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Short period sea level oscillations at Strait of Gibraltar: Observations versus model results

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A B S T R A C T

Tide gauge records from different ports of the Strait of Gibraltar area show events of short period oscillations (minutes to tens of minutes) that persist for several days although its charactestic duration is of the order of a day. These events are observed throughout the year although, when characterized by variables that account for their amplitude and duration simultaneously, they are biased toward summer months.

The frequencies of these oscillations, which accumulate energy within bands centered at 7.5, 12, 19, 25 min^{-1}, are characteristic of each port, with Tarifa showing a more selective tuning than Ceuta or Algeciras. The numerical model developed to investigate these oscillations confirms that they correspond to harbor resonance excited at the mouth of the port by oscillations in the Strait.

1. Introduction

The exchange of Mediterranean and Atlantic waters through the Strait of Gibraltar is a complex phenomenon which responds to physical forcing of different temporal and spatial scales (García Lafuente, 2002). The shortest time-scale that can be found in the Strait of Gibraltar corresponds to high-frequency sea level oscillations of only a few minutes called short period oscillations (SPO hereinafter) that affect the ports in the Strait area (Fig. 1). To this regard, it is important to remark that tide-gauge observations in Algeciras, Ceuta and Tarifa (Fig. 2) are frequently used as indices for the exchange, and these observations can be contaminated by the SPO. Its persistence of even days and ubiquity discard problems with the gauge devices and point to the existence of a physical mechanism. The presence of SPO along the year gives continuity to the phenomenon and adds interest to the topic as it suggests that suitable physical conditions are periodically met to trigger the oscillations.

Agitation inside ports depends on the period of the waves, the characteristics of the boundary and the geometry as well as on reflection and energy dissipation. Forcing waves may cause abnormal water fluctuations and unexpected damage if their period coincides with one of the normal modes of oscillation of the port (resonance). Resonant oscillations can have direct influence on the management of harbors, shipping and coastal utilization. Some examples are provided by "rissaga" events in the port of Ciutadella in the island of Minorca, Spain (Monserrat et al., 1991). Destructive SPOs at the port of Valencia (Del Río et al., 2004) or unexpected oscillation in open sea like those of the island of Alborán (Delgado, 2005) are less harmful examples of SPOs in other parts of Spanish. Sea level oscillations of a similar pattern are observed to occur regularly at certain places in the World's oceans and have specific local names: rissaga, marrubio, milghuba or abiki to mention a few. These waves are mainly associated with different types of atmospheric disturbances (atmospheric gravity waves, pressure jumps, frontal passages, squalls) which normally generate barotropic ocean waves in the open ocean and amplify them near the coast through specific resonance mechanisms (Monserrat et al., 2006)

Obviously, the influence of these SPOs on the water exchange or the internal dynamics of the Strait is negligible but yet the topic appears to be interesting in itself. The objective of this work is to investigate the occurrence of SPOs and provide a theoretical framework that explains their excitation in the region of the Strait of Gibraltar. The hypothesis is that the excitation of SPOs is closely related to the geometry of the different ports. The paper first addresses the characterization of SPOs in the three ports studied, Algeciras, Ceuta and Tarifa, quantifying their prevailing frequencies and other issues of interest such as their spatial coherence and its

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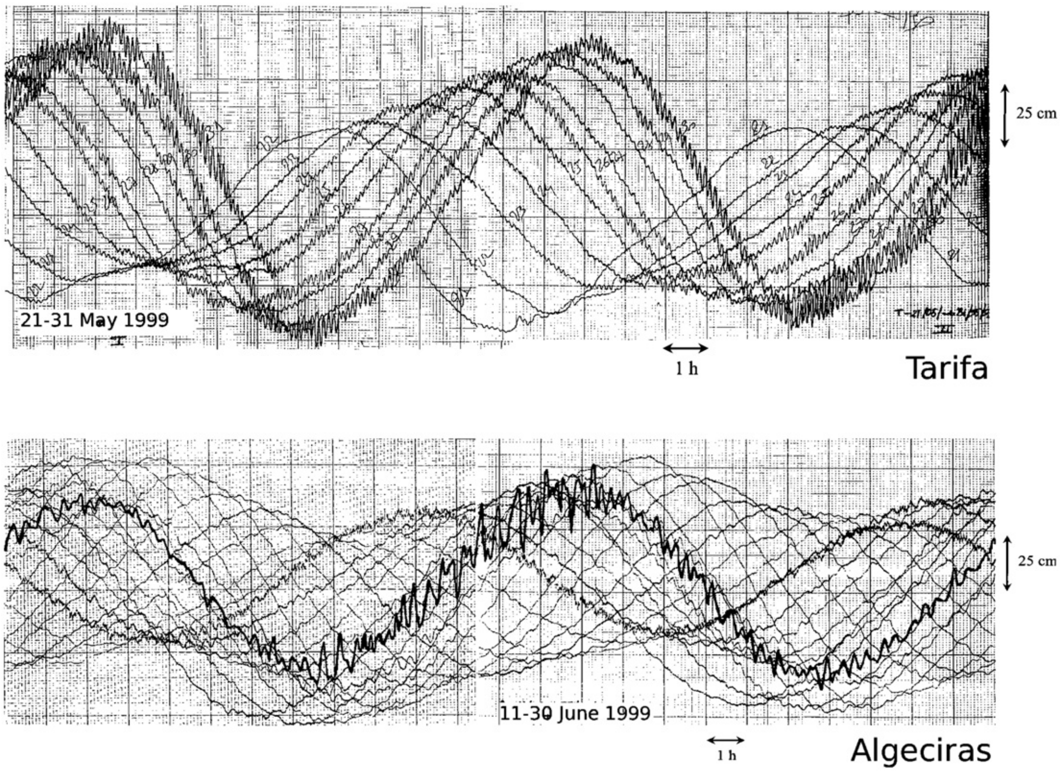

