Low-frequency vertical motions in the Medoc area of deep water formation

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ABSTRACT

In the area of deep water formation of the North-Western Mediterranean, estimates of low-frequency vertical motions are made from measurements of horizontal current and temperature on a single mooring, and from daily CTP measurements. The vertical velocity is evaluated in the geostrophic approximation, and on the basis of the "density" conservation equation. Although the number of observation levels is not sufficient to permit accurate estimation, the estimated vertical velocity seems to be in a significantly upward direction (~1 mm/sec) during the period of Winter-Spring 1977 (February-April). This fact, together with earlier direct measurements of vertical current (Stommel, Voorhis, Webb, 1971), suggests that the motions are generally upward in this surface "divergence" area; previously observed rapid sinking motions are probably Winter-time "episodic" phenomena, caused by the sinking of short-lived "puffs" of dense water.


INTRODUCTION

In the North-Western Mediterranean, a three-layer system is generally present: a surface layer (0-200 m), marked by waters of Atlantic origin; an intermediate layer (200-500 m) of relatively warm and salty water formed in the Eastern Mediterranean; and a deep layer of nearly homogeneous Western Mediterranean deep water (Lacombe, Tchernia, 1972). A persistent feature of NS hydrologic sections in this region is the doming of isopycnals. This doming is related to the cyclonic circulation of the currents, in which the upper two layers take part. The apex of the dome is usually found about 110 km off the French coast, on the line running through...
42°N, 5°E and 43°N, 8°E (Sankey, 1973). Surface "divergence", and consequent upward motions, are expected in the centre of the dome. This central doming, although always present, tends to be more pronounced in the vicinity of 42°N, 4°45'E during the early part of the Winter. Further evaporation and surface cooling continuously reduce the static stability in the centre of the dome, until finally a vertical mixing begins to occur in the surface layer. Among other records of the intense vertical mixing, the Medoc Group (1970) shows that it is apparently confined to a narrow region (~30 km of radius). A "chimney" of mixed, dense water appears, extending from the surface down to depths which more or less steadily increase to about 2000 m (the local bottom depth is about 2500 m). Smaller, local convective columns of about 10 km in size, are observed some 10 km from the main dense patch (Lacombe, 1974). This mixed dense water sinks and spreads away later when the weather becomes milder, and thus constitutes the newly formed deep water (Medoc Group, 1970; Sankey, 1973).

A striking feature is the existence of rapid sinking motions with speeds up to 10 cm/sec during the vertical mixing (Voorhis, Webb, 1970; Stommel, Voorhis, Webb, 1971; Gascard, 1973). These downward motions are normally expected when we consider the formation of deep waters at the surface. Nevertheless, the observed (Stommel, Voorhis, Webb, 1971), slowly upward, "aperiodic" motion (~1 mm/sec), with internally superimposed inertia-gravity waves, suggests that motions are continually upward during this period. The former, rapid sinking motions may be caused by the wind-induced breaking of large-amplitude internal waves (Saint-Guily, 1972); the latter, some slowly upward motions, are suggested (Gascard, 1978) to be related to baroclinic instability. But there is another explanation for the upward overall water flux: the doming of isopycnals induces the well-known surface divergence, rich in primary productivity (Minas, 1970; Jacques et al., 1976). Even in 1969, when intense vertical mixing had been observed during the Winter, a Spring bloom of phytoplankton was recorded (Coste, Gostan, Minas, 1972). This work contains our estimates of low-frequency vertical motions from the two six-month moorings and daily CTP measurements, and differentiates between two types of apparently distinct vertical motion. It has already been shown by Bryden (1976), that estimates of low-frequency vertical motions can be made from measurements of horizontal current and temperature at a minimum of two levels on a single mooring.

