Analysis of the high frequency dynamics of the bottom boundary layer in the Strait of Gibraltar by ADCP single-ping measurements

Simone Sammartino[1], Jesús García Lafuente[1], Cristina Naranjo[1], José Carlos Sánchez Garrido[1], Ricardo Sanchez Leal[2]

[1] Physical Oceanography Group, University of Málaga, Campus de Teatinos s/n, 29017, Málaga, Spain

[2] Spanish Institute of Oceanography, Cadiz Oceanography Center, Muelle de Levante (Puerto Pesquero), 11006, Cádiz, Spain

ABSTRACT

A series of single-ping Acoustic Doppler Current Profiler (ADCP) measurements carried out in the Strait of Gibraltar allowed for a preliminary assessment of turbulence parameters of the Outflowing Mediterranean Water, and its tidal variability. The variance method has been applied to single-ping ensemble measurements of the radial velocity, after a careful analysis of the accuracy associated to the fluctuation magnitude estimated by the instrument. Maxima of Reynolds' stress τ and dissipation coefficient ϵ are observed during flood tide in the bottom boundary layer, when the westward Mediterranean flow is strong and the derived turbulence is highest. A diurnal modulation is also observed, more marked in spring tides. The application of a logarithmic law to the near-bottom layer also confirms the magnitudes of τ and ϵ observed with the variance method and gives some hints of the presence of a double velocity maximum in this layer.

INTRODUCTION

Since 2004, the Physical Oceanography Group of the University of Málaga has been holding a monitoring station located at the western exit of the Strait of Gibraltar, with the aim of gathering data of the thermohaline properties of the Mediterranean Outflowing Water (MOW) and its dynamics. The station is constituted by a mooring line whose principal element is an up-looking RDI 75 kHz Acoustic Doppler Current Profiler (ADCP) embedded in a sub-surface buoy, deployed ~20m above the bottom, capable of obtaining profiles of the three-dimensional current along the whole water column. Although the principal aim of the project was to assess the long-term variability of the MOW dynamics, recently, the configuration of the instrument has been slightly modified to integrate a parallel study of the high frequency variability of the outflow. The present contribution describes the first results of this operation.

EXPERIMENTAL SETUP

Typically, the ADCP collects current profiles individually (pings) and then averages them over a fixed time interval (ensembles), with the aim to improve the statistical significance of the measure. In this experiment, however, we set the instrument to collect every individual ping (with a sampling interval of 36 seconds), treating them as single-ping ensembles, and applying all the post-sampling processing steps prescribed for the latter. The profiles have a vertical resolution of 8m and span from ~35m above the sea bottom to ~50m from the surface. This means that the frequencies that can be investigated are not purely turbulence, but involve also the internal waves dynamics.

THEORETICAL FRAMEWORK

The turbulent energy balance equation accounts for the different terms that contribute to the production and dissipation of turbulence in a fluid:

$$\frac{\partial E}{\partial t} = -\rho_0 \langle u'w' \rangle \frac{\partial U}{\partial z} - g\langle w\rho' \rangle - \rho_0 \epsilon \qquad (1)$$

The rate of variation of turbulent energy, the term on the lhs of equation (1), is the net sum of the production (P) of turbulent kinetic energy (TKE) by the advection of eddies characterized by the (Reynolds') stress $\langle u'w' \rangle$ by means of the mean sheared current U, the buoyancy flux characterized by the density fluctuations ρ', and the rate of loss of turbulent kinetic energy into heat through viscosity, characterized by the dissipation coefficient ϵ [2]. Here the prime symbol represents the instantaneous fluctuation of a quantity around its mean, as defined within a fixed time interval, and ρ_0 is a mean density. In a steady state, when TE can be assumed to be constant, in conditions of no convection, where the buoyancy fluxes are negligible, and in presence of vertical velocity shear, the balance can be simplified as:

$$\epsilon = -\langle uw \rangle \frac{\partial U}{\partial z} \qquad (2)$$

where the production of turbulent energy, ascribed to the mean shear flow as source of turbulent motion, is compensated by its dissipation through viscosity. These conditions are reasonably satisfied in the bottom boundary layer (BBL) where the stratification is weak and the velocity shear is usually high. In this framework, the ADCP measurements allow to estimate the vertical shear $(\partial U/\partial z)$ directly and the Reynolds' stress, $\langle u'w' \rangle$ and $\langle u'w' \rangle$, indirectly (the variance method).