Fig. 1. Top: tide-gauge record in Tarifa. SPOs of large amplitude are evident on May 30th and 31st, although they were visible since May 25. Bottom: tide-gauge record in Algeciras. Thick line highlights June 28th.

temporal distribution. Section 3 numerically investigates the nature of SPOs by means of a barotropic model of normal modes adapted to the ports' geometry (local domain) and Section 4 discusses the findings of the paper.

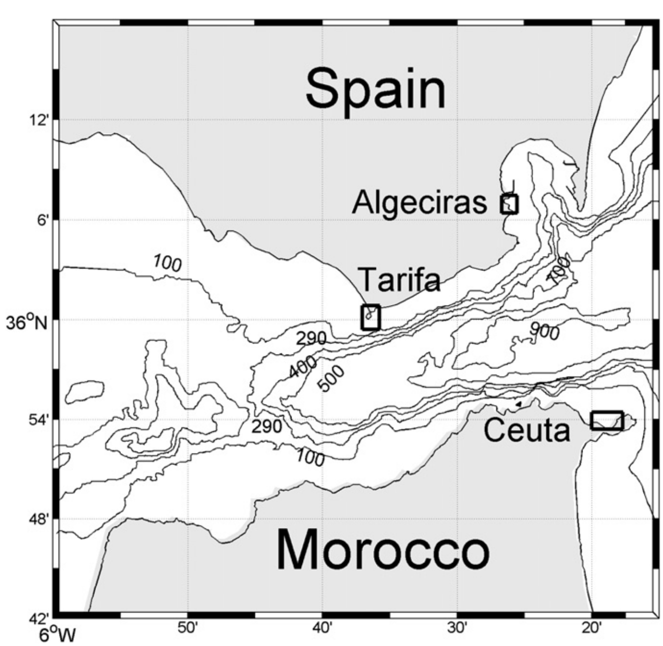

Fig. 2. Map of the Strait of Gibraltar showing the bathymetry (isolines of 0, 100, 290, 400, 500, 700 and 900 m depth) and the ports where SPOs have been observed.

2. Observation and characterization of short period oscillations in the Strait of Gibraltar

Sea level data come from the historical analogical records the *Instituto Español de Oceanografía* (IEO) has on the aforementioned ports, two examples of which are presented in Fig. 1. The records have been digitized at a sampling interval of 40 s to ensure the correct characterization of those SPOs whose typical periods are around 10–20 min. Prior to the digitization, a large set of graphs were scrutinized to identify SPO events of sustained amplitude and duration with the following criteria: (a), the quality of sea level records on which to apply the method of digitalization (details of the lengthy task of digitization have been omitted), (b) the possibility of collecting simultaneous events in the three locations, (c), if case (b) is not met, then search for simultaneous events in 2 of them, and (d) that they had some time coverage of the different seasons. Finally 10, 8 and 13 events were identified and digitized in Algeciras, Ceuta and Tarifa between 1991 and 1992, respectively, and represent the bulk data of this study. The events exhibit amplitudes of 1–10 cm, which are less than one order magnitude of the tidal amplitude, and duration ranging from 6 h to nearly three days.