DATA AND STATISTICS

During 1976-1977, two long-term subsurface moorings and daily CTP measurements were made by the Laboratoire d'Océanographie Physique (Kartavtseff, 1979; Geromon, Murail, in preparation) near the presumed centre of deep water formation (42°N, 4°45'E), where the manned Bouée-Laboratoire Borha II was anchored (Fig. 1). These observations are summarized in Table I. The original time-series are low-pass filtered by running mean process of 18 hours, which is the local inertial period, to show the low-frequency variations of observed current and temperature (Fig. 2). The pressure record shows that the depth of the mooring apex varied by less than ±0.9 m in depth over the whole mooring period. From July 12, 1976, the 250 m Aanderaa rotor probably malfunctioned; current speeds were consequently much reduced at this depth, with respect to those at 800 m in depth (Fig. 2). On July 22, 1977, the recording

![Figure 1](https://example.com/figure1.png)

**Figure 1**

Sites of moorings and Borha II depicted on the 1/500 000 bathymetric chart of Auzende, Monti and Olivier (1979). Also shown on the upper right corner, are the mean currents at both depths, 250 and 800 m, for moorings 1976 (black circle) and 1977 (white circle). For mooring 1977, the mean values of thermal wind, ∆V, and velocity of horizontal advection, V_ad, are presented.

### Table 1

**Descriptions of current meter moorings and daily CTP measurements.**

<table>
<thead>
<tr>
<th>Start</th>
<th>End</th>
<th>Position</th>
<th>Depth (m)</th>
<th>Instrument</th>
<th>Sampling interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mooring 1976</td>
<td>15 May</td>
<td>{41°59'N, 4°55'E}</td>
<td>250</td>
<td>Aanderaa</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>27 Nov.</td>
<td></td>
<td>800</td>
<td>VACM</td>
<td>15 minutes</td>
</tr>
<tr>
<td>Mooring 1977</td>
<td>6 Feb.</td>
<td>{42°02'N, 4°53'E}</td>
<td>250</td>
<td>Aanderaa</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td>26 Aug.</td>
<td></td>
<td>800</td>
<td>VACM</td>
<td>15 minutes</td>
</tr>
<tr>
<td>CTP measurements</td>
<td>15 Dec. 1976</td>
<td>42°00'N, 4°45'E</td>
<td>0-2350</td>
<td>Bissett</td>
<td>1 day</td>
</tr>
<tr>
<td></td>
<td>15 May 1977</td>
<td></td>
<td></td>
<td>Bermann</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CTP</td>
<td></td>
</tr>
</tbody>
</table>
of the 250 m Aanderaa was interrupted (Fig. 2) because of an electric failure (faulty batteries).

The original data of current and temperature are put through standard processing, which permits spectral analysis of either scalar or two-dimensional vector time series by performing the Fast Fourier Transform. The variance of temperature thus obtained at each frequency can be transformed into a perturbation potential energy (Dantzler, 1976), if there exists a linear relationship between temperature and salinity \( S' = c T' \); so between temperature and density \( \rho' = \alpha T' \):

\[
F_{\text{pot}} = \frac{1}{2} (\rho' g / \rho_0 N)^2 = \frac{\sigma_T^2}{2} (g / \rho_0 N)^2,
\]

where: \( \rho' \), \( S' \) and \( T' \) are, respectively, the perturbations of density, salinity and temperature, related to each other by

\[
\rho' = a T' + b S' = (a + bc) T' = \alpha T',
\]

\( g \), the gravity; \( \rho_0 \), the mean density; \( N \), the Brunt-Väisälä frequency; and \( \sigma_T^2 \), the variance of the temperature. As will be seen later, the statistical analysis of \( T' \) series and

