



PERGAMON

Continental Shelf Research 21 (2001) 455–471

CONTINENTAL SHELF
RESEARCH

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Barotropic aspects of the dynamics of the Gulf of Naples (Tyrrhenian Sea)

Daniele Gravili^a, Ernesto Napolitano^b, Stefano Pierini^{c,*}

^a *Centro Oceanologico Mediterraneo, Via della Libertà, 37. 90139 Palermo, Italy*

^b *ENEA, Divisione Clima Globale e Mediterraneo, Centro Ricerche Casaccia - F19, Sacco Postale 91, Via Anguillarese, 301. 00060 S. Maria di Galeria (Roma), Italy*

^c *Dipartimento di Fisica, Università dell'Aquila, Via Vetoio, 67010 Coppito (L'Aquila), Italy*

Received 19 January 1999; received in revised form 15 December 1999; accepted 18 May 2000

Abstract

Process-oriented studies are carried out in order to analyze barotropic dynamical features in the Gulf of Naples: gravitational normal mode oscillations (seiches) of the gulf and depth-averaged circulations induced directly by the wind and remotely by the large-scale Tyrrhenian circulation. The shallow water equations are solved numerically in a domain which includes the Gulf of Naples and an external buffer zone whose role is two fold: it is required to remove the effect of a fictitious boundary in the determination of the seiches and it allows the imposition of boundary conditions related to the large-scale circulation in the Tyrrhenian Sea, which contributes to determine the internal circulation via topographic coupling. The seiches are studied by means of a spectroscopic analysis in which eigenoscillations are generated by the relaxation of a wind setup. The eigenperiods corresponding to the main seiches are determined and the corresponding horizontal spatial structures are presented. Good agreement is found when comparing these numerical modelling results with tide gauge records. The wind and boundary-driven depth-averaged circulation in the gulf is then studied by imposing idealized local winds and external currents chosen on the basis of realistic modelling of the wind-driven circulation of the Tyrrhenian Sea. Both quasi-steady and typical transient-time dependence are taken into account, so that a series of circulation schemes is obtained representing typical dynamic scenarios in the Gulf of Naples. The results are related to the observations and good agreement is found. © 2001 Elsevier Science Ltd. All rights reserved.

Keywords: Barotropic dynamics; Numerical modelling; Shallow water equations; Seiches; Gulf of Naples; Tyrrhenian Sea

*Corresponding author. Tel.: +39-0862-433081; fax: +39-0862-433033.

E-mail address: stefano.pierini@aquila.infn.it (S. Pierini).