THE VARIANCE METHOD

The variance method [3] consists in estimating the Reynolds' stress by means of the ADCP radial velocity fluctuations with respect to some time averages:

$$\langle u'w' \rangle = \frac{\overline{U_1'^2} - \overline{U_2'^2}}{4\, sin\,\theta\, cos\,\theta}; \quad \langle v'w' \rangle = \frac{\overline{U_3'^2} - \overline{U_4'^2}}{4\, sin\,\theta\, cos\,\theta} \qquad (3)$$

where θ is the slant angle of the ADCP, U_j is the radial velocity along the j-th transducer, and $U_j'^2$ stands for the variance of the fluctuations of this velocity. Notice that in case of tethered ADCP, as it is our case, equations (3) get much more complicated by the inclusion of the tilt angles.

ADCP NOISE

By using single-ping records we pay for the relative low precision of the instrument (ADCP noise). In order to employ these measurements to assess the current variability, we have to account for this noise. To this aim, a series of a-posteriori ensemble averages, with varying pings-per-ensemble (ppe) value, have been simulated, and an asymptotic behavior of the ensemble standard deviation around 15 ppe (~10 minutes) has been observed. We hence established the time interval of 10 minutes as the width of the average window to compute the current fluctuations. Then, we simulated a series of synthetic random variables and we sampled them with an accuracy corresponding to the ADCP noise defined for our system (~15 cm s^{-1}), and so we estimated our capability of obtaining reliable measurements of the real current fluctuations. The highest accuracy is achieved during flood tides, when the Mediterranean westward current is strongest on the BBL, and the relative overestimation of the ensemble standard deviation by ADCP noise is less than 10%.

RESULTS AND DISCUSSION

The series of Reynolds' stress obtained by applying the variance method to the radial velocities computed on the ADCP records corrected by tilt angles, shows a marked semidiurnal periodicity, with maxima of ~2 Pa occurring in flood tide, according with the highest westward current in the BBL (Fig. 1a).

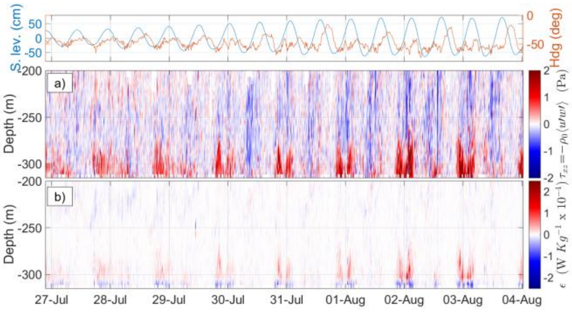

Fig. 1. Fragment of the series of Reynolds' stress $\langle u'w' \rangle$ (panel a), and dissipation coefficient ϵ (panel b). The top panel shows the sea level and the low-passed series of the ADCP heading.

A strong modulation at diurnal timescale is also observed, stronger in spring tide. The corresponding ϵ values (Fig. 1b), estimated as in (2), show peaks of $O(10^{-4})$ W Kg^{-1}. Both results are coherent with previous estimates by [4] and [5].

From the same assumption of (2), we can define the logarithmic law that describes the vanishing behavior of the velocity toward the bottom:

$$U(z) = u_* / k\, ln(z/z_0) \qquad (4)$$

where u_* is the friction velocity, k is the Von Kármán constant (0.41), and z is the distance from the sea bottom. Based on (4) we can obtain estimations of τ and ϵ, assuming $\tau = \rho_0 u_*^2$ and $\epsilon = u_*^3/kz$, respectively [2].

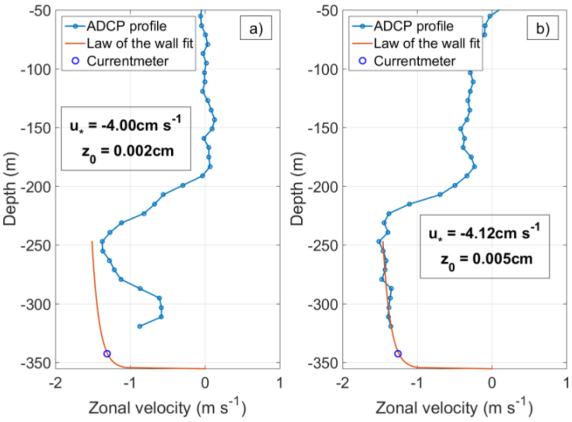

Fig. 2. Two examples of zonal velocity profiles with the near-bottom layer fitted by the law of the wall, in presence (a) and absence (b) of the double maximum.

With a friction velocity u_* of ~4 cm s^{-1}, we derived estimates of τ of ~2 Pa and ϵ of $O(10^{-3})$ W Kg^{-1}, in a good agreement with results from the previous approach. A stable and permanent double maximum structure of the very near-bottom layer is also observed, likely related to some topographic interaction of the flow upstream (Fig. 2).

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