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Slantwise convection: A candidate for homogenization of deep newly formed dense waters

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[1] Observations between 1000 and 2750 m, from a site in the 2800-m deep part of the western basin of the Mediterranean Sea located in between the Provençal and Algerian subbasins, indicate large variations in water mass properties and stability that are associated with, but not directly caused by, dense-water formation to the north of the site. These variations are apparently dominated by local convection induced by small-scale eddies and propagation of inertial waves in stratified and homogeneous layers. Hereby is the horizontal component of Coriolis parameter important, governing slantwise, tilted convective mixing. This mixing creates marginally stable deep waters that are as spicy as near-surface waters. It is found across some 200–400 m thick layers, which thickness is beyond the typical vertical buoyancy scale relevant for double diffusion. The observed convection is hypothesized to be important for dense-water formation away from near-surface sources, modifying the ocean's lower half.

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1. Introduction

[2] Cold and dry northwesterlies, blowing in winter in the western basin of the Mediterranean Sea between Pyrenees and Alps, make surface waters denser in the Gulf of Lions and the Provençal subbasin (Figure 1a). Offshore convection in the latter [*Schott and Leaman*, 1991] has always been assumed [e.g., *Millot*, 1999] to be more efficient than cascading from the former, even when observations over shelf and slope show intense cascading, such as during the 2004–2005 winter [*Canals et al.*, 2006]. During that winter, huge amounts of dense waters were thus formed in both areas before spreading in the deeper part of the Provençal subbasin [*Font et al.*, 2007] and the Algerian subbasin. Here, we investigate such newly formed deep waters away from their formation areas, and we contrast them with local internal mixing. We analyse CTD and moored current-meter observations obtained in between Provençal and Algerian subbasins from April 2005 to February 2006.

[3] In any convective area mixing will initially occur vertically, in the direction of gravity (Figure 1b, dash-dotted line). After some time, the vertical plumes will become affected by the rotation of the Earth Ω, due to the high aspect ratio by its horizontal component $f_h = 2\Omega\cos\varphi$, φ the latitude, besides the more familiar inertial frequency $f = 2\Omega\sin\varphi$. Except at the pole, this will result in a tilting over angle $\pi/2-\varphi$ with gravity (vertical, z) of a convective tube, so that constant density layers become aligned with constant momentum surface M along Ω (Figure 1b, solid line): [planetary] slantwise [vertical] [*Straneo et al.*, 2002] or 'tilted' [*Sheremet*, 2004] convection. If stratification is any larger than that due to alignment along Ω it will be stable in a slantwise convective sense (Figure 1b, dotted line). The minimum stratification N_{min} for which planetary slantwise convection just about cannot occur is estimated at $N_{min} = 2f_h$ or $4f_h$, depending on the stability model used, except near the equator $|\varphi| < 1.5°$ [*van Haren*, 2008]. Note that this convective mixing does not necessarily commence near the sea surface but also in its interior, i.e., in weakly stratified layers capped by well-stratified ones.

[4] The above process bears resemblance with slanted [horizontal] convection in strongly stratified shear flows [*McIntyre*, 1970], in which shear dominates over f_h (Figure 1c). This convection follows horizontal differential advection, e.g., across fronts and boundary currents [*Ruddick*, 1992]. It occurs in rather thin O(1–10 m) stratified layers, alternated by slightly thicker double diffusive layers. These layers are tilted at only a few degrees to the horizontal. In areas like the Arctic the weakly stratified layers may grow up to 60 m thick, but the aspect ratio is still very low [*Walsh and Carmack*, 2003]. This layering is similar to that found in the present Mediterranean data between about 300 and 1200 m, but we do not consider it here. Different are the O(100 m) thick layers below 1200 m that are discussed in this paper. However, the two processes are related, of course, in their stability balance.