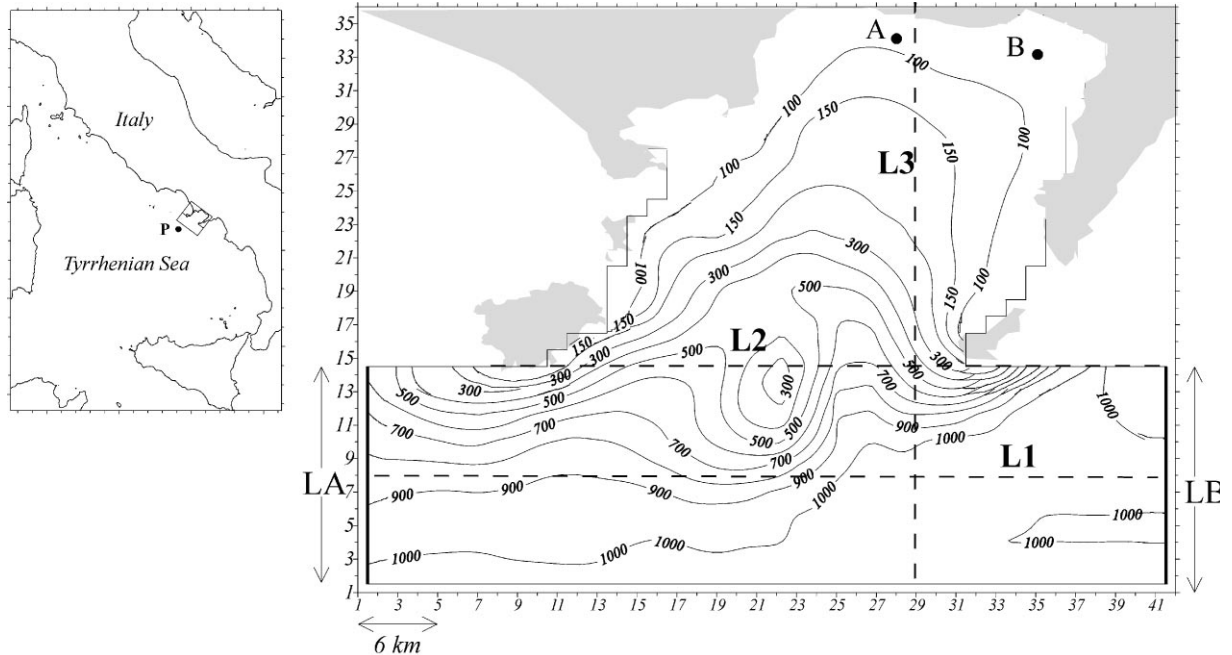


Fig. 1. The Gulf of Naples and the external buffer zone included in the domain of integration. Water depth contours are shown.

1. Introduction

The Gulf of Naples (Fig. 1) is a small semi-enclosed sea located over the continental shelf in the south-eastern Tyrrhenian Sea (Western Mediterranean). The islands of Ischia and Procida and the Phlaegrean Fields in the north, and the island of Capri and the Sorrento peninsula in the south, separate the gulf from the Tyrrhenian circulation. However the latter contributes to determine the interior circulation through the large opening separating the islands of Ischia and Capri, called “bocca grande”, in the middle of which a canyon (“Dohrn”) is located. The Gulf of Naples is very interesting oceanographically because, due to its peculiar morphology, it represents a prototype of a nearly rectangular semi-enclosed sea. In addition, significant polluted fresh water runoff is present in the gulf and the ecological and social relevance of monitoring their spreading in such a highly populated coastal zone is obvious. This makes the understanding of the dynamics in this gulf particularly interesting.

Several oceanographic campaigns have been carried out to gather hydrological and current meter data in the gulf (e.g. Moretti et al., 1977; De Maio et al., 1985). This has undoubtedly contributed to a fairly good understanding of the local regime of circulation in particular meteorological and oceanographic conditions. Theoretical modelling studies are however still lacking but they are needed, for instance, in order to (i) describe and possibly forecast, in detail, the local circulation induced by the simultaneous action of the meteorological forcings and the large-scale Tyrrhenian circulation and to (ii) develop process studies aimed at analysing local

dynamical features in a relatively idealized context, with the aim of understanding the basic dynamical responses to typical forcings.

In this paper the second approach is adopted. Process studies will be carried out aimed at analyzing dynamical features in the Gulf of Naples in a relatively realistic framework, yet with relatively idealized forcing conditions, so as to maintain a degree of simplicity that will allow us to focus on the main aspects of the phenomena. Basically barotropic motions are considered such as the gravitational normal mode oscillations of the gulf (analyzed by Caloi and Marcelli, 1949), which can have a significant influence on the local sea-surface height. The wind-driven circulation is also studied. The first direct effect produced in the ocean by the wind stress is the transfer of energy and momentum in the form of surface Ekman currents. The Ekman pumping and the presence of coasts then produce a sea-surface topography so that pressure-driven geostrophic currents are generated. The latter are typically barotropic so that, although a baroclinic compensation (e.g. as a result of the interaction of baroclinicity with topography) can arise, the analysis of the barotropic component of the wind-driven motion can nevertheless be considered a good first step in a process-oriented study such as the present one.

We therefore make use of the shallow water equations for a homogeneous fluid in a domain which includes the Gulf of Naples and an external buffer zone whose role is twofold: it is required to remove the effect of a fictitious boundary along the “*bocca grande*” in the determination of the seiches and it allows the imposition of boundary conditions related to the large-scale circulation in the Tyrrhenian Sea, which contributes to determine the gulf circulation via topographic coupling through the mechanism of conservation of potential vorticity.