Fig. 3a–c show the spectral density of SPO events longer than 38 h performed with the multitaper method (Thomson, 1982). The length allows for a satisfactory spectral resolution of the different peaks. All spectra show energy between 7 and 30 min and suggest a clear relationship between the location and the excited frequencies. For convenience four frequency bands named A (7–8 min), B (11–14 min), C (17–21 min), and D (23–27 min), have been defined. SPOs at Algeciras and Ceuta (Fig. 3a and b) present maximum spectral density in band B. Algeciras also shows energy in band D that is not excited in Ceuta and, occasionally, in band C, which is not present at all in any of the other two ports. The spectral density at

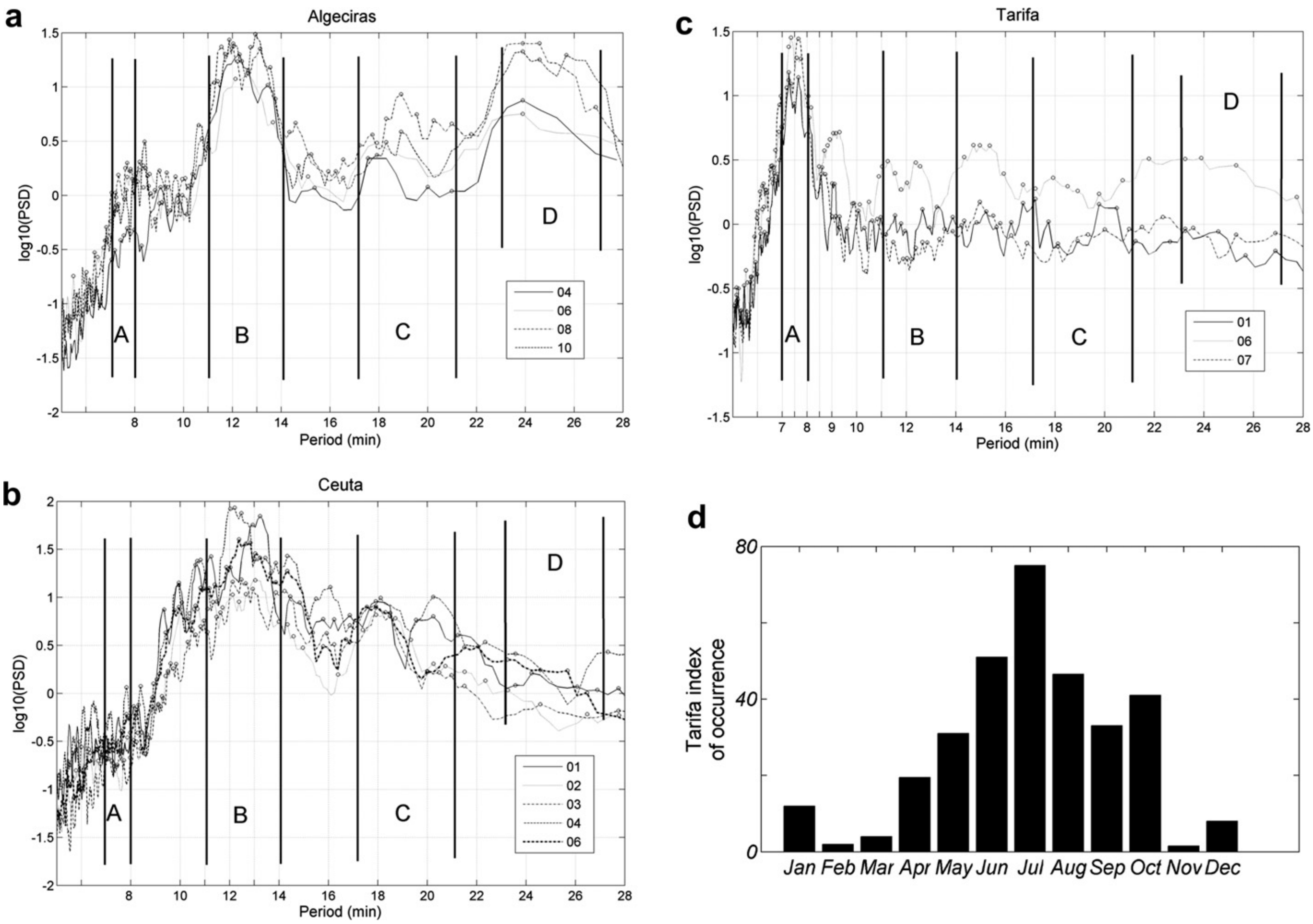

Fig. 3. Spectral density (logarithmic scale) of SPO at Algeciras (a), Ceuta (b) and Tarifa (c). Energy bands A, B, C and D (see text) have been indicated The different lines in each spectral density (a, b or c) label an SPO episode in one location; this label has no correspondence with label in the other two locations. (d) Monthly SPO index (see text) showing more activity in summer than in winter.