[5] Convection involves wide ranges of space and time scales, leading to mid-depth vertical velocities of several 10^{-2} m s^{-1} [*Schott and Leaman*, 1991] and horizontal velocities up to 0.5 m s^{-1} near the bottom [*Millot and Monaco*, 1984]. There, it forms Western Mediterranean Deep Water (WMDW) involving relatively warm and salty waters originating from the eastern basin such as Levantine Intermediate Water (LIW) and Tyrrhenian Dense Water (TDW) that is warmer, saltier and less dense than WMDW. Waters cascading from the shelf are initially fresher and cooler, but they markedly mix with the previous ones over the slope since in a basin all waters are driven by horizontal density gradients along the isobaths counterclockwise, due to the earth rotation [*Millot*, 1999].

[6] The consequent heterogeneity of hydrological characteristics that must thus be expected in and close to a dense water formation area, originating near the surface, is intensified in the deep when densest waters reach the bottom, before mixing progressively along their route and being

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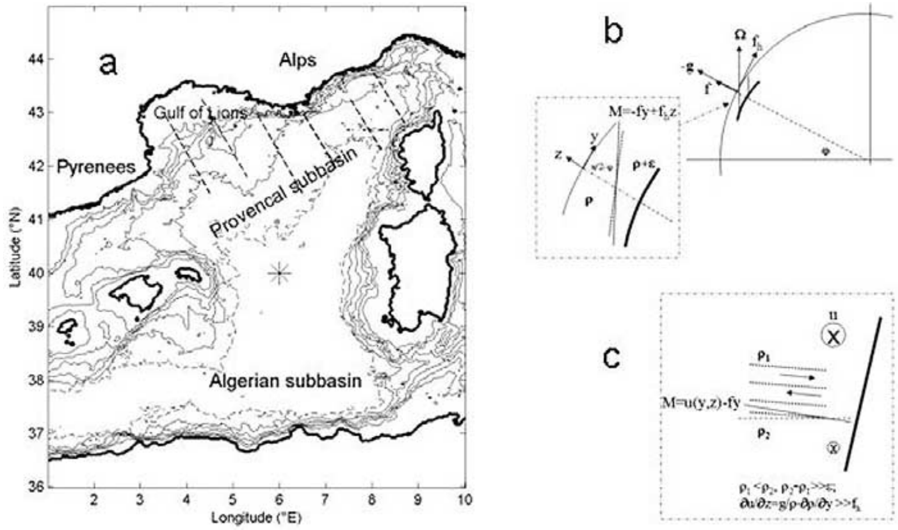

Figure 1. (a) Western Mediterranean Sea with observational site marked by an asterisk. Depth contours every 500 m, for [500, 2500] m and 2750 m contour. Hatched indicates area of dense-water formation. (b) Sketch of planetary slantwise vertical convection in weak stratification when surfaces of constant density (ρ) align with surfaces of constant momentum M (solid line), instead of vertical (dash-dotted) or less inclined to the horizontal as in stronger stratification (dotted). (c) Sketch of slanted horizontal advection in strong stratification, which becomes tilted in baroclinic shear flows in thermal wind balance.

finally uplifted by more recent and denser water. Another spreading from the convection area is associated with small-scale O(1–10 km) sub-surface eddies [*Testor and Gascard*, 2003]. In the vicinity of dense water formation areas, a marked heterogeneity of dynamical characteristics is therefore also expected.

[7] The heterogeneity in hydrological and dynamical characteristics occurs in the deep over large depth ranges of O(100–1000 m) where density gradients are weak. Therefore, small-scale eddies may create local vertical convection just like meso-scale eddies [*van Haren et al.*, 2006], although after times of dense water formation and over a much longer period. One must also consider inertio-gravity waves (IGW) that can transit without attenuation between stratified and homogeneous layers O(100 m) thick [*van Haren and Millot*, 2004]. IGW at f always pass the transition between such different layers without attenuation, regardless of their orientation in the horizontal plane. In homogeneous layers, IGW vertical velocities, notably w(f), show ratios w/(u, v) of 0.1–1, occasionally even >1 [*van Haren and Millot*, 2005], which thus create convective plumes like small-scale eddies. Here we hypothesize that such eddies and/or inertial IGW induce slantwise convection for dense water formation in deep weakly stratified areas away from near-surface sources in order to explain similar water mass characteristics in homogeneous and stratified waters.