In Section 2 the model and its implementation are discussed. In Section 3 the study of the seiches is carried out. The eigenperiods corresponding to the main seiches are determined through a spectroscopic analyses and the corresponding horizontal spatial structures are presented. Good agreement is found when our modelling results with tide gauge records are compared. In Section 4 a study on the depth-averaged circulation in the gulf, as induced directly by the wind and “remotely” by the large-scale Tyrrhenian circulation is carried out. External boundary conditions are chosen on the basis of realistic modelling of the wind-driven circulation in the Tyrrhenian Sea (Pierini and Simioli, 1998). Simple idealized local wind forcings are also considered. Both quasi-steady and transient forcing are taken into account, so that a series of circulation schemes is obtained representing typical dynamic scenarios in the Gulf of Naples. The results are compared with observations and good agreement is found. Finally, in Section 5 conclusions are drawn.

2. The model

In order to analyze barotropic aspects of the dynamics of the Gulf of Naples, a barotropic circulation model is applied to a domain shown in Fig. 1, which includes the whole gulf (the openings between the islands are assumed closed) and a buffer zone that extends into the Tyrrhenian Sea. The role of the buffer is to avoid “cutting” the gulf along the islands of Ischia and Capri, in so missing the relevant topographic effect of a canyon located in that transect (see Fig. 1), and thereby minimizing the effects of lateral boundaries on the domain of interest. In addition, the buffer allows us to impose prescribed mass fluxes across the lines L_A and L_B representing large-scale Tyrrhenian circulations, as discussed below.

Under the assumption of negligible Jebar effects (e.g. Holland, 1973; Huthnance, 1984) the depth-averaged velocities (here defined as the barotropic component of the motion) satisfy the shallow water equations (e.g. Pedlosky, 1987):

$$\begin{aligned} u_t + uu_x + vu_y - fv &= -g\eta_x + A_H \nabla^2 u + \frac{(\tau_{w1} - \tau_{b1})}{\rho H}, \\ v_t + uv_x + vv_y + fu &= -g\eta_y + A_H \nabla^2 v + \frac{(\tau_{w2} - \tau_{b2})}{\rho H}, \\ \eta_t + (Hu)_x + (Hv)_y &= 0, \end{aligned} \quad (1)$$

where $\mathbf{u}(\mathbf{x},t)$ is the vertically averaged velocity (including the Ekman current and the pressure-driven geostrophic current), $\eta(\mathbf{x},t)$ is the free surface displacement, ρ the density, f the Coriolis parameter, g the acceleration of gravity, A_H the lateral eddy viscosity coefficient, τ_w the wind stress, $\tau_b = \rho C_{Db} |\mathbf{u}| \mathbf{u}$ the bottom stress, $H = D + \eta - d$, where D is the average depth and $d(\mathbf{x})$ is the bottom relief. The grid and time steps are $\Delta x = \Delta y = 1.5$ km and $\Delta t = 1.5$ s respectively, $A_H = 200$ m²/s and $C_{Db} = 0.002$. The value of the eddy viscosity coefficient was chosen as the smallest one required to prevent numerical instabilities, while the effect of the bottom friction was found to be virtually negligible in all the runs performed. The initial-boundary value problem with initial conditions of vanishing velocities and surface displacement and free-slip boundary conditions along the borders of the domain is solved by means of an explicit leap-frog finite-difference scheme on the Arakawa C-grid, as described in Pierini (1996) where the technical details relative to the mass flux imposed along the lateral boundaries of the buffer zones are also discussed (see also below). Runs were performed with and without the nonlinear terms and we found that nonlinearities are always negligible. This is particularly relevant in connection with the spectroscopic analysis of Section 3, which is meaningful only in a linear (or weakly nonlinear) regime. Runs with flat topography were also carried out and dramatically different results were obtained. The gravitational eigenperiods underwent large frequency shifts and the corresponding eigenmode structures were sensibly modified. In the runs on the circulation, large differences were also found, and in particular the circulation induced in the gulf by the boundary-driven flow turns out to be very weak, unlike the one obtained with the realistic topography. This is clearly associated with the absence of the strong topographic effect in the potential vorticity balance.

