STRATIFICATION AND INTERNAL INERTIAL WAVES. LISBON MREA04 EXPERIMENT

M. B. Aguiar-González, A. Rodríguez-Santana, J. Cisneros-Aguirre & A. Martínez-Marrero

Department of Physics , University of Las Palmas de Gran Canaria, Spain, Edificio de Ciencias Básicas, Campus Universitario de Tafira, 35017, Las Palmas de Gran Canaria

e-mail: miguel.aguiar101@estudiantes.ulpgc.es; jcisneros@dfis.ulgpc.es

1. INTRODUCTION AND DATA

We have used oceanographic measures that were taken as a part of MREA04 experiment (Maritime Rapid Environmental Assessment 2004) by NATO Undersea Research Centre (NURC) on the southwest coast of the Iberian Peninsula from 27 March to 18 April 2004. Analyzing ADCP (Acoustic Doppler Current Profiler) measures at two locations on the Setubal Bay shelf, we have observed internal inertial waves at several times during the experiment period.

The region is characterized by fluvial inputs from Sado and Tagus estuaries. These inputs are important because they are rich in nutrients fertilizing the zone and generating high biological productivity. Figure 1 shows the Study Area II on the Setubal Bay for the present work. This fluvial input from Sado estuary was clear with CTD (Conductive, Temperature, Depth) data at the first meters when the signal of inertial waves had disappeared.

When the inertial waves were acting, the stratification decreased and the estuarine waters appeared mixed with the oceanic waters, indicating that these waves can play a key role on diapycnal mixing processes. Here we focus on the records of Barny North ADCP (Figure 1). A low-pass filter (Godin, 1972) was applied to this serial of data to attenuate high frequencies and retain low frequencies unchanged. Then, the rotary spectral method (Emery and Thomson, 1997), cross spectral analysis among currents measured at different depths and response tidal analysis method were used to interpret the diurnal and semidiurnal horizontal current oscillations (Cartwright et al., 1969). The dominant interval frequency was the diurnal band that corresponds to the inertial frequency at this latitude. Moreover, fluctuations for these currents were polarized toward clockwise sense, characteristic behaviour for the inertial waves in the North hemisphere (Millot and Crepon, 1981).

To study the connection between these internal waves and diapycnal mixing processes we analyzed the behaviour of the vertical structure of the water column during the sampling period comparing four vertical profiles at different moments from CTD data (station nº 67 A, station nº 67 B*, station nº 67 B, station nº 67 C; Figure 1) with four vertical profiles from Barny North ADCP data at the same times. With this objective vertical profiles of Brunt-Väisälä frequency squared, N2, vertical shear squared, S2, and gradient Richardson number, Ri, were calculated.

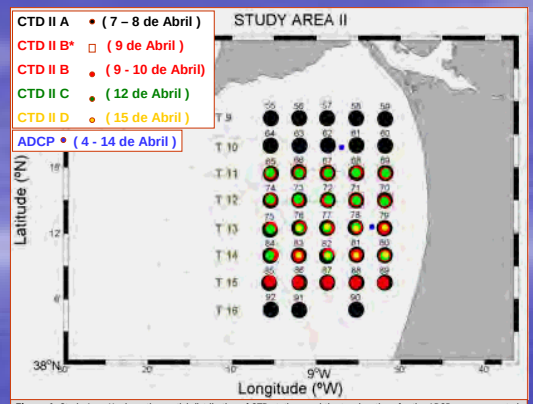

Figure 1. Study Area II where the spatial distribution of CTD stations and the two locations for the ADCP are represented. Blue circles are the two locations for the ADCP: Barny North (included at the transect T10) and Barny South (included at the transect T13) respectively.