2. Data and Observations

[8] A mooring equipped with 6 single-point current meters immersed between 1685 and 2720 m, was deployed at 49°0′N, 6°0′E (H = 2760 m) from 13/04/2005 to 12/02/2006 (Figure 1a). During the deployment/recovery cruises, 3 to 5 SeaBird-911 CTD-profiles were obtained near the mooring in a yoyo-fashion within a 3–4-hour delay while the ship was kept by motor within ~1 km from the mooring. Yoyo-ing was performed between about 1400 and 2500 m, due to cable limitation, in 2005 and between 1000 and 2750 m in 2006 (several 2006 downcasts were very noisy for unknown reason and are not considered further).

[9] Detailed profiles show substantial variations in hydrographic properties during each cruise and between the two cruises (Figure 2). Compared with observations in the Algerian subbasin, where an 800-m thick homogeneous layer is generally observed below 2000 m [*van Haren and Millot*, 2004], a similar but slightly less thick σ-homogeneous layer is observed here while being higher in the water column (1700–2400 m in 2005 and 1600–2100 m in 2006; Figure 2a); note that, in 2005 in particular, this σ-homogeneous layer can be markedly heterogeneous in both T and salinity S (Figures 2b and 2c), while a relatively thick stratified layer is found below, clearly in 2006 and very probably in 2005. The former being significantly older (oxygen content about 75% saturation; Figure 2d) than the latter (80%), the same homogeneous layer has probably been sampled in both the study area and the Algerian subbasin. This layer is in fact uplifted by more recent, less homogeneous and denser waters that circulate in the area. These more recent waters feed the deeper layer of the Algerian subbasin [*Millot*, 2009].

[10] The T-variability with depth and time (Figure 2b) is consistent with moored T and current C variability (Figure 3), which basically indicates two different periods before and after days 260–270. The first period shows large T, C small-scale eddy fluctuations, while the second is more quiet but still shows significant T- and C-variations dominated at f. C is markedly barotropic in both σ-homogeneous and -stratified layers as well as during both periods (Figure 3d). Such overall features indicate either that the general circulation in the study area suddenly changed during days 260–270, first rapidly advecting at on average 0.07 m s^{-1} an