Tarifa (Fig. 3c) concentrates on a narrow band A with energy exceeding the energy in the other sites.

SPOs can appear at any time in the year, but neither with the same intensity nor with the same duration. In order to quantify this occurrence, the index *I* defined:

$$I = \sum_{\text{Events}-\text{months}} \text{amplitude (cm)} \times \text{duration (days)}$$

has been used to investigate the monthly persistence and amplitude of SPOs. To do so, data from the Tarifa tidal gauge from 1998 to 2002 was used due to the very good quality of time series. Fig. 3d shows that more suitable conditions to trigger SPOs are met from April to October. The maximum is found in July when *I* reaches maximum values due mainly to the intensity of the SPOs rather than to their duration. In February, March and November *I* index takes negligible values although the phenomenon is still detectable.

Spectral analysis shows the existence of SPOs but says nothing about the time they took place. An interesting question is whether or not SPOs in different ports have a common forcing. Empirically, the finding of SPO in marigram of one port guaranteed success in finding SPO registration in other ports. Simultaneous SPOs have been searched; carefully scanned so as to maintain theoriginal quality and, finally, only a few examples between Algeciras–Ceuta and Tarifa–Ceuta were found. Cross-correlation analysis is not a good tool to investigate the spatial correlation of SPOs since the different ports tend to excite their own frequencies (Fig. 3), which in turn will give near-zero correlation coefficients even though they may have a common origin. The S-transform technique, which gives instantaneous information about the frequency composition of the signal (Stockwell et al., 1996), has been used instead. The maximum of amplitude at the prevailing frequency band in each port provided by the S-transform has been extracted to obtain a time series of the amplitude of SPOs. Fig. 4a and b show two examples of these series among another 6 examples of simultaneous SPOs in 1991–1992 (best observational period). They show how the correlation between Ceuta and Tarifa is greater than between Ceuta and Algeciras in spite of the fact that these two ports have energy in the common band B (the other examples not shown suggest the same). A speculative explanation is that Tarifa and Ceuta are “open sea” ports affected by similar offshore dynamics while Algeciras remains isolated as it is well inside a natural embayment. The analysis suggests a spatial scale for the driving force of the length of the Strait of Gibraltar.

3. Normal gravitational modes of the ports

3.1. The numerical model

The selective frequency response at the different sites suggests that SPOs are the excitation of normal modes of the ports by

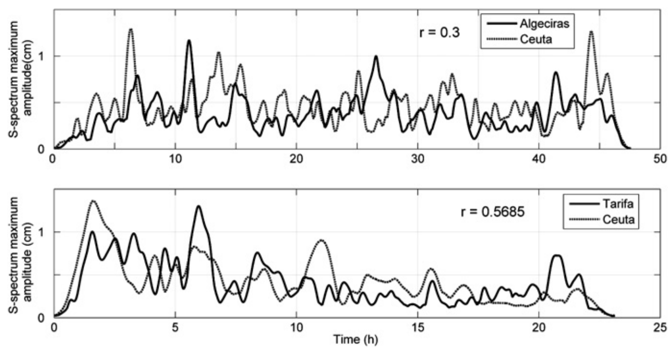

Fig. 4. a) Time series of the S-spectrum maximum amplitude within the B-band at Algeciras Ceuta. b) Same as a) for the D-band at Tarifa and B-band at Ceuta.

suitable conditions. To investigate this hypothesis a two-dimensional, barotropic, frictionless model that does not include earth-rotation has been used. The model equations are:

$$\frac{\partial \vec{u}}{\partial t} + g\vec{\nabla}\eta = 0 \qquad (1)$$

$$\frac{\partial \eta}{\partial t} + \vec{\nabla}\cdot(h\vec{u}) = 0 \qquad (2)$$

where u is the horizontal velocity η is the sea level and h the water depth. The general solution is obtained after separating spatial and temporal dependence (which is the assumed periodic of the form $e^{i\omega t}$):

$$\eta(x,y,t) = \sum_j e^{i\omega_j t}\eta_j(x,y) \qquad \vec{u}(x,y,t) = \sum_j e^{i\omega_j t}\vec{u}_j(x,y) \qquad (3)$$

Replacement of (3) in Eqs. (1) and (2) gives a set of uncoupled equations (Wilson, 1972; Sobey, 2006) that lead to an eigenvalue problem. The equation for η is:

$$\vec{\nabla}\cdot(h\vec{\nabla}\eta) = -\frac{\omega^2}{g}\eta \qquad (4a)$$

which is solved with the conditions

$$\eta = 0 \text{ at the open boundary} \qquad (4b)$$

$$h\vec{\nabla}\eta\cdot\vec{n} = 0 \text{ at the solid boundaries} \qquad (4c)$$

of no oscillations in the open boundary and no normal flow to the solid boundaries.

