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A note on sea-breeze-induced seasonal variability in the K_1 tidal constants in Cádiz Bay, Spain

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Abstract

The response of Cádiz Bay to sea-breeze wind stress and tidal boundary forcing—individually and in combination—is studied using a 2D depth-averaged, non-linear, high-resolution hydrodynamic model. Linear superposition of the solution for the K_1 and S_1 constituents, like the solution obtained with an allowance for both the input functions together, is shown to give rise to a modulation of the K1 tidal dynamics. It is precisely this modulation which is responsible for the observed seasonal variations in the K_1 tidal constants in Cádiz Bay.

Keywords: sea breeze; K_1 tidal modulation; numerical modelling; Cádiz Bay

1. Introduction

As has already been indicated elsewhere, the atmospherically induced tidal variability shows up in the upper Delaware Bay where, according to Wong and Trowbridge (1990), it is due to the interaction of wind waves and low-frequency currents with tides. Another example of the tidal variability on the seasonal time scale was provided as applied to Cádiz Bay by Tejedor et al. (1997). We shall show that the observed seasonal variations in the K_1 tidal constants in Cádiz Bay, which have not been explained yet, are of sea-breeze origin. Because sea breezes are universally present along about two-third of the earth's coasts (Simpson et al., 1996), such variations can be detected throughout and so their study is of great interest.

Sea breezes have long been known to modify water motion in coastal regions. In particular, O'Brien et al. (1997), Rosenfeld (1988), Craig (1989), Chen and Xie (1997) and Hyder et al. (2002) discussed the impact of sea breezes on diurnal currents in shelf seas. Militello and Kraus (2001) demonstrated that sea breezes could result in the generation of diurnal and higher harmonics of sea surface elevation in nontidal embayments. Pattiaratchi et al. (1997) provided information on sea-breeze-induced changes in wave climate, current velocity and beach topography on a continental shelf. Thus, the role of sea breezes in the development of nearshore processes has been extensively studied. The same cannot be said with respect to the effect of sea breezes on tidal dynamics in coastal waters. All we know is that sea breezes are mainly responsible for the formation of the S_1 solar diurnal tide. A number of tidal lists, including Shureman (1941), Munk and Cartwright (1966) and Zetler (1971), followed this viewpoint. There were, however, dissenters. So, Godin (1990) speculated that the S_1 tide, even though its gravitational potential is weak, is of gravitational origin and determined by a diurnal inequality in the tide-generating force because of a slight asymmetry in the shape of the geoid. The lack of a common opinion is, of course, a distressing fact. Nevertheless, for sea-breeze-induced oscillations with a frequency of 1 cpd do occur, it is necessary to understand whether their interaction with gravitational K_1

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tides causes the observed seasonal variations in the tidal constants in the region of interest. This is the purpose of the present note.

The paper is organized as follows: Section 2 covers the available experimental data on the sea-breeze wind velocity and the K_1 tidal constants in Cádiz Bay. In Section 3 a two-dimensional (2D), depth-averaged, non-linear, high-resolution hydrodynamic model is briefly described. It is applied to simulate the sea-breeze-induced and tidal (appropriate to the K_1 constituent) dynamics—individually and in combination—in Cádiz Bay. Section 4 provides a comparison of model predictions with observational data. Its results make it possible to judge the origin of the observed seasonal variations in the K_1 tidal constants in the region of interest. Concluding remarks in Section 5 complete the paper.

2. The investigation site and initial information

Cádiz Bay is near latitude 36.5°N on the south-west coast of Spain. It faces west towards the Gulf of Cádiz and is landlocked around its south-western, south and eastern margins by the mainland. The bay is subdivided into two parts, the shallower Inner Bay and the deeper Outer Bay, connected by the narrow Puntales Channel (Fig. 1). The bay is relatively shallow, with a maximum depth of 20 m at its seaward edge, and is characterised by predominantly semidiurnal co-oscillating tides with an amplitude of ~1 m for the M_2 constituent and ~0.4 m for the S_2 constituent. The typical amplitudes of the K_1 and S_1 tides are about 0.06 and 0.01 m, respectively.