In the study of typical circulation patterns of the Gulf of Naples (Section 4) idealized boundary fluxes across lines L_A and L_B are imposed in order to model the effect of the large-scale Tyrrhenian circulation (see Commodari and Pierini, 1999, for a similar approach applied to the Ross Sea). Currents in the form $\mathbf{u} = (u(y), 0)$ are prescribed in such a way that the volume transport $H\mathbf{u}$ across both L_A and L_B is independent of y and the total transport across L_A equals that across L_B (Pierini, 1996). No conditions are imposed on the surface elevation, but a rapid geostrophic adjustment is achieved. The bottom topography along the external line at $y = 0$ was fixed at a constant mean value so that the u -component of the velocity is the same at the left (L_A) and right (L_B) boundary and the geostrophically adjusted velocity is parallel to the outer boundary at $y = 0$, so that the spurious effects induced by it on the inner circulation are minimized.

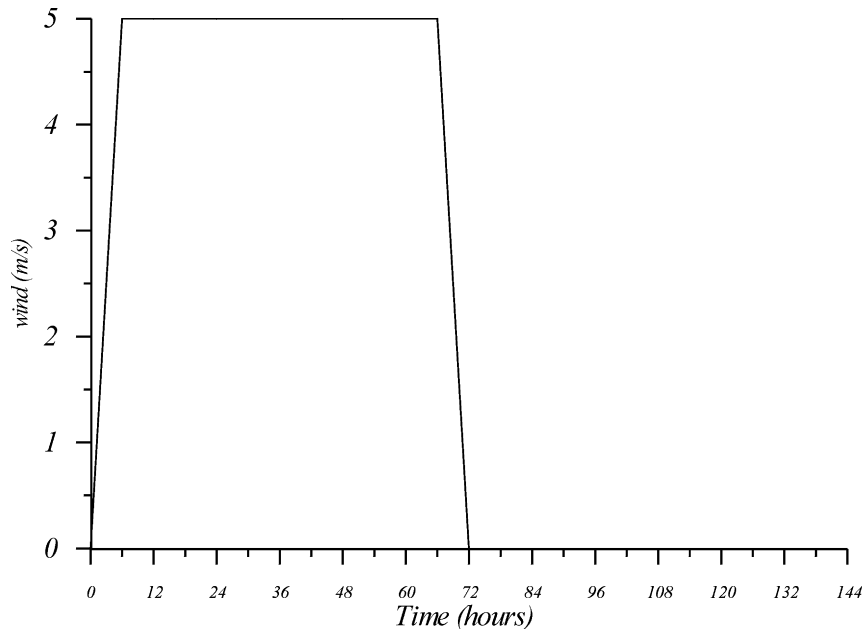


Fig. 2. Time dependence of the spatially constant wind used to excite the seiches of the gulf.

3. The seiches of the Gulf of Naples

We have already noticed that the Gulf of Naples is connected to the Tyrrhenian Sea through a wide opening separating the islands of Ischia and Capri, the so-called “bocca grande”. Nevertheless, the internal geometry (including the three main islands) and the steep topographic slopes at the opening allow for multiple reflections of long surface gravity waves and can therefore support gravitational normal mode oscillations, otherwise called seiches (e.g. Defant, 1961). The main ones are virtually decoupled from the Tyrrhenian Sea, as documented by Caloi and Marcelli (1949). In order to obtain a theoretical description of such motions we use the barotropic circulation model described in Section 2 with the aim of identifying and analyzing the seiches of the gulf.