The eigenvalue problem (4a,b,c) is linear, independent of the meteorological forcing. It provides a complete basis function set to represent the irrotational motions in the study area (Kowalik and Murty, 1993). It is solved numerically applying finite element discretization (Partial differential equation toolbox of Matlab, 2008). A panels of Figs. 5–7 show the spatial discretization carried out for each port. To avoid numerical instabilities, the bathymetry has been smoothed by averaging over several elements where depth gradient is too sharp. The average is constrained by volume conservation, which is preserved. B panels of Figs. 5–7 shows the smoothed bathymetries.

3.2. Normal modes of the ports

The mouth of Ceuta port is the natural open boundary to close the domain and the place to prescribe the boundary condition (4b). Panel C of Fig. 5 shows the fundamental mode of the port that exhibits the expected pattern of a quarter-wave standing oscillation with the antinode located in the western part and the prescribed node at the mouth. The model gives a period of 12.8 min for this oscillation, within band B in good agreement with observations.

The geometry of Tarifa port does not suggest a unique place to define the open boundary to close the domain. Three choices (labeled I, II and III in panel A of Fig. 6) have been tried and the period of the fundamental mode of each of them has been compared with observations. Choice III that closes the port by the innermost section gives a period of 4.3 min, far from those deduced from observations, and a spatial pattern with near-zero amplitude in the position of the tide-gauge, which also disagrees with observations. The two other choices give fundamental oscillations of 7.8 min (option I) and 7.0 min (option II) inside the band A. When tides are taken into account option I appears more realistic, as shown later on. Panel E of Fig. 6 shows the spatial pattern of the fundamental mode of this option, which corresponds with a quarter-wave resonance. For this configuration the tide-gauge remains between the antinode at the head and the node at the mouth, indicating that the amplitude of the oscillation at the head would be greater (by around 20–30%) than that recorded by the tide-gauge and therefore the phenomenon be more relevant.

The building of new docks in Algeciras has modified the old geometry of the port and quite probably the features of SPOs presented in this article. Panel B of Fig. 7 is the bathymetry of the 90 s. A first glance line (III) appears to be the right place to prescribe the open boundary. Panel C shows the spatial pattern of the fundamental mode (8.7 min period) that lies outside of band B. A detailed inspection of the bathymetry shows rocky shoals north and south of the inlet's entrance that break at the sea surface. For this reason new possibilities (lines I and II), which enlarge the volume in which oscillations are excited, have been tried. Panels D and E of Fig. 7 show the shape and period of the fundamental mode for these choices. The associated periods are 13.7 and 12.4 min within band B, matching the observations, and in both cases the antinode is located near the tide-gauge location.

3.3. Influence of the vertical tide

Water depth $h(x,y)$ in Eq. (4) is not a function of time and is referred to the port datum (the lowest sea level achievable). Resonant periods computed above are only valid for this specific situation. However, SPOs can take place at any point of the tidal cycle (Fig. 1) in which case the water depth becomes a function of time that changes significantly during the tidal cycle since tidal range can be 20% the mean depth of the port. Periods of the fundamental modes of oscillation of the ports will change with time accordingly. The time-dependent water depth, h', would be

$$h'(x,y,t) = h(x,y)\Delta h(t) \qquad (5)$$

where $\Delta h(t)$ is the contribution of the vertical tide (current sea level variation above the local datum). It is worth mentioning that SPOs and tides act in very different frequency ranges and quite probably they interact linearly. In this case, tides, $\Delta h(t)$, may be taken as quasi-stationary modification of $h(x,y)$ and the time-dependent period of the fundamental modes at a given time t_0 can be computed solving the eigenvalue problem (4) with $h'(x,y,t_0)$ instead of $h(x,y)$. Table 1 shows the modification of the period of the fundamental modes in the three ports produced by tides. The range