Inland from the Cádiz Bay coast, the land is flat, terrain heights being less than 100 m, and the temperature contrasts between land and water remain strong throughout the period from spring to autumn. Accordingly, much of the year the Cádiz Bay region is subjected to clearly defined sea breezes penetrating offshore to several kilometres (Lopez et al., 1997).

At Rota near the northern coast and at San Fernando near the southern coast of the bay, two meteorological stations providing regular meteorological observations are in operation. Of all datasets at our disposal, the three-year time series of wind velocity for the period from 1996 to 1998 (during this period monthly tide-gauge and bottom pressure measurements were made) were employed to evaluate representative sea-breeze wind velocities at the Rota and San Fernando stations. With this in mind, a standard spectral analysis of these time series of wind velocity, based on the fast Fourier transformation (FFT) method, was carried out with a sampling interval of 1 h. For a detailed description of the technique used see, e.g., Godin (1972). The obtained spectra showed that sea breezes were marked off by strong spectral peaks at the S_1 frequency, their magnitudes being far in excess of 95% significance levels (Fig. 2). Then, given characteristics of the peaks, amplitudes of the along- and across-shore sea-breeze wind velocity components were calculated, assuming that the S_1 constituent of the wind-velocity spectrum can be specified as a monochromatic oscillation with a certain frequency and amplitude.

We have already mentioned that over the period from 1996 to 1998 monthly tide-gauge and bottom pressure measurements were made at various sites of Cádiz Bay. Their locations, together with the location of tide-gauge measurements at Pto. Cádiz, where these cover the entire year 1989 and the monthly period from 5.02.97 to 6.03.97, are indicated in Fig. 1. These data were harmonically analysed and the resulting tidal constants were verified by inference calculations (Foreman and Henry, 1989), so as to estimate as well as possible the amplitude and phase of every resolvable tidal harmonic. The corresponding values of amplitude and phase for the K_1 and S_1 tidal constituents are listed in Table 1. Their inspection suggests that the K_1 tidal constants undergo seasonal variations. Specifically, at Pto. Cádiz the K_1 tidal elevation amplitude and phase vary over a year by 2.4 cm and 22°, whereas at Rota these vary from winter to summer by 1.4 cm and 6.8°, respectively. That is, the observed seasonal variations in the K_1 tidal constants in Cádiz Bay are appreciable. This fact may be explained as follows: the K_1 tidal response to boundary forcing is obscured by sea-breeze disturbances and cannot be extracted from monthly time series due to the impossibility of separating the K_1 and S_1 signals (Foreman and Henry, 1989). However, if the S_1 signal is present, its superposition on the K_1 signal will produce a seasonal modulation of the K_1 tidal dynamics and, hence, seasonal variations in the K_1 tidal constants. Incidentally, the same reason implying that the K_1 tidal constants for different months cannot be considered as being independent of one another makes it impossible to assess the statistical significance of the observed variations in the K_1 tidal constants. Some of the supporting evidence for these variations comes from the results of numerical experiments presented in Section 4.

Before proceeding further, we briefly describe the model which serves as the basis for predicting the sea-breeze-induced seasonal variability in the K_1 tidal dynamics in Cádiz Bay.

3. The model

The model is based on the mass-conservation and momentum equations in depth-averaged form. Its starting presumption is that the K_1 tide as a tide of gravitational origin is generated under boundary forcing, while the S_1 tide which is of combined (gravitational and sea-breeze) origin is generated under boundary forcing and sea-breeze wind stress. Boundary