The first step consists in performing a spectroscopic analysis by introducing energy into our system, analyzing the spectrum of response and identifying eigenfrequencies corresponding to significant peaks, in a manner analogous to what was done by Pierini (1996) to study rotational normal modes in the Strait of Sicily. For this purpose, we use spatially uniform wind forcing along either x or y with a time dependence as indicated in Fig. 2. After a setup is achieved, the wind is switched off abruptly; the potential energy thus stored is then converted during the following free evolution into the seiches of the system, as shown (Fig. 3) in the spectra of the sea-surface elevation taken at points A and B (see Fig. 1) for both south-easterly (i.e. along the negative x -direction) and south-westerly (i.e. along the positive y -direction) winds. In order to assess the sensitivity of the eigenfrequencies to the shape of the domain used outside the gulf, three different cases are considered: the first includes the whole domain shown in Fig. 1, the second is an intermediate case delimited by the line L_1 while in the third case the domain is cut approximately

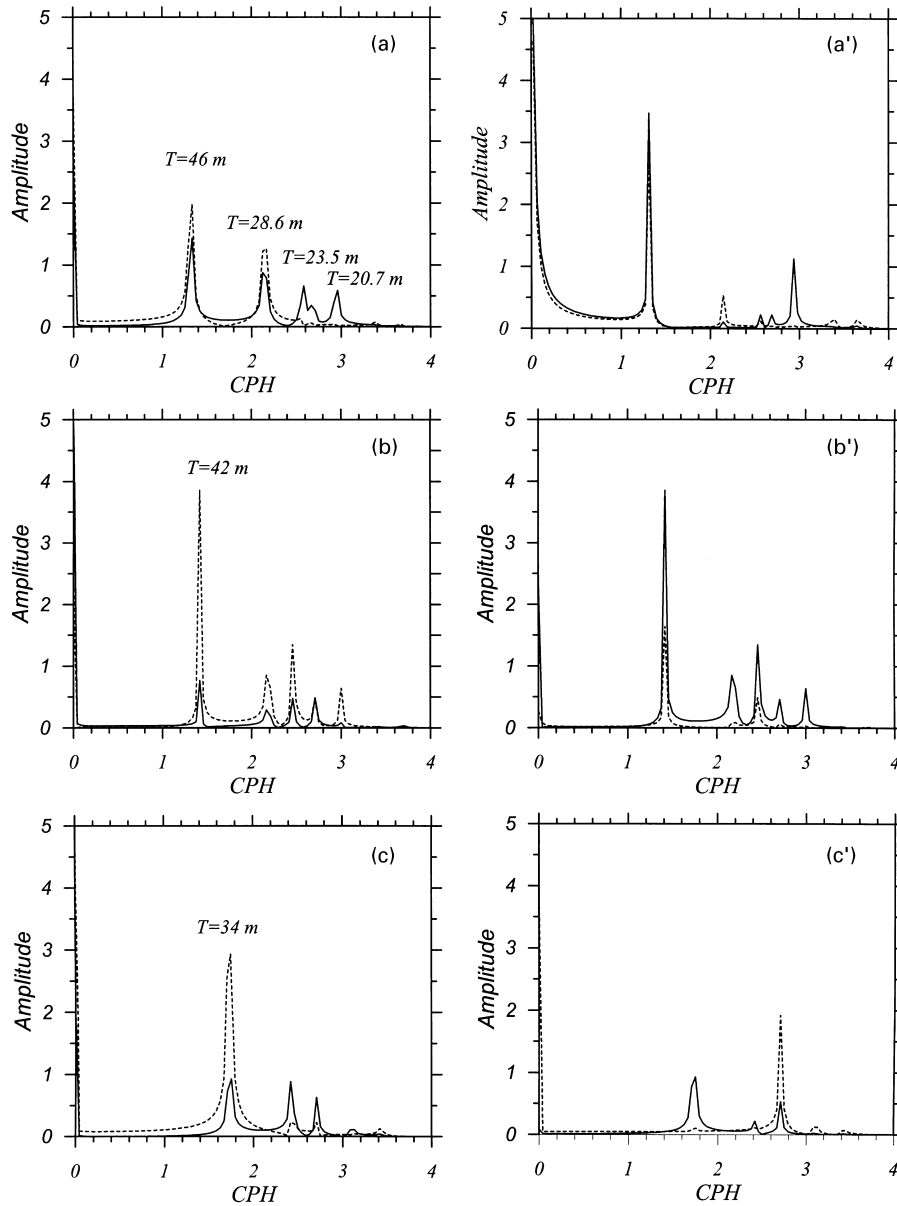


Fig. 3. Spectra of the sea-surface elevation computed after the relaxation of the wind setup taken at points A (solid line) and B (dashed line), for south-easterly (left column) and south-westerly (right column) winds. (a,a') refer to the complete domain, (b,b') to the domain delimited by line L_1 of Fig. 1 and (c,c') to the domain delimited by line L_2 of Fig. 1.

at the “bocca grande” along line L_2 . The results are presented in Table 1, where the experimental periods reported by Caloi and Marcelli (1949) are also given. Four main peaks are evident in the case of the extended domain at periods $T_1=46$ min, $T_2=28.6$ min, $T_3=23.5$ min and $T_4=20.7$ min. The three numerical periods T_1, T_3, T_4 show good agreement with the experimental

Table 1

The eigenperiods of the seiches observed by Caloi and Marcelli (1949) (left column) and the eigenperiods identified by the analysis of Section 3 (right column)

Experimental data	Numerical simulations
$T = 58\text{--}59$ min	—
$T = 48$ min	$T_1 = 46$ min
—	$T_2 = 28$ min
$T = 22$ min	$T_3 = 23$ min
$T = 17.8$ min	$T_4 = 20$ min

periods reported by Caloi and Marcelli (1949), while the numerical period T_2 has no experimental counterpart and the experimental period $T' = 59$ min has no numerical counterpart.