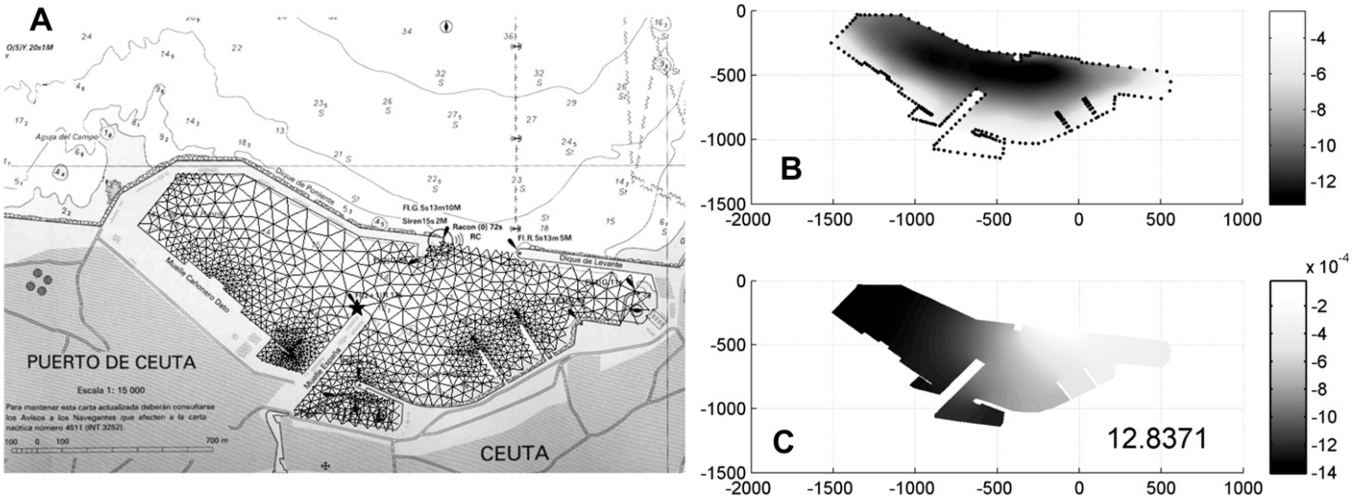

Fig. 5. (A) Grid of the numerical model at Ceuta. The star marks the position of the tide-gauge. (B) Bathymetry used in the numerical model. (C) Spatial pattern of the fundamental mode (period of 12.8 min). Axis units are meters from an arbitrary origin. Contours in panel C are meters $\times 10^{-4}$ Notice that these units are sowewhat arbitrary due to the linearity of Eq. (4).

of variation would partially explain the bandwidth of the frequency bands in the spectra of Fig. 3. We must keep in mind that resolution of observation and the method used to compute the spectra spread energy from peaks to adjacent frequency area too.

4. Discussion and conclusion

Historical analogical records of sea level at three different ports at the Strait of Gibraltar show the recurrent occurrence of SPO that,