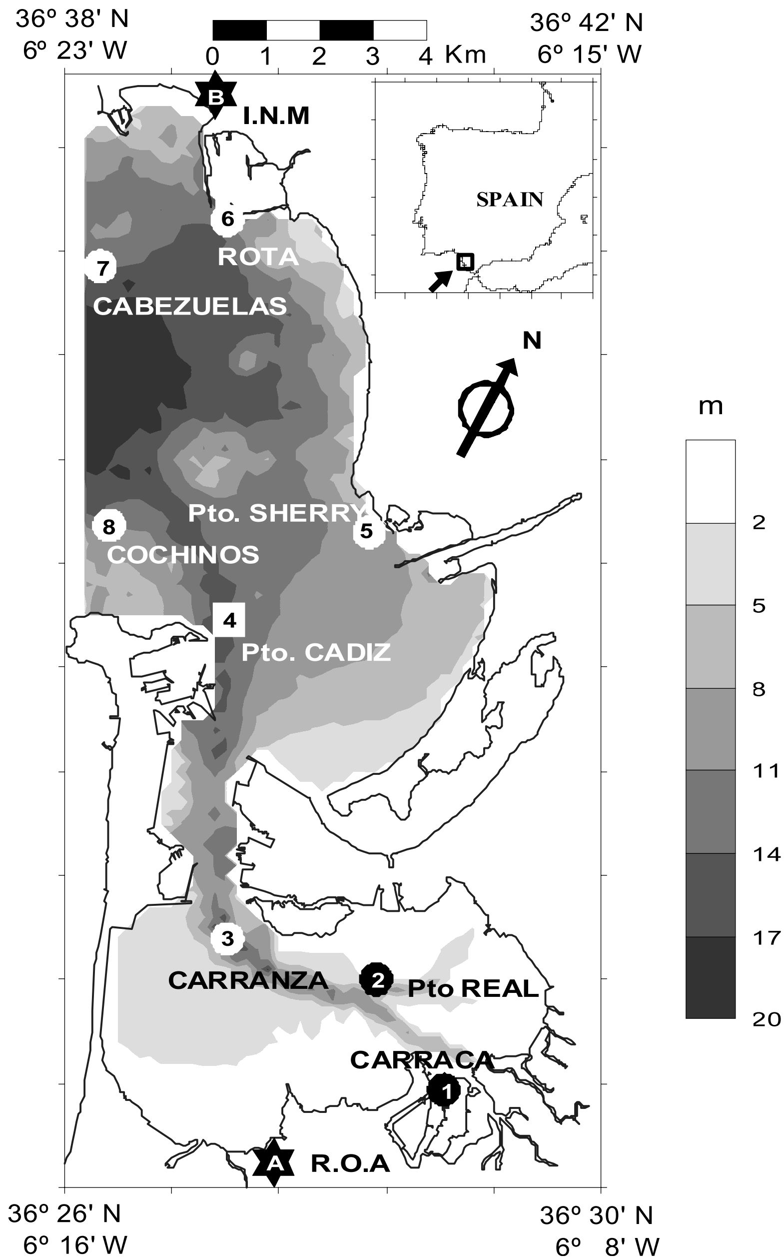


Fig. 1. Map of Cádiz Bay superimposed on the bottom topography (in m). Also shown are the locations of the tide-gauge, bottom pressure and meteorological stations referred to in the text. These stations are marked off with the square, open and filled circles and stars, respectively. A general location map is shown in the text.

forcing for the K_1 and S_1 tides is prescribed through a radiation condition at the open boundary, written in terms of deviations of tidal elevation and velocity from their observed values. The application of this condition ensures that, when disturbances are generated, they all propagate away from the model domain. For the K_1 constituent the observed values of tidal elevation and velocity were set, after prior removal of the sea-breeze effect, from observational data, and for the S_1 constituent these were derived from a solution of the model equations in an extended domain. This is because, without invoking such a solution, the inclusion of the far-field sea-breeze effect becomes impossible. However, if the response of the bay to a local sea-breeze wind stress is of prime interest, boundary forcing for the S_1 constituent is set equal to zero. At the coastal boundary a free-slip condition is imposed. Finally, the state of rest is specified as an initial condition.

