical subduction, which is much faster and deeper than estimated hitherto.

[18] In addition, comparing a 12-hour duration of the w decrease (from background values down to $\sim -3 \cdot 10^{-2}$ m s^{-1}) with a ~6-km/day propagation speed of an eddy leads to assume the existence of a ~3-km wide "frontal edge" where the subduction occurs, which is extremely thin compared to the ~100–200-km eddy diameter. This would explain the (un-measurably) small upwelling $w \sim +3 \cdot 10^{-4}$ m s^{-1} outside this frontal edge, assuming continuity. Finally, although we expect $w < 0$ in a thin edge ring around the entire eddy, the observed weaker values near the "rear edge" suggest that such a mesoscale eddy was creating some kind of a wake away from the coast in the whole deep layer.

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