Three-Dimensional Evolution of Large-Amplitude Internal Waves in the Strait of Gibraltar

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INTERNAL WAVES IN THE STRAIT OF GIBRALTAR

Internal waves are together with winds, the main responsible for diapycnal mixing in the ocean, crucial in the development of marine ecosystems and with implications for the global circulation and associated heat transport (Walter Munk 1997). Realistic modelling of global long-term processes such as climate change require a deep understanding of where and how oceanic waters are mixed, and therefore of the dynamics of internal waves.

The Strait of Gibraltar, the only connection between the Atlantic Ocean and the Mediterranean Sea, is a well known scenario of inverse estuarine circulation, with an undercurrent of saltier Mediterranean water flowing at depth toward the Atlantic and a surface current of warmer and fresher Atlantic water moving opposite exceeding slightly the deep flow to compensate the net evaporative loses in the Mediterranean reservoir (Bryden and Kinder, 1991). Together with the well revised baroclinic exchange, the presence of tidally generated large-amplitude internal waves (LAIWs) at Camarinal Sill (CS, figure 1), with amplitude surpasing 100 m (see figure 1) and associated mixing processes is one of the more striking phenomenon. Here we present a combined numerical and experimental study of the three-dimensional evolution of LAIWs in the Strait of Gibraltar.

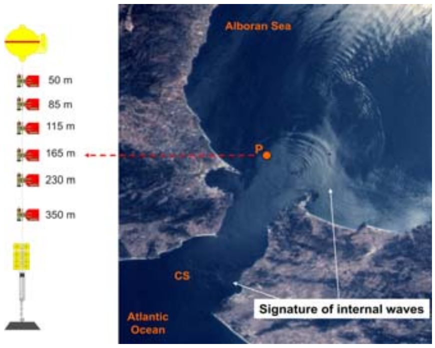

Figure 1.- Sea-surface manifestation of a group of LAIWs propagating from the strait toward the Alboran Sea (Courtesy of ESA). CS is Camarinal Sill; Symbol P denotes the location of the mooring deployed in the Alboran Sea.

OBSERVATIONS

During May 2003, one mooring line was deployed at the entrance of the Alboran Sea (36º3.35'N, 5º10.09'W; position P in figure 1). The mooring array consisted of several currentmeters at different depths that measured velocity and temperature every 2 minutes. Figure 2a shows a five-day temperature time series registered at 85 meters depth. Packets of LAIWs can be clearly identified here by abrupt temperature oscillations recorded every tidal period. The comparison of Figures 2b, 2c and 2d, showing a zoom area of the oscillations, reveals a clear difference between the wave packets indicating that the expected rank-ordered structure (waves organized in decreasing order of amplitude from the front to the rear due to nonlinear dispersion) is not a necessary attribute of all wave packets measured in the strait. Really, the statistical analysis of the whole ensemble of the recorded wave trains revealed that only 46.5 % of all packets can be identified as well rank-ordered wave trains similar to that presented in Figure 2b. The rest, i.e. 53.5 % of all packets were clearly non-rank-ordered, as it is seen in Figures 2c or 2d. This empirically obtained fact of unexpected clear tendency to disorder in wave packets is numerically investigated.

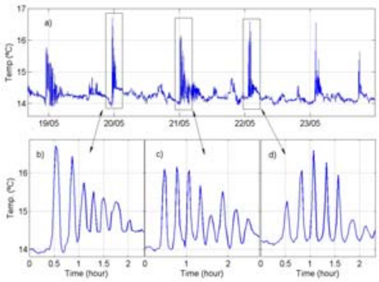

Figure 2.- (a) Fragment of the temperature time series recorded by P-mooring at 85m depth (see Figure 1). Panels (b), (c) and (d) are zoom of three particular fragments representing a well organized (b), partly rank-ordered (c) and non-rank ordered (d) packets of LAIWs.

THE NUMERICAL MODEL

It is assumed that internal wave observed in the Strait are the result of disintegration of a baroclinic bore generated by the barotropic tide interacting with Camarinal Sill. After the generation, the baroclinic bore propagates eastward along the Strait and disintegrates into a packet of solitary waves, which further enters into the Alboran Sea, as presented on the Synthetic Aperture Radar image in Figure 1.The task is split into two subtasks:

(i) the first step is the model initialization, i.e. the preparation of the initial field of solitary waves. This is described in detail in Vlasenko et al., 2005.

(ii) the second objective is to study of the wave evolution itself when the LAIWs propagate along the strait and interact with the 3D bottom topography and shoreline.