It is interesting to notice that all the numerical peaks are present also in the two reduced-domain cases, though with slightly different periods in the intermediate case and with larger departures in the reduced domain. For example (Fig. 3), T_1 yields the values 46, 42, 34 min in the three cases. This implies that the eigenoscillations feel only weakly the unrealistic boundaries located in the Tyrrhenian Sea in the complete-domain case and therefore they are likely to represent seiches internal to the gulf. It is worth noticing that while no difference in the frequencies of the peaks is found for different wind directions (as it is to be expected for normal modes of oscillation), the amplitude of the normal modes does depend on the direction of the wind that has produced the setup. For example, comparing Figs. 3a with a' one can see that the amplitudes of the T_1 and T_4 seiches for south-easterly winds are larger than for south-westerly winds, though maintaining almost the same amplitude ratio. Moreover, while the amplitudes of the T_2 and T_3 seiches are comparable to those of the T_1 and T_4 seiches for south-easterly winds, they are much smaller for south-westerly winds. In particular the amplitude of the T_3 seiche excited by south-westerly winds is so small that this appears to be the least significant seiche energetically.

Let us now analyze the motions associated with the main seiches, of periods T_1, T_2, T_4 . In order to investigate the single frequency, we force the system with a single Fourier component, spatially uniform wind stress:

$$\tau_w = \alpha \sin(\omega t), \quad (2)$$

where the constant α corresponds to a wind of 5 m/s, $\omega = 2\pi/T$ is the angular frequency and T the forcing period, and the wind direction is taken both south-easterly and south-westerly. Fig. 4 shows the sections along line L_3 (see Fig. 1) of the sea-surface elevation as obtained by solving (1) with initial conditions of vanishing velocities and surface displacement after forcing the system with (2) for 5 cycles (after which an almost repeating cycle is achieved) and an additional cycle of free evolution. It is worth noticing that, as for the spectral response, the spatial structure of the seiches is very weakly dependent on the wind direction, as can be seen by comparing Figs. 4a–c with Figs. 4a'–c' corresponding to the two wind forcings. According to our choice of line L_3 , along which the sections of Fig. 4 are computed, we can denote the seiche corresponding to period T_1 as “uninodal”, while those of periods T_2 and T_4 as “binodal”. As far as their spatial structure is concerned, Fig. 5a–c show the sea-surface elevation at a given phase for each of the three seiches.