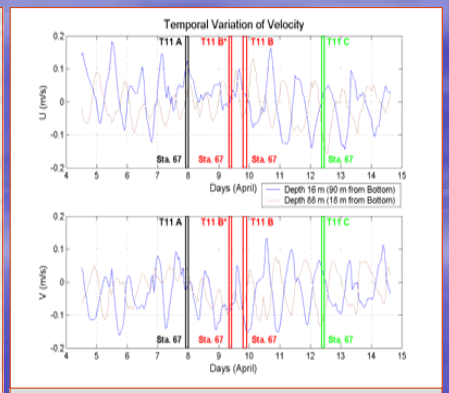

Figure 2. Horizontal velocity temporal variations close to the surface (blue line) and close to the bottom (brown line) from Barny North ADCP. The two vertical lines for each transect indicate its beginning and its end. The upper plot is represented for the component *u* of the velocity, east-west; and the lower plot is represented for the component *v*, north-south.

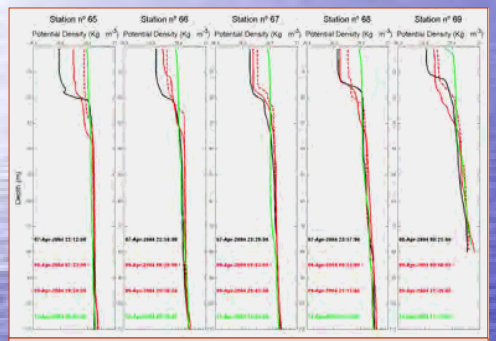

Figure 3. Vertical profiles of potential density for the transect T11 during the four different moments which are represented as vertical lines in Figure 2. Black solid lines correspond to transect T11 A; red dotted lines correspond to transect T11 B*; red solid lines correspond to transect T11 B; and, green solid lines correspond to transect T11 C. Dates of each sampling are referenced.

2. RESULTS

From the horizontal velocity record of Barny North ADCP (Figure 2) we observe on several times the characteristic change of phase of 180º for inertial waves between surface and bottom (Millot and Crepon, 1981; Orlic, 1987). This change of phase was present during 4 - 6 April and 10 - 15 April, showing likely the presence of the internal inertial waves during those days. Thus we appreciated that the only moment with change of phase corresponded to the station nº 67 C included within the transect T11 C, whereas the stations nº 67 A, B* and B, included within the transects T 11 A, B* and B, did not present it. On the period 10 - 15 April, and specially on 12 April when the CTD nº 67 C was taken, the change of phase for the directions U and V was highly strong, indicating high values of vertical shear. However, this strong change of phase was absent for the moments at which stations nº 67 A, B*, and B were taken (Figure 2).

Analyzing the profiles of potential density (Figure 3) for the transect T11, where Barny North ADCP was included, we observe that the entire transect was affected by a noticeable estuarine plume (less dense water) between 0 – 20 meters and that it was present during the samples A, B* and B of the transect T11, when the internal inertial waves seemed to disappear. Nevertheless, we observe that this signal of estuarine waters was not present during the sample of the transect T11 C, when the signal of the internal inertial waves was clear.

Near surface, there was a maximum of N2 at 18 meters of ~ 1.5·10-4 s-2 for the stations nº 67 A, B* and B, whereas this maximum was absent for the last sample, station nº67 C, with values about 2.8·10-4 s-2 due to the decreasing of the stratification associated to the disappearance of the estuarine signal (Figure 4). Near bottom, we can appreciate that there was other remarkable maximum of N2 about 2.8·10-5 s-2 at 74 meters, but only present at the station nº 67 C, where we observed a strong change of phase (Figure 2) and a variation of potential density (Figure 3) for those depths able to support the baroclinic mode of the inertial wave.

Respect to S2 (Fig. 5) we found two zones with maximum values that coincide with the analyzed depths previously. On the one hand, high values on ~ 9·10-4 to 9·10-5 s-2 of S2 were obtained at the stations nº 67 A, B* and B within the first 20 meters, what would explain the observed mixed layer in the potential density profiles; and, on the other hand, high values on ~5.5·10-5 s-2 of S2 at 74 meters were found for the station nº 67 C, associated to an abrupt change of phase at that depth in presence of the inertial wave.