\( \rho' \) series from CTP measurements, reveals that these two parameters are significantly correlated to each other, with a correlation coefficient of about 0.6 lying much above the 99% significance level. At each frequency, the obtained 4 series (2 moorings x 2 depths) are averaged to show the overall mean pattern of energy distribution. For the purpose of comparing energy distributions between two mooring periods, their first moments \( \omega F (\omega) \) are averaged only over the considered depth interval (250-800 m), and are depicted on the semi-logarithmic coordinates. The results indicate that the motions measured during 1977 are very different in energy distribution (Fig. 3 a and b) and vertical structure (Fig. 4 a and b), from those of mooring 1976: the 1977 low-frequency motions have less kinetic energy (Fig. 3 a), but more perturbation potential energy (Fig. 3 b); they are much more baroclinic in dynamic structure, with a vertical phase difference of about 120° (Fig. 4 a); and they are much more disturbed in thermal structure, with a low vertical coherence (Fig. 4 b). Further observations would be required to explain this difference of motions between two mooring periods. It should also be noted here that the large kinetic energy observed during the Winter-Spring 1977, at the inertial frequency (Fig. 3 a), is in contradiction with earlier studies on inertial oscillations in Winter in this area (Gonella, 1970; Gascard, 1973). The corresponding CTP measurements, carried out during the mild Winter 1977, did not show any
remarkable, convective, vertical mixing, but a static
stability persisting over the whole observation period
(Fig. 5 a). The large fluctuations in in-flows of hot and
salty intermediate water, as shown by the variation of
salinity (Fig. 5 b), proved, however, that advection is
important in this area.

THEORY

One can write the density-conservation equation:

$$\frac{\partial \rho}{\partial t} + \left( \frac{U}{f_0} \right) \frac{\partial \rho}{\partial x} + \left( \frac{V}{f_0} \right) \frac{\partial \rho}{\partial y} + \frac{\partial \rho}{\partial z} = 0,$$

(1)

where: \( \rho \) is the potential density, and \( U, V, W \) are current
velocities in \((x, y, z) = \) (Eastward, Northward, upward)
directions. The non-dimensional number characterizing
the size of each term is written in parenthesis below each
term: \( U \) is the typical magnitude of the horizontal
velocity, which has the typical horizontal length scale \( L \),
the vertical length scale \( H \), and the frequency \( \omega \); and \( f_0 \)
\((= 10^{-4} \text{ sec}^{-1}) \) is the local inertial frequency. The
observed low-frequency motion typical of this region has
\( \omega \) smaller than 1 cycle/month and \( U \) smaller than
10 cm/sec (Seung, 1979); \( L \) seems to be larger than
10 km, since eddies of 10 km in diameter have frequently
been observed (Medoc Group, 1970; Gascard, 1978).
This gives:

\( \varepsilon = \omega / f_0 = 2.5 \times 10^{-2}, \) and \( R_0 = \frac{U}{f_0} L \sim 10^{-1}. \)

The deformation radius, \( L_R \), appears about 6 km:

\( L_R = \frac{NH}{f_0} \approx \frac{3 f_0 \times 2 \text{ km}}{f_0} = 6 \text{ km}; \)

Gascard (1978) also estimated it at about 5 km. It would
thus be reasonable to take the typical deformation
radius, \( L_R \), as smaller than 10 km, so that the vertical
advection \((\sim R_0 L_x^2 / L^2)\) be generally smaller than the
horizontal advection \((\sim R_0)\).

Equation (1), vertically averaged over the considered
depth interval \((250-800 \text{ m})\), can be written:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{U}{f_0} \frac{\partial \bar{\rho}}{\partial x} + \frac{V}{f_0} \frac{\partial \bar{\rho}}{\partial y} + \frac{\partial \bar{\rho}}{\partial z} = 0,$$

(2)

where bars “—” denote the vertical average, and
parentheses \( (\ldots) \), the time average. The vertical velocity,
\( w \), can then be obtained from the known, vertically
averaged local time variation, \( \bar{\rho} \), and horizontal
advection of density, \( AD \):

$$w = \frac{\bar{\rho} \partial \bar{\rho}}{\bar{\rho} \partial z} = \frac{\bar{\rho} \partial \bar{\rho}}{\bar{\rho} \partial z},$$

(3)

where the mean vertical gradient of density, \( \partial \bar{\rho} / \partial z \), is
estimated to be about \(- 5 \times 10^{-4} \text{ cm}^{-1} \) from the CTP
data.