The sea-breeze wind stress was related to the sea-breeze wind velocity by a linear resistance law with a constant drag coefficient of 1.2×10^{-3} times the mean wind velocity, and the bottom stress was related to the depth-averaged current velocity by a quadratic resistance law with the drag coefficient 3×10^{-3}. The mean

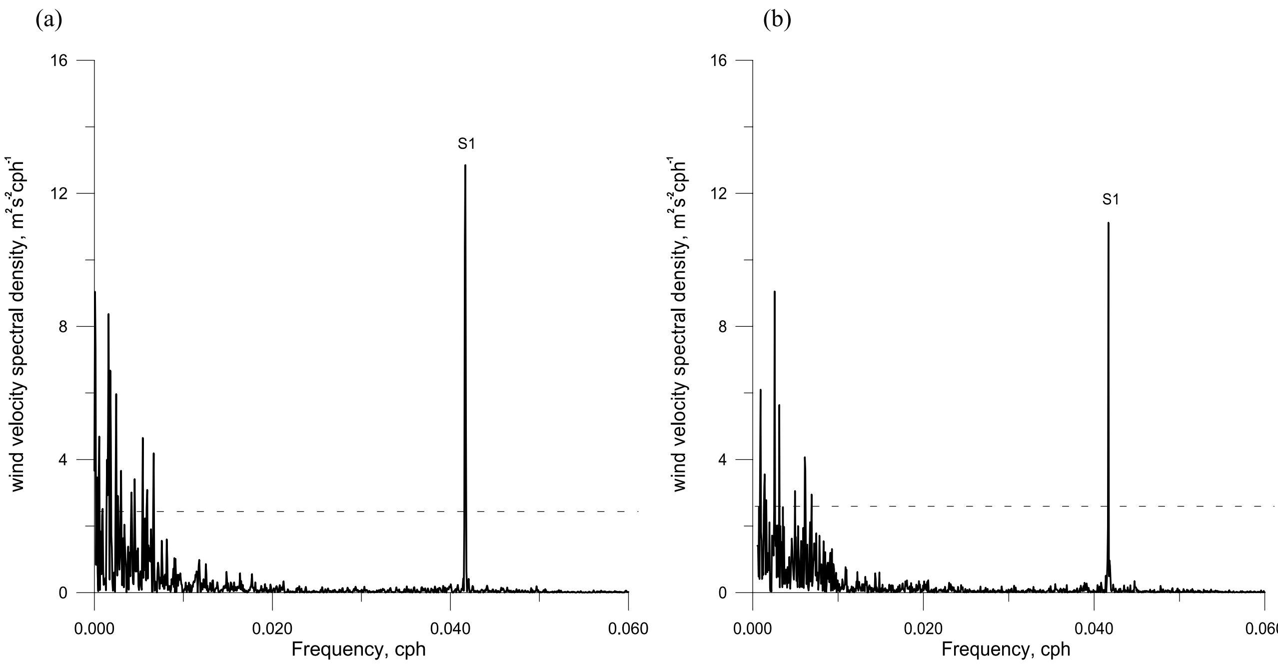


Fig. 2. Spectra of surface wind velocity at Rota (a) and San Fernando (b) for 1996–1998. The dashed lines are 95% significance levels.

wind velocity was specified as 3.7 m s^{-1} from observational data for the period from 1996 to 1998. Amplitudes and phases of the across- and along-shore components of sea-breeze wind velocity for the same period were prescribed to be equal to the averages of their observed values at the Rota and San Fernando stations, that is, 0.91 m s^{-1}, 273° and 0.33 m s^{-1}, 111°, respectively. The bathymetry was taken out from IHM chart number 443.

The model equations were integrated on an Arakawa C staggered grid using a semi-implicit Crank–Nicolson scheme. A spatial resolution of 210 m and time step of 30 s were chosen. For the solution to be smooth the equations of motion were supplemented by a Laplacian horizontal eddy viscosity operator acting on the tidal velocity throughout the model domain except for its boundaries. The horizontal eddy viscosity was kept, for pure computational considerations, to a minimum of 1 m^2 s^{-1} to suppress short-wavelength numerical disturbances but, at the same time, to avoid excessively strong smoothing of the derived solution. The model was run from the state of rest for 10 tidal periods to achieve a stable time-periodic solution. After establishing this solution the model run was continued for one more tidal period so as to determine the K_1 and S_1 tidal constants. Then cotidal charts and the maps of tidal velocity ellipse parameters were constructed.