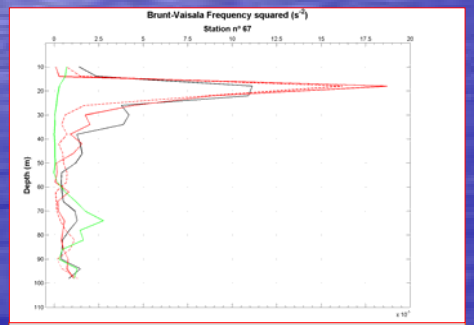

Figure 4. Vertical profiles of Brunt-Väisälä frequency squared for the station nº 67 at the transect T11 during the same moments which are represented in Figures 2-3. *Note that the scale is on 10-4.*

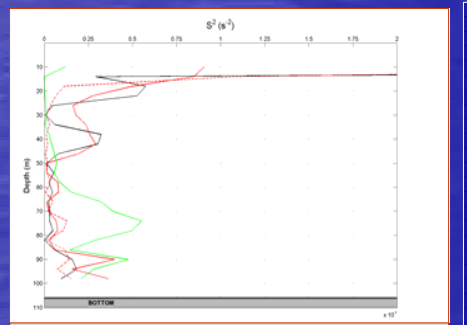

Figure 5. Profiles of vertical shear squared S^2 from ADCP Barny North during the same moments that in Figures 2-4 for the station nº 67 of the transect T11. *Note that the scale is on 10-4.*

3. DISCUSSION

Richardson number ($Ri = N^2 / S^2$) allows us to determine the conditions to produce instabilities generated by the vertical shear in a stratified fluid. Thus, we obtained the lowest values of Ri for the station nº67 C between 40 – 60 meters coinciding with a zone of very low stratification (Figure 6).

Nevertheless, we also found values of Ri generally lower than 0.5 for the station nº67 C between 60 – 80 meters, coinciding with zones of high stratification (high values of N^2) but very high S^2 what could induce the generation of Kelvin-Helmholtz instabilities in the water column near the depth where the change of phase of the horizontal velocity was detected.

Finally we estimated the vertical diffusion coefficient, k_u, associated to the instabilities induced by the observed vertical shear to analyze the diapycnal fluxes which were acting between 60 – 80 meters, the depths where the change of phase of the inertial internal waves was evident for the station nº 67 C. For this estimation we used the parameterization of diapycnal diffusivity of Pacanowski and Philander (1981).

Thus, for the station nº 67 C was found a value of ku=1.5·10-4 m2 ·s-1 at 74 meters for Ri = 0.5, a relatively high value of ku for stable stratified zones (typical values are on ~10-5 m2 ·s-1; Ledwell *et al*, 1993). Using this value we obtained a vertical density flux of Fz = 4.48·10-7 kg·m-2·s-1 and a convergence zone of -3·10-8 kg ·m-3·s-1 at the same depth.

These values in addition to a divergence zone of ~3·10-8 kg·m-3·s-1 at 78 meters show a range of depths where the convergence and divergence of the fluxes may modify the vertical distribution of the potential density in a certain characteristic timescale.

We conclude that instabilities induced by the vertical shear associated to the detected internal inertial wave may affect to the stratification that supports its baroclinic mode, being a possible source of energy to transport properties along the entire water column.

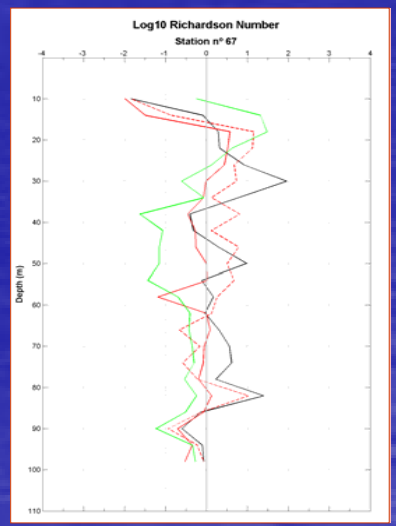

Figure 6. Vertical profiles of Logarithm of Ri at the four different moments represented in Figures 2-6 for the station nº 67 of the transect T11. Line in grey marks Ri = 1.

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