The horizontal advection of density for low-frequency
motions can be estimated in a similar manner to that
employed by Bryden (1976). The thermal wind equations:

$$f_0 \frac{\partial u}{\partial z} \left[ 1 \pm \Omega (\varepsilon, R_0) \right] = \frac{\rho_0}{\rho_f} \frac{\partial \bar{\rho}}{\partial y},$$

$$f_0 \frac{\partial v}{\partial z} \left[ 1 \pm \Omega (\varepsilon, R_0) \right] = - \frac{\rho_0}{\rho_f} \frac{\partial \bar{\rho}}{\partial x},$$

allow the horizontal advection of density for low­
frequency motions to be written:

$$\bar{AD} = - \frac{\rho_0}{\rho_f} \left( \frac{\partial \bar{\rho}}{\partial x} - \frac{\partial \bar{\rho}}{\partial y} \right) \left[ 1 \pm \sqrt{2} \Omega (\varepsilon, R_0) \right]$$

(4)

which, in polar coordinates, becomes:

$$\bar{AD} = - \frac{\rho_0}{g} \frac{f_0}{R} \frac{\partial \varphi}{\partial z} \left[ 1 \pm \sqrt{2} \Omega (\varepsilon, R_0) \right].$$

where \( R \) is the modulus of the current, and \( \varphi \), the current
direction in radian measured positively counter-
clockwise from East. In estimating the horizontal advection of density by (4), we thus assumed that the motions are nearly geostrophic and hydrostatic.

CALCULATIONS

The measured current and temperature are low-pass filtered by a running mean process of 90 hours, in order to eliminate high-frequency motions. This can also result in the reduction of measurement errors which are estimated later. The corresponding CTP data are likewise averaged over 4 days, a period comparable to the 90-hour sampling interval. These 4-day-averaged CTP data are used solely to obtain the relation which permits the transformation of the *in situ* temperature $T^\circ\text{C}$ measured at two depths, 250 and 800 m, into the vertically-averaged potential density:

$$\bar{\rho}_a = -(1.1 \, T_{250} + 6.7 \, T_{800}) \times 10^{-5} + 1.030 \pm 3.4 \times 10^{-6} \text{ g/cm}^3.$$  (5)

To obtain (5), the temperatures ($T_{250}$, $T_{800}$) from CTP data are first related to the vertically-averaged potential temperature from CTP measurements by using the method of multiple regression:

$$\bar{T} = 0.166 \, T_{250} + 1.022 \, T_{800} - 2.374 \pm 0.020 \text{ C}.$$  

This is then combined with another result obtained from the CTP data set, after testing the linearity $\bar{\theta} = \bar{S}$ (Seung, 1979):

$$\bar{\rho}_a = -6.6 \, \bar{\theta} \times 10^{-5} + 1.030 \pm 3.15 \times 10^{-6} \text{ g/cm}^3.$$  

The multiple correlation coefficient for the relation $\bar{\theta} = (T_{250}, T_{800})$, which is about 0.7, and the correlation coefficient for the relation $\bar{\rho}_a = \bar{\theta}$, which is about 0.6, both lie above the 99% significance level. The standard error in (5) is given by the root square sum of the error in $\bar{\rho}_a = \bar{\theta}$ and the error due to $\bar{\theta} = (T_{250}, T_{800})$. It may thus be assumed that this relation is applicable to temperatures measured at mooring points which are separated from the Bouée-Laboratoire by horizontal distances of about 10 km.

To estimate measurement errors, Figures for sensor accuracy provided by the manufacturers are used (Table 2). The accuracy in speed of VACM, which is better than that of Aanderaa, is not presented in Table 2, where the former is replaced by the latter. Measurement errors in the estimate of local time variation are related only to thermistor sensitivity, since the almost constant bias errors, due to imprecise calibration are eliminated through the subtraction of two consecutive values of temperature.