Additional details of the numerical scheme as well as a verification of the model may be found in Álvarez et al. (1997) and Álvarez (1999). Here, although a sensitivity study to the model set-up is beyond the scope of the paper, it is nevertheless pertinent to note the following point: when different initial information on wind velocity (e.g., for 1999 instead of the period 1996–1998) is used, maximum distinctions between the fields of the S_1 tidal elevation amplitude and phase amount to

Table 1
Periods of tide-gauge and bottom pressure measurements and the K_1 and S_1 observed tidal constants at the measurement locations in Cádiz Bay

			K_1		S_1	
Station		Period	Amplitude (cm)	Phase (deg.)	Amplitude (cm)	Phase (deg.)
Carraca	(1)	21/7/96–30/8/96	7.0	47.4	–	–
PTO. Real	(2)	5/12/97–14/1/98	5.7	45.5	–	–
P. Carranza	(3)	11/2/97–13/3/97	5.2	45.4	–	–
PTO. Cádiz	(4)	5/2/97–6/3/97	5.5	40.9	–	–
PTO. Cádiz	(4)	1/1/89–31/12/89	6.2	43.5	1.0	264.4
PTO. Sherry	(5)	11/2/97–13/3/97	5.2	42.1	–	–
Rota	(6)	11/1/96–12/2/96	5.5	35.7	–	–
Rota	(6)	14/6/96–16/7/96	6.9	42.5	–	–
B. Cabezuelas	(7)	11/2/97–13/3/97	5.2	43.8	–	–
B. Cochinos	(8)	11/2/97–13/3/97	5.1	42.7	–	–

0.1 cm and 0.07°, respectively. These are at least one order of magnitude less than predicted values of the above characteristics by themselves and sought—for seasonal variations in the K_1 tidal constants. The latter means that the modelling results discussed in the next section are to a certain extent robust.

4. Modelling results

First the S_1 predicted tidal elevation amplitude and phase will be considered. The first of them is kept nearly constant varying around 1.1 cm no more than 0.1 cm throughout. At Pto. Cádiz where the duration of measurements allows for separating the K_1 and S_1 signals, it is in fair agreement with observational evidence. Namely, the predicted amplitude equals 1.1 cm, the observed one is 1.0 cm. The predicted field of the S_1 tidal elevation phase (Fig. 3a) shows that cotidal lines are nearly orthogonal to the sea-breeze direction, the sea-breeze wind velocity being about 1 h ahead of the S_1 tidal elevation. The S_1 maximum tidal velocities (not shown) occur in the Inner Bay where they are of the order of 1 cm s^{-1}, comparable to the order of the K_1 maximum tidal velocities. Noteworthy also are the local gyres in the field of the S_1 tidal velocity that are associated with the bay geometry. The indicated properties of the S_1 tidal elevation and velocity fields