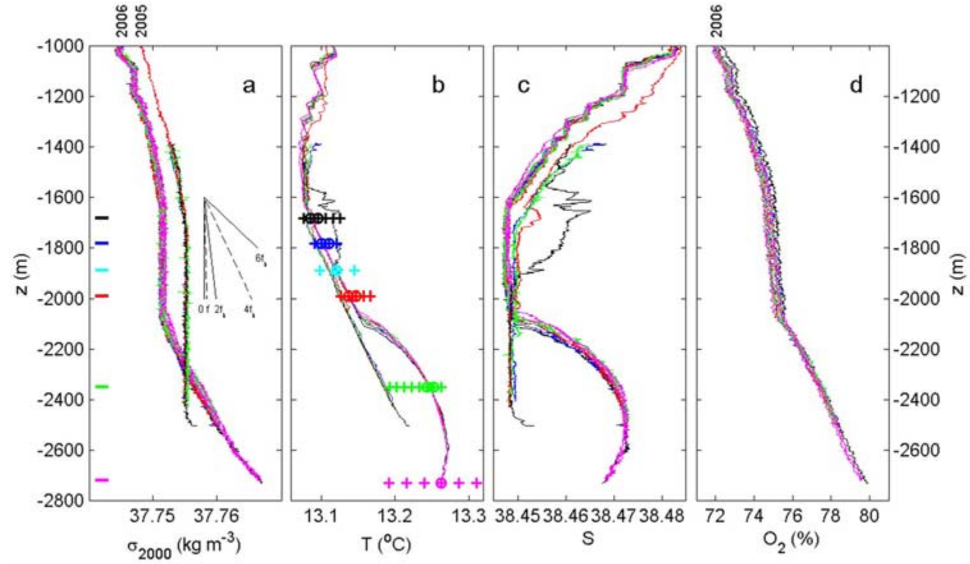

Figure 2. CTD-4 h yoyo-data from April 2005 (all down- and up-casts shown) and February 2006 (less variable data; only one downcast in green). Data are not off-set deliberately. (a) Potential density anomaly (to 2000 dbar) together with particular slopes, immersions of moored instruments (same color as in Figure 3). (b) In situ temperature. Moored data during the first day are indicated by pluses, and those during the last 10 days are indicated by circles. (c) Practical salinity. (d) Oxygen saturation, for 2006 only.

eddy field (maximum current speeds 0.3–0.45 m s^{-1}) then slowing down markedly, or that some kind of large-scale front permanently separated an active zone from a much quieter one, the front having passed over the mooring during days 260–270 (we cannot decide between both hypotheses from our single-point observations).

[11] In the relatively cool homogeneous layer, T can increase in its upper part, when the stratified layer above sinks temporally or spatially, as well as in its lower part, when the near-bottom stratified layer is uplifted, as well as, perhaps, from the sides. For example, between days 190 and 210 T is constant at the upper three levels while T(1980 m) increases above its adiabatic value and deeper Ts are not at their adiabatic values: the bottom layer moved upward, higher than 1980 m. Inertial motions have small amplitudes in this period. Relatively large near-bottom f-motions are observed at days 138 and 146 (Figure 3b), implying that they can be transferred through homogeneous layers, there-

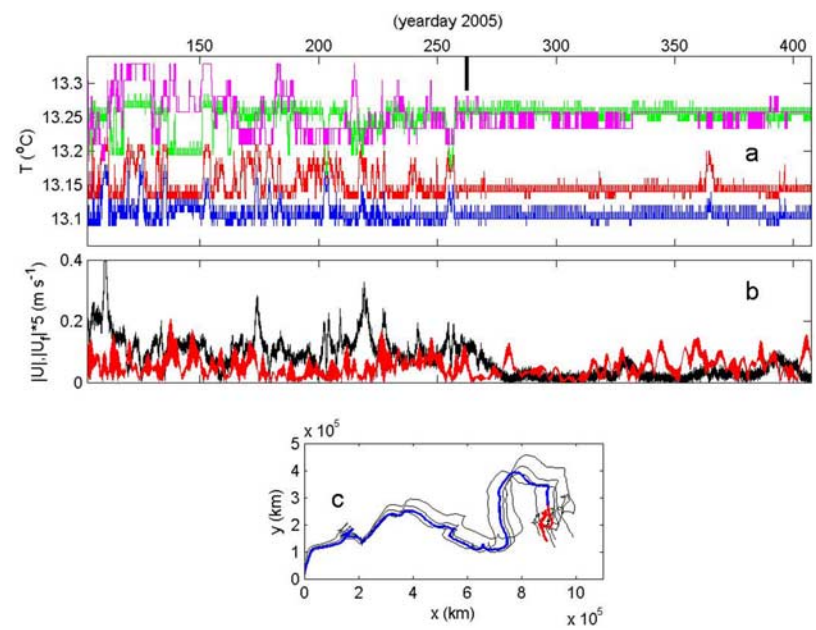

Figure 3. (a) Some T time series (yearday 0.5 = 12 UTC, 1 January 2005 and days in 2006 are +365) using color-coding of instruments' depths in Figure 2a. T-data are calibrated using 2006-CTD. (b) Total current amplitude at 1700 m (black) and band-pass filtered |C| at 2700 m (red). (c) Progressive vector diagrams: first half of record (blue) and second half (red).