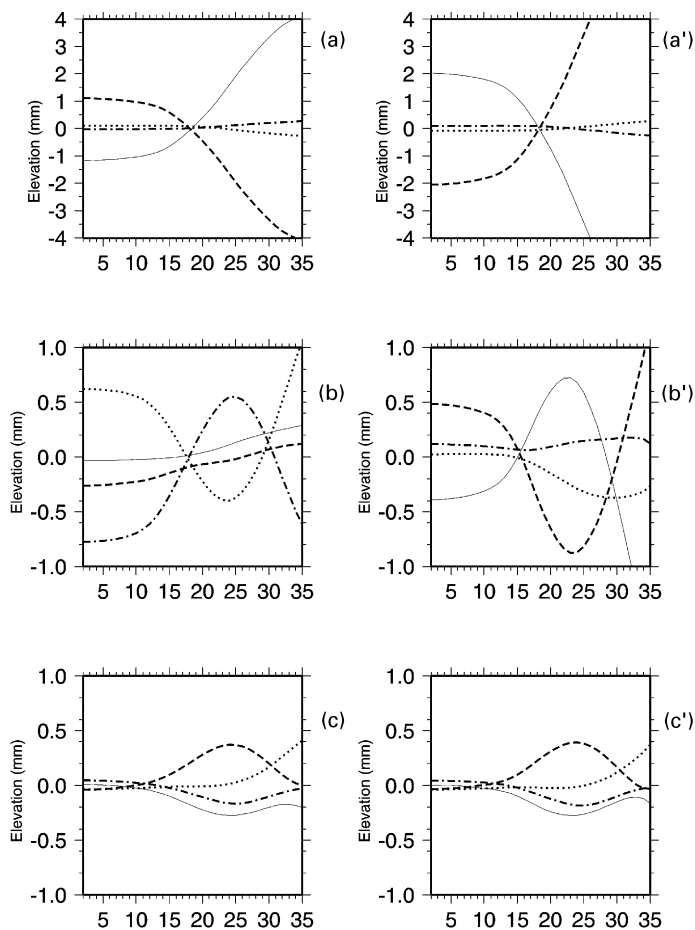


Fig. 4. Sea-surface elevation taken along section L_3 of Fig. 1 and produced by forcing (2) active for 5 cycles over the complete domain. The lines (solid, dashed, dotted, dotted-dashed) refer to the times $t = 6T + kT/4$, where $k = 0, 1, 2, 3$ respectively. The left (right) column refers to south-easterly (south-westerly) winds. In (a, a') $T = T_1$, in (b, b') $T = T_2$, in (c, c') $T = T_4$.

The fundamental seiche T_1 has a relatively simple structure, typical of a unimodal gravitational eigenoscillation in an almost rectangular gulf. The two binodal seiches T_2 and T_4 , on the other hand, yield small-scale amplifications in the Gulf of Pozzuoli (T_2) and the Gulf of Castellammare (T_4).

As we have already mentioned, the seiche of $T' = 59$ min observed in the Gulf of Naples by Caloi and Marcelli (1949) is not reproduced by our spectroscopic analysis, while the T_2 seiche was not observed experimentally. As far as T' is concerned, its absence in the numerical spectra can be explained by recognizing that the period $T = 55$ min corresponds to a seiche of the Tyrrhenian Sea with a strong signal in the Gulf of Naples, as shown in a numerical investigation of Speich and Mosetti (1988). Therefore, in addition to the seiches produced by reflections inside the gulf, other eigenoscillations typical of the Tyrrhenian Sea can cause peaks in the spectra of sea-surface elevation inside the gulf, such as that corresponding to T' . Finally, as far as the T_2 seiche is