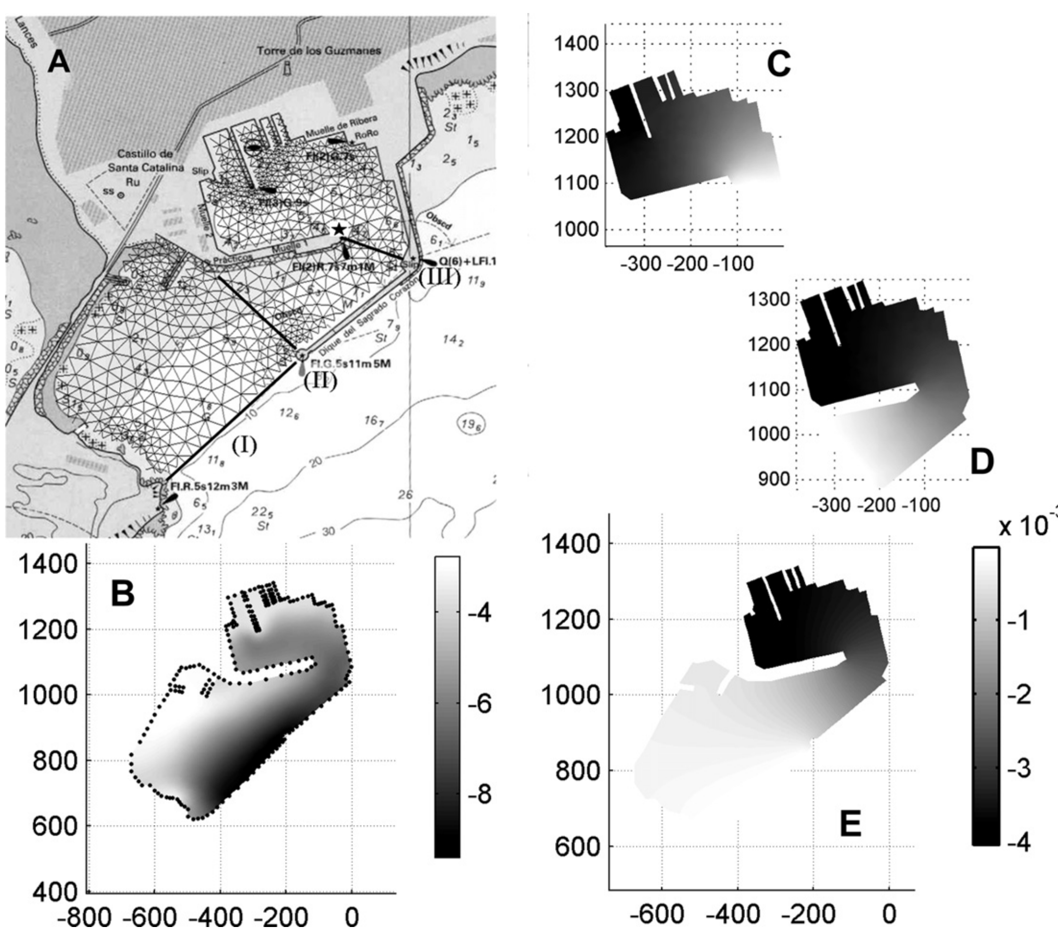

Fig. 6. The same as Fig. 5 for Tarifa. Lines I, II and III indicate three choices of the open boundary. (C), (D) and (E) are spatial pattern of the fundamental mode with period of 4.3, 7.0 and 7.8 min for open boundary at III, II and I respectively.

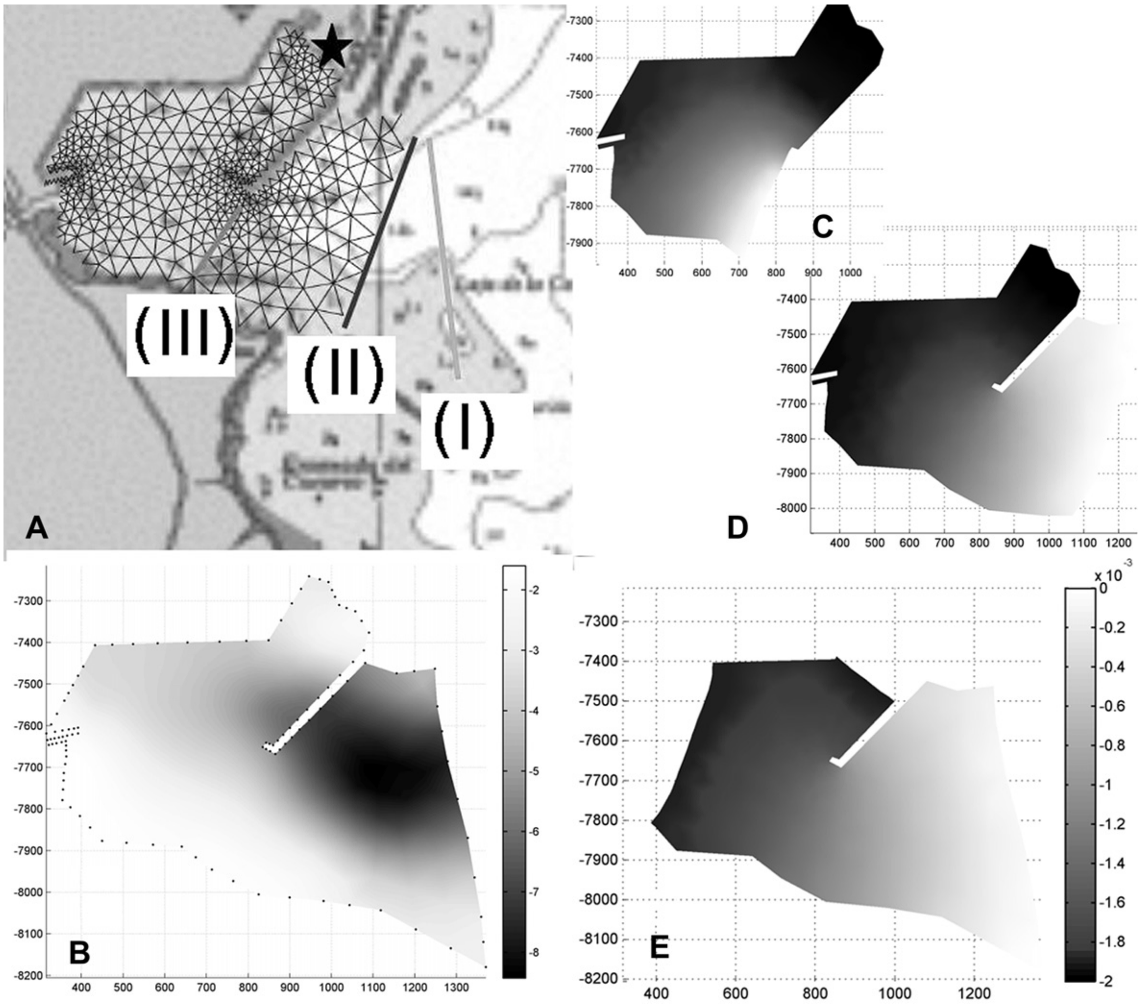

Fig. 7. (A) The same as Fig. 5 for Algeciras. (C), (D) and (E) are fundamental mode with period 8.7, 12.4 and 13.7 min for open boundary at III, II and I respectively.