An estimate of vertically-averaged local time variation $\bar{\Delta}$ is rendered straightforward by using the relation (5):

$$\bar{\Delta}L = \frac{\Delta \bar{\rho}_a}{\Delta \bar{T}} = (3.4 \, T_{250} + 20.7 \, T_{800}) \times 10^{-11} \pm 1.5 \times 10^{-11} \text{ sec}^{-1},$$  

where "$\Delta$" denotes the increment of the considered parameter corresponding to $\Delta t = 90$ hours. The corresponding measurement error, of the order of $3 \times 10^{-13} \text{ sec}^{-1}$, may be neglected in comparison with the regression error, $1.5 \times 10^{-11} \text{ sec}^{-1}$.

In order to estimate the vertically-averaged horizontal advection of density, $AD^*$, we assume that the kinetic energy $\bar{R}^2(\varphi)$ and the current direction $\varphi(\varphi)$ vary linearly with depth. Vertical averaging of (4) then gives $AD^*$ in terms of vertical mean square of speed, $\bar{R}^2$, and the veering of horizontal current, $\Delta \varphi$:

$$AD^* = -\frac{\Delta \bar{\rho}_a}{\bar{\rho}_a} \bar{R}^2 \Delta \varphi [1 \pm \sqrt{2} \bar{O}(\varphi, \bar{R})],$$  (7)

where

$$\bar{R}^2 = (R_{250}^2 + R_{800}^2)/2 \quad \text{and} \quad \Delta \varphi = \varphi_{250} - \varphi_{800}.$$  

The error due to the theoretical assumptions, $\sqrt{2} \bar{O}(\varphi, \bar{R})$, is considered to be $10^{-1}$, based on the estimate of non-dimensional characteristic numbers as shown before in Equation (1). The error in Eastward or Northward-velocity components for 90 hour-averaged series is estimated to be:

$$\delta u = \delta v = \sqrt{\frac{1}{2n} \left(\sum (\delta R)^2 + \sum (\delta \varphi)^2\right)},$$  

where $n$ is the number of measurements averaged to give one 90-hour-averaged value ($n=90$ for Aanderaa; $n=360$ for VACM); and $\delta R$ and $\delta \varphi$ are errors in speed and direction for each measurement (Table 2). The root mean square of current speed is used to represent $R$; $R = 5 \text{ cm/sec}$. The errors in speed, $\delta R$, and direction, $\delta \varphi$, for 90 hour-averaged series are then:

$\delta R_{250} = 0.09 \text{ cm/sec} \quad \text{and} \quad \delta \varphi_{250} = 0.025 \text{ rad. for Aanderaa;}$  

$\delta R_{800} = 0.04 \text{ cm/sec} \quad \text{and} \quad \delta \varphi_{800} = 0.011 \text{ rad. for VACM.}$

The measurement errors in horizontal advection $AD^*$, estimated by using the above values, are variable; they are smaller than 1% for relatively large advections. The total errors in horizontal advection $AD^*$, given approximately by the root square sum of theoretical and measurement errors, amount to a few $10^{-12} \text{ sec}^{-1}$ for relatively small advections, and to about $2 \times 10^{-11} \text{ sec}^{-1}$ for relatively large advections. It should be noted that there still remains the error due to the underestimation of current speeds, as a result of the
vertical mixing begins to occur. According to earlier observations, the intense vertical mixing involves a rapid sinking motion, although the latter does not appear to be permanent during the Winter-Spring period. This cyclonic gyre induces surface divergence at the centre, which is connected to the upward motion and the doming of dense water. The centre of gyre is situated precisely where the sinking motion, although the latter does not appear to be significant. In any case, this mean upward motion is linked more to the cyclonic gyre, which generally becomes notable during Winter. This cyclonic gyre induces surface divergence at the centre, which is connected to the upward motion and the doming of dense water. The centre of gyre is situated precisely where the vertical mixing begins to occur. According to earlier observations, the intense vertical mixing involves a rapid sinking motion, although the latter does not appear to modify the general system of cyclonic gyre (upward motion) in the basin, and in fact, seems to occur only over a short period of time in a very confined area; previous observation (Stommel, Voorhis, Webb, 1971) shows that this rapid sinking motion occurs only during 5% of the total observation period, whereas the slow upward motion is permanent during the Winter-Spring period. It should be noted that only the low-frequency motion is estimated here, so that only the mean feature over a 90 hour period, can be determined.