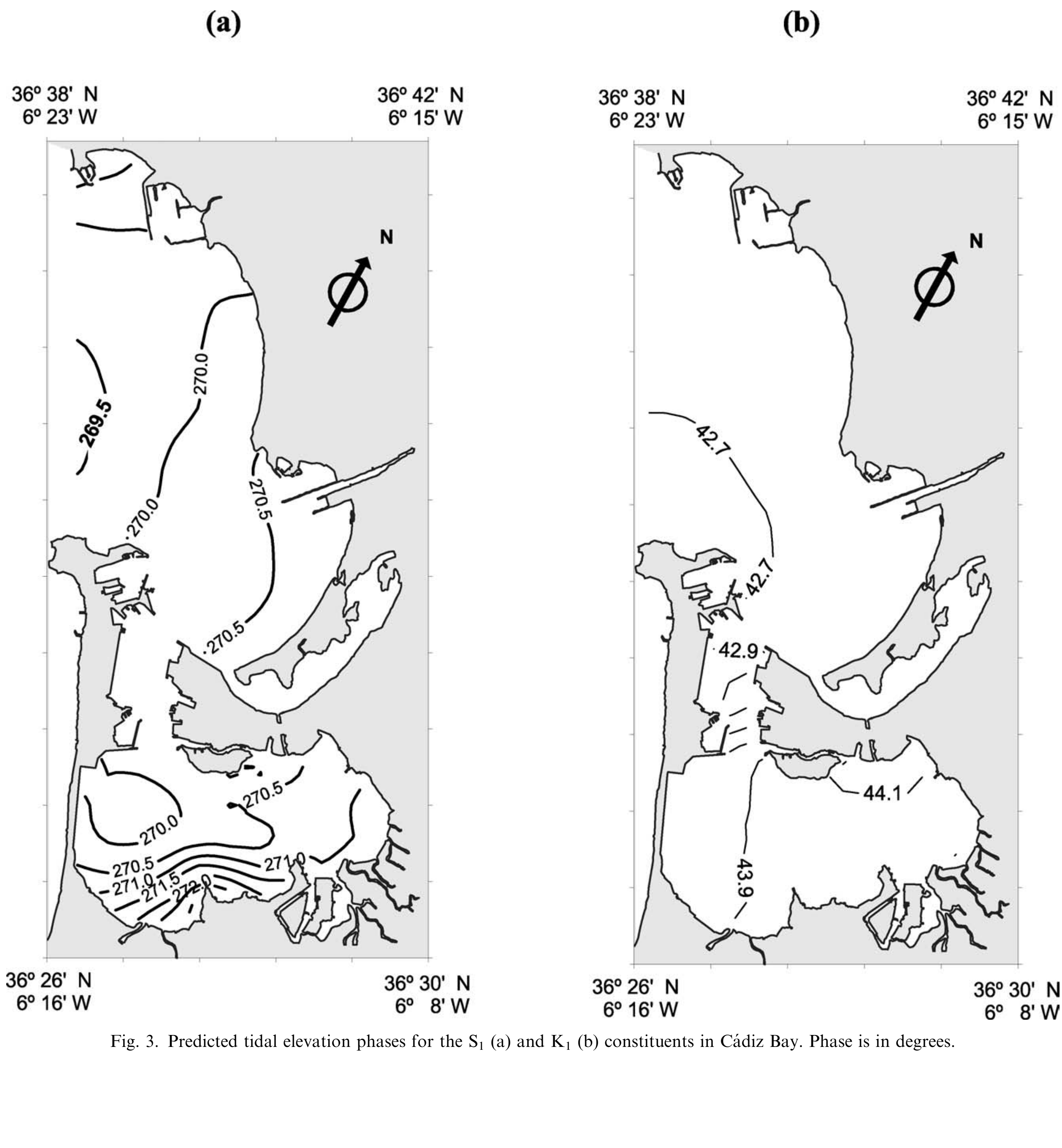
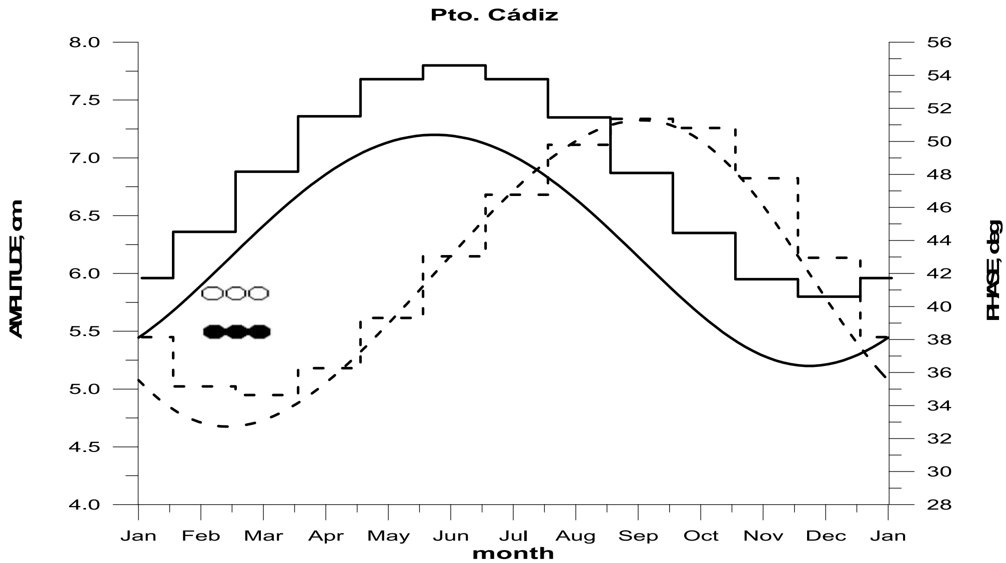


Fig. 3. Predicted tidal elevation phases for the S_1 (a) and K_1 (b) constituents in Cádiz Bay. Phase is in degrees.