For both problems the Massachusetts Institute of Technology general circulation model (MITgcm) was used; the MITgcm solves the non-hydrostatic, non-linear equations and has a free surface formulation allowing it to trace the position of the solitary wave in (x,y)-space. The model resolution in x and y directions was equal to 50 m and 200 m, respectively, whereas the vertical step was equal to 7.5 m in upper 300 m layer and 50 m below it. The mean vertical profile of stationary density was obtained by averaging the historical CTD profiles from MEDATLAS data base collected near TN point. The bottom topography was extracted from the fine-resolution bottom chart. Assuming strong wave breaking and water mixing near lateral boundaries of the strait, the Richardson number-dependent parameterization (Pacanowski and Philander, 1981) of turbulent closure for viscosity and diffusivity was chosen.

ONE-WAVE EXPERIMENT

The 'one-wave experiment' considering propagation of only one internal solitary wave. This experiment allows one to study an effect of a single wave so that the response of the Strait to a wave packet can be treated in terms of a nonlinear superposition of several individual signals. In the first numerical experiment the amplitude of incident wave was taken equal to 83 m. The result of the wave evolution is presented in Figure 3. Here the free surface elevation produced by the internal wave of depression (a few centimeters, in fact) are shown in red. Note, that an internal wave of elevation produces a similar small-scale depression at the free surface shown in Figure 3 by blue colour. At the initial stage of evolution the incident wave retains basically the characteristics of a two-dimensional wave in the whole computational domain except of two fragments at the lateral boundaries where the 'edge' effects of wave-bottom interaction (refraction and breaking) are evident (find curved periphery of propagating internal wave at depths between 300 and 100m in Figure 3a).The wave-bottom interaction is getting stronger over time in the course of wave propagation, and in addition to the refraction and wave breaking, another important process, - viz. the energy reflection from the lateral boundaries of the strait, starts to develop in the shallow water zone. As a result of back scattering and dissipation, the propagating internal wave loses its energy pretty fast during the next six hours of evolution. The wave contains 82%, 44% and 31% of its initial total energy (kinetic and available potential) at the time-spans 2.3, 4.5 and 5.3 hours (indicated with black numbers in panel a,b and c). This energy leakage, in turn, leads to the formation of a system of secondary internal waves attached to the initial wave. This system is clearly seen behind the leading wave in Figure 3b and 3c. Note that the intensity of wave-topography interaction occurring near the straits boundaries is much stronger at the southern periphery (near the African coast) than that developing in the northern part of the strait (near the Spanish coast).

The reason is that the Coriolis force leads to the energy transition from the central and the northern parts of the wave to the right hand side boundary of the strait. At the final stage of evolution the internal waves (both initial, and secondary) leave the strait and enters into the Alboran Sea (Figure 3d). After 10 hours of propagation since the time span presented in Figure 3d, the initial wave is transformed into a structure which resembles the characteristics of the satellite image presented in Figure 1. An obvious similarity of these two patterns (produced numerically and acquired from space) leads to the conclusion that the model clearly captures the basic features of the phenomenon, i.e. the three-dimensional evolution of LAIWs in the Strait of Gibraltar and beyond it.

The very last remark about the experiment, when the system of internal waves leave the Strait (figure 3d), they contain 21 % of the initial total energy. The bulk of it, 79%, is either dissipated due to lateral effects (wave breaking, mixing, viscosity), or transformed into secondary scattered short-scale internal waves located beyond the contour.

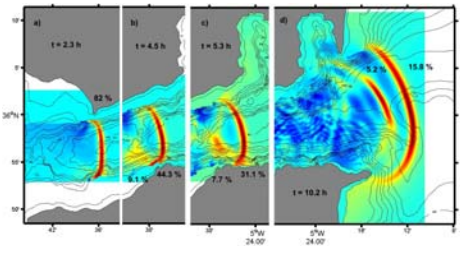

Figure 3.- Sea surface topography produced by a LAIW of depression at different stages of evolution. Initial amplitudes of propagating wave was 83m. Surface elevations and depressions are shown by red and blue colours, respectively. Bottom topography is shown by solid lines. The black numbers nearby show how much wave energy (in percents to the initial wave energy at t=0) .

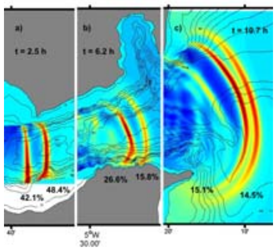

Figure 4.- The same as in Figure 3 but for two propagating LAIWs with initial amplitudes of 83 and 73m for the first and second waves, respectively.