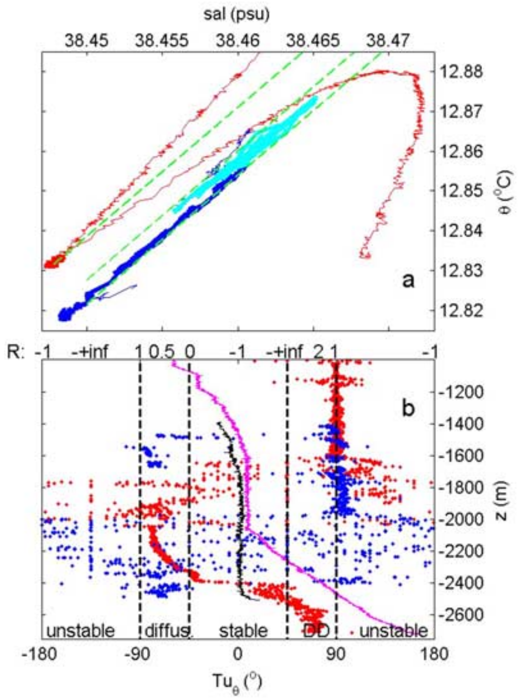

Figure 4. Stability and mixing from CTD-4 h yoyo-data. (a) Potential temperature-salinity diagrams representative of 2005 (blue) and 2006 (red). Thick portions of both diagrams correspond to the large σ-homogeneous layer, while the light-blue 2005-portion corresponds with 1550–1700 m part of upper stratified layer. Dashed-green lines indicate constant density anomalies referenced to 2000 dbar. (b) Density R and Turner angle for profiles in Figure 4a. For reference, their properly colored density profiles from Figure 2a are given (arbitrary scale): in Figures 4a and 4b red profiles correspond to the purple 2006 density anomaly, and blue profiles correspond to the black 2005 density anomaly.

by moving water up and down. After day 270, T(2350 and 2700 m) are not at adiabatic levels, despite little variations with time. In this 'quiescent' period vertical variations remain occurring.

[12] Such rapid variability is also seen between individual yoyo-profiles, which show different T and S characteristics. While σ-anomaly remains virtually unchanged during each group of yoyo-profiles (Figure 2a), T and S variations (Figures 2b and 2c), confirmed by the 1st and last 10 days of moored data, suggest that slantwise convection governs these resulting in the observed σ-compensated heterogeneity in T, S.

[13] Comparisons between 2005 and 2006 CTD casts are made using θ-S diagrams (Figure 4a). The 1600–2100 m homogeneous layer in 2006 is concentrated in a small θ-S-portion and probably corresponds to those values that, in 2005, were the coolest and freshest in the lower part of the σ-homogeneous layer: they clearly indicate relatively old WMDW that might have transited through the Algerian subbasin. The deeper 2006-stratified layer shows more recent water, formed in the north during the 2004–2005 winter, that can be considered as new WMDW influenced by LIW and TDW, either markedly, near T- and S- intermediate maxima, or slightly, near T- and S-minima near the bottom.

3. Discussion

[14] Most eye-catching T and S variations in our CTD profiles (e.g., black and red 2005 profiles, Figure 2) are larger than instrumental noise (0.001°C, 0.0015) and occur in both the upper stratified layer (above 1700 m) and the σ-homogeneous (1700–2100 m) one, apparently not affected by the transition in density. This implies density compensation that might be different at different depths. The stratified layer above the large σ-homogeneous layer has buoyancy frequencies $N \approx 2f_h$ in both 2005 and 2006. We find $N \approx 4f_h$ below 2400 m in 2005 and 2050 m in 2006. Both N-values are equal to minimum values for stability along Ω [*van Haren*, 2008]. This σ-compensated heterogeneity in T, or better potential temperature θ, and S observed in the deep resembles the one commonly observed in the surface mixed layer [*Rudnick and Ferrari*, 1999]. There, it is attributed to horizontal shear dispersion, slumping and mixing processes resulting in a density ratio $R = \alpha\Delta\theta/\beta\Delta S = 1$, α and β denoting expansion coefficients of heat and salt, respectively. From enthalpy arguments, 'conservative temperature' must be used in weakly stratified layers [*McDougall et al.*, 2009]. However, differences in using θ are not measurable so that we consider R (as $\alpha\Delta\theta/\beta\Delta S$), and Turner angle [*Ruddick*, 1983; *McDougall et al.*, 1988], $Tu_\theta = \tan^{-1}((\alpha\Delta\theta - \beta\Delta S)/(\alpha\Delta\theta + \beta\Delta S))$.