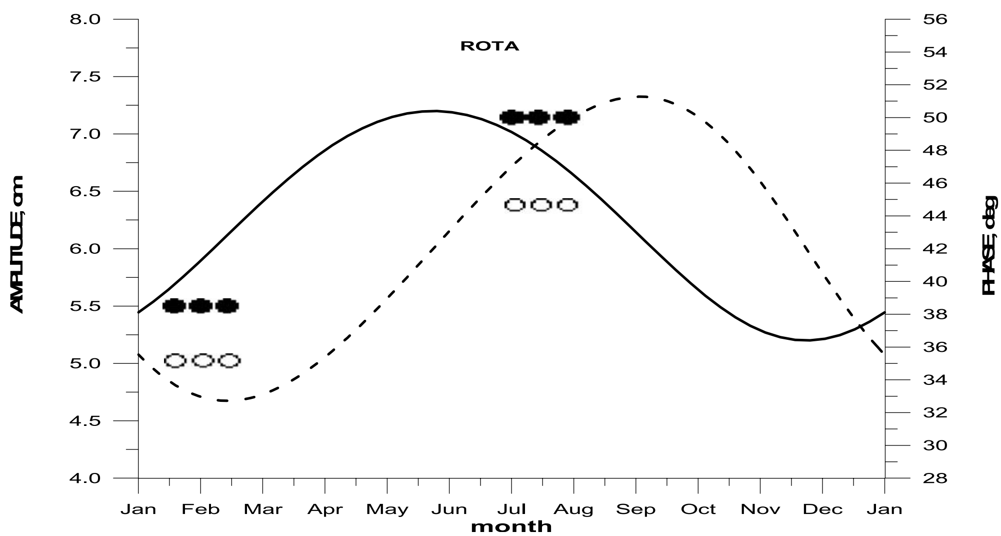


Fig. 4. Seasonal variations in the K_1 tidal amplitude (solid curves) and phase (dashed curves) at Pto. Cádiz and Rota, computed with an allowance for both the input functions together and using linear superposition of the solutions for the K_1 and S_1 constituents. The left scales refer to amplitude in centimetre; the right scales, to phase in degrees. The filled and open circles are the K_1 tidal elevation amplitude and phase, respectively, obtained from monthly time series; the solid and dashed stepwise lines indicate the K_1 tidal elevation amplitude and phase obtained by dividing the yearly time series at Pto. Cádiz for 1989 into monthly sub-series.

remain qualitatively and to a certain quantitatively unchanged depending on whether far-field sea-breeze effects are taken into account or not. This is supported by a comparison of the model predictions obtained in Cádiz Bay and extended domain (not shown).

Once the cotidal chart and the maps of tidal velocity ellipse parameters for the S_1 constituent are available, the K_1 tidal constants appearing in the radiation condition at the entrance of the bay and derived from monthly time series of tidal elevation and velocity measurements can be corrected to eliminate the sea-breeze effect. Thereafter the tidal dynamics problem for the K_1 constituent is solved. The relevant modelling results, exclusive of those for the K_1 tidal elevation amplitude (it varies around 6.2 cm over a few millimetres range) are shown in Fig. 3b. As can be seen, the K_1 tidal elevation gradients in the Inner and Outer Bays have much more uniform spatial distributions and, hence, are less (being of the same order of magnitude) than the S_1 ones. The reverse situation is predicted in the Puntales Channel due to an increase in the along-channel gradient of tidal elevation.