EVOLUTION OF WAVE TRAINS

The results of the one-wave experiment can give some ideas on the behavior of wave packets in the strait. As it was mentioned above, the propagating LAIW radiates its energy in the course of evolution, and this process eventually leads to the formation of a second solitary wave with the comparable amplitude. Applying this result to the propagation of wave trains it is not clear, however, whether these secondary waves radiated from the leading wave will propagate further independently as solitary waves (scenario 1), or they will be absorbed by the subsequent incoming LAIWs (scenario 2). The answer to this question can be found in Figure 8 where three stages of evolution of two initially isolated LAIWs are presented. The methodology of this experiment is the same as described above. The only distinction is that the initial field in this experiment contains two LAIWs with amplitudes of 83m and 73m for the leading and second waves, respectively, instead of only one wave as it was in the first run. Scrutiny of the wave patterns presented in Figure 4 shows that scenario 2 of the wave evolution is realized. In other words, the waves radiated by the leading LAIW near the strait boundaries are absorbed by the second LAIW. This process of absorption is so efficient that the second wave is getting even larger than the first one (figure 4b). Another interesting effect, i.e. wave-wave interaction, can develop in the wave packet at the final stage of evolution. The nonlinear collision of two internal solitary wave is possible when the leading wave is not the largest one. If this is the case, the rear internal wave starts to overtake the leading one because of the greater phase speed. This overtaking eventually leads to the collision of two internal solitary waves during which the rear wave transfers part of its energy to the leading wave. Note, however, that only initial stage of this process is presented in Figure 4c. In the next numerical experiment the initial internal wave packet contains three internal waves with amplitudes of 83, 73 and 63m of the first, second and third waves, respectively. Figures 5a and 5b show two intermediate stages of the packet evolution. Scrutiny of the spatial structure of the wave fields in these two patterns as well as the comparison them with each other and Figures 4 allows one to conclude that the mechanism of energy transfer from the leading wave to the wave tail works in the "three-wave" experiment even more efficiently.

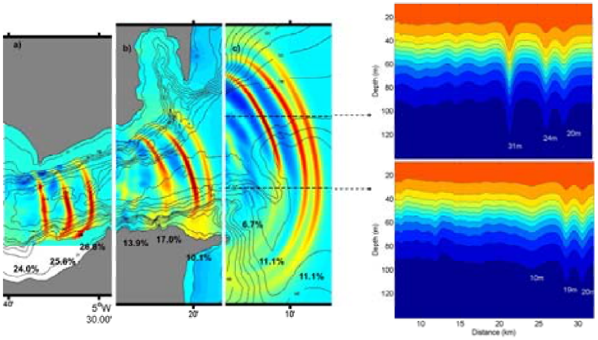

Figure 5.- Sea surface topography produced by a rank-ordered system of LAIWs of depression. Initial amplitudes of propagating waves were 83, 73 and 63m (from the right to the left), respectively. All designations are as in Figure 3. The panels on the right side of the figure show two cross sections of the density field indicated in panel c).

SUMMARY AND CONCLUSIONS

The results of the numerical simulations presented above illustrate a number of important aspects on the dynamics of the tidally generated internal waves in the Strait of Gibraltar. In particular, it was found that initially two-dimensional packets of LAIWs propagating along the strait reveal remarkable three-dimensional behaviour. Three-dimensional characteristics of the wave dynamics include multiple reflections from lateral boundaries and wave breaking near the shoreline, leading to a fast attenuation of the propagating waves.

Another result found in the present study concerns the wave-wave energy transfer in internal wave packets propagating along the strait. The leading wave loses its energy much faster than those in the wave tail. The latter in fact absorb part of the energy scattered by the leading wave in the course of its evolution. As a result, the initially rank-ordered wave packet (the usual assumption for the generation mechanism) loses its regular structure and transforms into a non-rank ordered wave packet in term of energy.

It should be noted that the rank-ordered structure of wave packets arranged by the energy does not necessarily mean the similar rank order in terms of wave amplitude.

This effect takes place because of substantial three-dimensionality of the problem. In some cross-sections the amplitude of successive waves can be even larger so that the greatest amplitudes can be recorded in the less energetic (in global sense) wave. Such an example is illustrated by Figure 5 where two cross-sections of the same wave packet are presented. This contradictory result can be explained by a substantial cross-strait variability of the wave characteristics which is the consequence of the Coriolis force, three-dimensional effects such as wave reflection, focusing and refraction.

From the point of view of observations, this randomness would explain the similar proportion of rank and non-rank ordered LAIWs packets found in the temperature records at the mooring P (Figures 1 and 2). It is expected that these results, obtained for the Strait of Gibraltar, can also be valid for some others strait of the World Ocean.

References:

Bryden, H. L., and T. H. Kinder (1991), Steady two-layer exchange through the Strait of Gibraltar, *Deep Sea Res.*, Part I, **38**, S1, S445–S463.
Munk, W. (1997) Once again: once again tidal friction. Progress in Oceanography, **40**, 7-35.
Pacanowski, R. C., and S.G.H. Philander (1981), Parameterisation of vertical mixing in numerical models of Tropical Oceans. *J. Phys. Oceanogr.*, **11**, 1443-1451.
Vlasenko V., J.C. Sánchez Garrido, N. Stashchuk, J. García Lafuente and M. Losada (2008), Three Dimensional Evolution of large-amplitude internal waves in the Strait of Gibraltar, *Journal of Physical Oceanography*, Submitted.