Superimposed on this steady upward motion, large fluctuations in horizontal and vertical advection, with a time-scale of about 20 days, are evident in Figure 6. There are related to eddies, probably generated by unstable baroclinic waves. The peaks of horizontal advection, and thus of vertical advection, are an order of magnitude greater than the corresponding local time variations of the density. The fact that the horizontal advection, which is the non-linear term in Equation (1), is much larger than the local time variation, means that low-frequency waves are non-linear; this, in turn, can explain why many eddies have been observed during Winter in this region (Gascard, 1978). Our results suggest that baroclinic activity is stronger in Winter and early Spring than in Summer and Autumn.

The thermal wind $\Delta V$ and the horizontal current component perpendicular to it, $V_{sd}$, are computed from the observed 90 hour-averaged current data; $|\Delta V|$ is proportional to the vertically-averaged horizontal density gradient, and $V_{sd}$, the velocity of the vertically-averaged horizontal advection, in a direction parallel to the density horizontal gradient. The results show that the thermal wind $\Delta V$ has a generally NW direction, parallel to the local isobathic lines (Fig. 1). It should be noted that the mean currents of mooring 1976 are also North-West of the South and Caston's hypothesis (1973) that the local bathymetry, which traps the relatively dense waters by cyclonic circulation, is a significant factor in determining where deep mixing occurs.

The balance between horizontal and vertical advections of density implies, according to Equation (2), that:

$$\frac{\bar{w}}{V_{sd}} \approx -|\nabla \rho| \frac{\partial \langle \rho \rangle}{\partial z} = \gamma$$

since

$$\Delta \bar{D} \approx |V_{sd}| \cdot |\nabla \rho| \cdot$$

where $\gamma$ represents the vertically-averaged slope of isopycnal surface. The peaks of horizontal advection, and of vertical advection, in Figure 6, therefore correspond to the motions in which water particles move nearly parallel to the isopycnal surface. Using the obtained values of $|V_{sd}|$ and $\bar{w}$, we can estimate the mean slope:

$$\gamma = \frac{3 \text{ mm/sec}}{4 \text{ cm/sec}} = 7.5 \%.$$
CONCLUSIONS

The low-frequency vertical motions were estimated from measurements of horizontal current and temperature on a single mooring, in the North-Western Mediterranean area of deep water formation. An assumption concerning the variation with depth of horizontal current was indispensable, since only two current-meters were used in the depth interval considered (250-800 m). Two different assumptions led to the identical conclusion that motions are significantly upward (~ mm/sec) during the Winter-Spring 1977, though of differing magnitudes. This would suggest that motions are generally upward, though variable in time, in this surface "divergence" area (42°N, 4°45'E), as was hinted both in studies on the primary productivity (Minas, 1970; Coste, Gostan, Minas, 1972), and to a certain extent by direct measurements of vertical current (Stommel, Voorhis, Webb, 1971). The previously observed rapid sinking motions, the probability of which amounts to only 5% in the most prolonged observation of vertical current ever made (Stommel, Voorhis, Webb, 1971), are likely to be Winter-time "episodic" phenomena, related to the sinking of short-lived "puffs" of dense water. Nevertheless, baroclinic activity appears to be more important in Winter-Spring than in Summer-Autumn.

Measurements of conductivity by current-meter can eliminate the need to use other specialized hydrological instruments. Although measurements of hydrologic parameters by current-meter are less accurate, the resulting errors are not expected to be serious since, in the estimate of local-time variations of density, sensor precision is the only determinant factor, and this can be improved by averaging processes, or still further by repeated measurements. In this way, we are able to eliminate the large regression error due to the transformation of temperature into density. A great number of current-meters would be required to reduce the errors due to ignorance of the variations of density and current with depth over the considerable depth interval involved.

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