The previously obtained fields of tidal elevation and velocity for the K_1 and S_1 constituents enable us to assess a resulting response of the bay to combined (boundary and sea-breeze) forcing. To this end, let us consider superposition of two harmonics with amplitudes A_{K1}, A_{S1}, phases φ_{K1}, φ_{S1} and frequencies ω_{K1}, ω_{S1}. This superposition, as known, can be expressed in terms of an amplitude- and phase-modulated oscillation:

$$\xi(t) = A_{\mathrm{mod}}(t)\cos(\omega_{\mathrm{m}} t + \varphi_{\mathrm{mod}}(t)), \tag{1}$$

where

$$A_{\mathrm{mod}}(t) = [A_{K1}^2 + A_{S1}^2 + 2A_{K1}A_{S1}\cos(2\omega_{\mathrm{mod}} t - (\varphi_{K1} - \varphi_{S1}))]^{1/2}, \tag{2}$$

$$\tan\varphi_{\mathrm{mod}}(t) = \frac{A_{K1}\sin(\omega_{\mathrm{mod}} t - \varphi_{K1}) - A_{S1}\sin(\omega_{\mathrm{mod}} t + \varphi_{S1})}{A_{K1}\sin(\omega_{\mathrm{mod}} t - \varphi_{K1}) + A_{S1}\sin(\omega_{\mathrm{mod}} t + \varphi_{S1})}, \tag{3}$$

t refers to time.

It is apparent that, because ω_{K1} and ω_{S1} slightly differ from each other, the modulation frequency $\omega_{\mathrm{mod}} = 0.5(\omega_{K1} - \omega_{S1})$ is small compared to the mean frequency $\omega_{\mathrm{m}} = 0.5(\omega_{K1} + \omega_{S1})$, so that Eq. (1) describes a quasi-harmonic oscillation with the frequency ω_{m} and the slow-time-varying amplitude $A_{\mathrm{mod}}(t)$ and phase $\varphi_{\mathrm{mod}}(t)$.

Making use of the above model predictions for the K_1 and S_1 tidal elevations, we can establish the sea-breeze-induced seasonal variations in the K_1 tidal constants at the measurement locations within Cádiz Bay. Some of these variations are shown in Fig. 4. Also shown here are the K_1 tidal constants obtained from all monthly tidal elevation time series at the different locations and from a yearly tidal elevation time series at Pto. Cádiz. The latter was first divided into 12 monthly sub-series and every sub-series was employed to derive more conclusive results with respect to the seasonal variability in the K_1 tidal constants. One can see from Fig. 4 that the model predictions are in good agreement with the observational data and are in essence indistinguishable from those provided by direct simulation of the bay response to the combined impact of sea-breeze wind stress and tidal boundary forcing. This finding (its reflection is coalescence of the appropriate curves in Fig. 4) implies that the effects of non-linear interaction between the K_1 and S_1 harmonics are negligible. But what is more important is that both direct simulation of the combined $K_1 + S_1$ tidal dynamics and linear superposition of the solutions for the K_1 and S_1 constituents show that the observed seasonal variations in the K_1 tidal constants in Cádiz Bay owe their existence to sea breezes.

5. Concluding remarks

In this paper the response of Cádiz Bay to sea-breeze wind stress and tidal boundary forcing has been studied individually and in combination using a 2D depth-averaged, non-linear, high-resolution hydrodynamic model. It is shown that linear superposition of the solutions for the K_1 and S_1 constituents gives rise to a seasonal modulation of the diurnal tidal dynamics. This finding is independently supported by the solution obtained with an allowance for both the input functions together. All of the proceeding leaves no doubt that the observed seasonal variations in the K_1 tidal constants in Cádiz Bay are of sea-breeze origin.

The sea-breeze effect is only one of the reasons for observed variations in tidal constants. These variations are well known to be associated with the seasonal cycle of sea ice in high latitudes. Other reasons are the seasonal wind-wave-generated variability (Kagan et al., 2001) and the interannual variability of non-gravitational nature (Gutierrez et al., 1981). In general, there are grounds for believing that the variability in tidal constants is a commonly occurring phenomenon and that its lack is the exception for the near-coastal shallow regions rather than the rule.

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