[15] As shown in Figure 4b, we find R = 1 (Tu_θ = 90°) between 1000 m and the top of the homogeneous layer near 1600 m in 2006, even down to 2000 m within that layer in 2005. R = 1 contrasts with R = 2 that is typically found in the stratified layers of the global ocean, below the surface mixed layer all the way to the bottom [*Schmitt*, 1999]. In our data, the situation is relatively complex below 2000 m in 2005 and between 1600 and 2400 m in 2006 ($-\inf < R < 1$). We find $R \rightarrow 2$ only deeper than 2600 m in 2006.

[16] R = 1 is a result of density compensation in which θ-S correlations provide water that has large 'spice τ', which reads in relative form [*Veronis*, 1972] as, $\delta\tau = \beta\delta\theta - \alpha\delta S$. Spice exaggerates what already has been observed in Figure 2: it emphasizes heterogeneity in θ and S even though density may be homogeneous. Our data of spicy R = 1 evidence slantwise convection, at least according to *Sheremet* [2004], who interpreted similarly spicy data collected by *Pickart et al.* [2002] in strongly convective and thus σ-homogeneous near-surface waters of the Labrador Sea. In our θ-S diagram (Figure 4a) it is clearly seen, on the 2005-profile, that the mixing observed here implies switches between different isopycnals. The transfer between such isopycnals is partially diapycnal and partially isopycnal and in a similar direction in either σ-homogeneous or stratified layers; note that this direction in 2005 is equal to the θ-S path in the diffusive portion of the lower stratified layer in 2006.

[17] Figure 4b shows that the water column is marginally stable with clear suggestions for double-diffusive (DD) convection and Rayleigh-Turner instability. This can be inferred from the 2005-profile between 1400 and 1950 m, i.e., from the upper stratified layer well into the large σ-homogeneous layer, and from the 2006-profile above

1600 m, i.e., within the upper stratified layer. Likewise, the 2006-profile indicates a diffusive unstable layer between 2000 and 2400 m, i.e., in both σ-homogeneous and lower stratified layers, some stability between 2400 and 2500 m, and some weak DD-instability or salt-finger regime below 2600 m associated with R = 2, where $N > 4f_h$. As a result, the expectation that σ-homogeneous layers are unstable and stratified layers are stable in a static sense is not found true from our data. Even though the 2005 and 2006 sets of CTD profiles did correspond to different distributions of water mass properties, as supported by the time series, they show large similarities in stability and heterogeneity.

[18] The CTD casts supported by T-time series that we collected at 1000–2700 m in between the Provençal and Algerian sub-basins thus demonstrate density-compensated heterogeneity in T and S, presumably due to deep local convection across the transition between σ-stratified and -homogeneous layers. In the present case, this is verified across the transition to a deep thick (>100 m) density-homogeneous layer. These waters are spicy, thereby resembling typical near-surface waters. As temperature variations continue to persist from spring through summer to autumn, the underlying convection process cannot be associated directly with dense-water formation. In the second part of the observational period mainly, one quasi-deterministic oscillatory, i.e., the inertial, current component, dominates in the absence of large tides. Under weak stratification, N being a few times f_h, no longer gravity but the earth's rotational axis sets the direction of free convection: 'slantwise convection' leads to non-zero stratification in the vertical [*Straneo et al.*, 2002; *Sheremet*, 2004]. As inertial motions and small eddies transfer energy between homogeneous and weakly stratified layers without attenuation, thereby attaining a relatively large vertical component, they can initiate similar convective mixing in stratified, i.e., slantwise-homogeneous, and vertically homogeneous layers, resulting in continuous spice across the stratification interface, for example.

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