after a rather laborious digitization process and a conventional spectral analysis, showed periods ranging from 5 to 30 min. The SPOs exhibit a selective amplification of certain frequency band that depends on the location. With the band classification shown in Fig. 3, SPOs at Ceuta and Algeciras tend to crop in band B while Tarifa does so in the higher frequency band A. Occasionally, Algeciras also shows SPOs in bands C and D (Fig. 3) that are not observed in the two other locations. This selective behavior confirms that SPOs corresponds with the normal modes of oscillation of the ports. The observed amplitude at the site of the tide-gauge can reach 10 cm and it will increase toward the head of the ports where the antinode of the standing oscillation is usually found (Figs. 5–7).

Simultaneous events of SPOs have been observed in the different ports; even when the local response means that SPOs have different frequencies, the simultaneity of these wave-trains allows us to speculate on a common forcing whose spatial scale should be at least the size of the Strait. This forcing mechanism appears to be stable during the 10-year record used here in the sense that SPOs show a certain seasonal pattern, especially within band A in Tarifa. Summer gathers the most suitable conditions to trigger SPOs, although it is possible to detect them all year round.

A simplified, barotropic numerical model confirms that the period of the fundamental mode of each port lies within the corresponding experimental frequency band, A in Tarifa, and B in Ceuta and Algeciras. However, bands C and D at Algeciras are not properly modeled with this local domain. A simple tentative calculation using Merian's formula (Kowalik and Murty, 1993) suggests that these bands might be resonant modes of the bay of Algeciras. The eigenvalue problem (4) applied to the bay of Algeciras suggests the same. Tides, which change the water depth periodically, have been incorporated into the model following a quasi-stationary approach (replacing the datum bathymetry by the water depth at a given

Table 1
Period of the fundamental mode of oscillation in each port for three representative moments of the tidal cycle: low water (LW), mean sea level (MSL) and high water (HW). Numerical values of $\Delta h(t)$ have been calculated as average amplitude using the results in Garcia Lafuente (1990). In all cases, $\Delta h = 0$ corresponds with low water.

Port	Tidal status	Δh (m)	T_0 (min)
Tarifa	LW	0	7.8
	MSL	0.55	7.4
	HW	1.10	7.0
Ceuta	LW	0	12.8
	MSL	0.4	12.4
	HW	0.8	12.0
Algeciras	LW	0	12.4
	MSL	0.4	11.5
	HW	0.8	10.8

time of the tidal cycle). They are responsible for a spreading of about 5% around a central value of the fundamental period (the most affected one, see Table 1) and may limit the sea level oscillations observed because the input of energy occur in a quasi resonant condition. Friction, which is not included in the model, is responsible for small frequency shifts and, especially, for the decay of SPOs. Assuming a lineal friction of the form $\vec{\tau}_b = c_b \rho_0 u^* \vec{u}$ with a drag coefficient $c_b\, 4\cdot 10^{-3}$, the frequency shift due to friction is less than $2\cdot 10^{-5}$ s^{-1}, much less than the observed frequencies that lie in the range $0.5–1\cdot 10^{-2}$ s^{-1}. Notice that a greater value has been chosen for c_b above than the standard value of $1.5\cdot 10^{-3}$ to emphasize the effect of friction which, nevertheless, remains negligible. Friction does not significantly change the natural frequency of oscillation. The persistence of SPOs during many cycles shown in Fig. 1 also indicates a secondary role for friction that, in any case may be included later as a perturbation in the time evolution equation.

The main unresolved question is what phenomenon excites these normal modes. Most probably they are uncorrelated with issues related to the dynamics of the water exchange through the Strait. Neither do they seem to be linked to seiches, induced by wind stress, as it cannot account for the amplitude of the largest observed SPOs. The bias of SPO to summer (Fig. 3D) recalls the findings of Monserrat et al. (2006) who reported the largest "rissagas" in the Balearic area in summer linked to favorable summertime conditions for the occurrence of atmospheric gravity waves in the Mediterranean area. We speculate that fluctuations in wind speed and/or atmospheric pressure induced by similar atmospheric gravity waves in the Strait area could generate low-frequency gravity waves at sea that excite a resonant response in the ports. Obviously high-frequency sampling of atmospheric conditions during periods of SPO occurrence is necessary to validate this hypothesis.

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