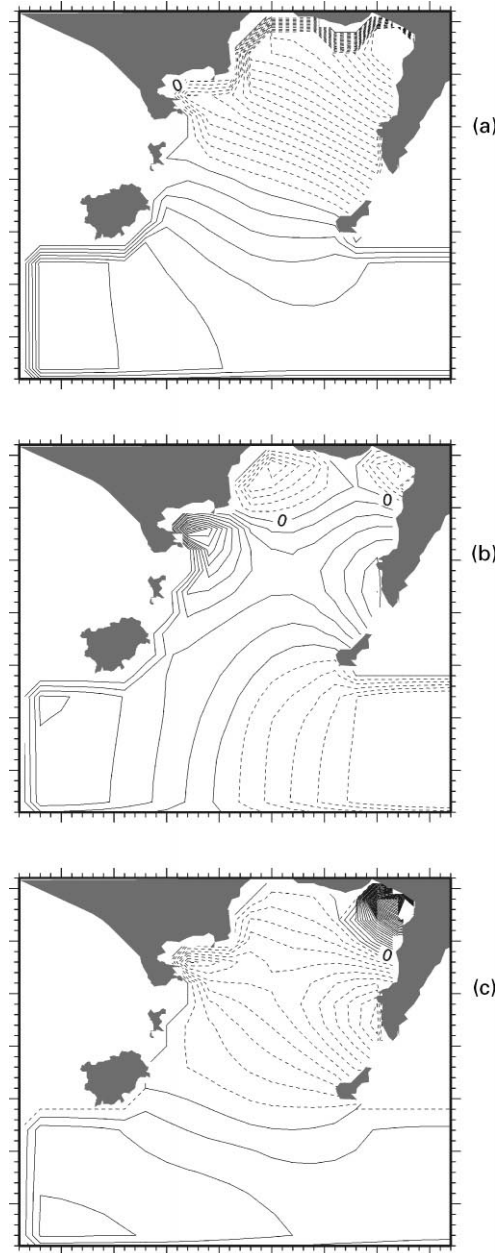


Fig. 5. Sea-surface elevation corresponding to the dashed line of Fig. 4a (a), to the dotted-dashed line of Fig. 4b (b) and to the solid line of Fig. 4c (c).

concerned, we noticed above that its amplitude is very sensitive to the direction of the wind that produces the setup, being very small if the wind is from south-west. This sensitivity implies that the excitation of the T_2 seiche is expected to be more sporadic than the others, leading to the conjecture that this seiche was simply not included in the tide gauge records of Caloi and Marcelli (1949).

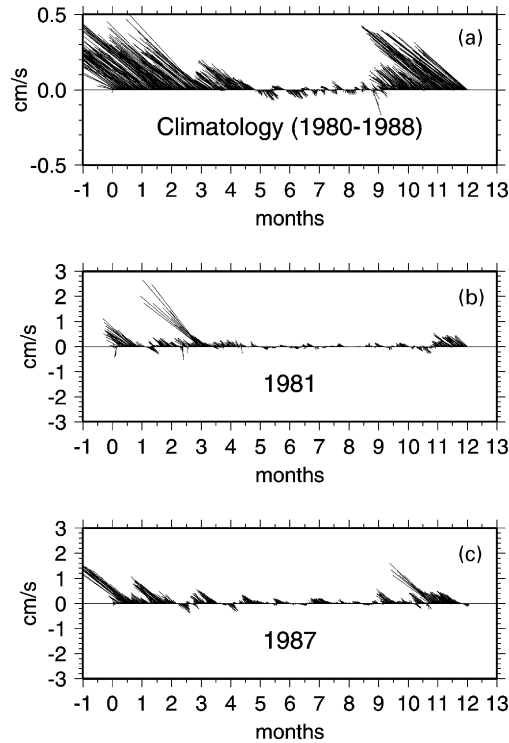


Fig. 6. Stick diagrams of depth-averaged currents taken at point P of Fig. 1 and forced by climatological (a) 1981 (b) and 1987 (c) “National Meteorological Center” momentum fluxes (from Pierini and Simioli, 1998).

4. Numerical simulation of circulation patterns

The study of the depth-averaged circulation in the gulf as induced directly by the wind and “remotely” by the large-scale Tyrrhenian circulation will be the subject of this section. A realistic modelling study of this nature aimed at analysing the local current variability would require the use of winds obtained by meteorological operational analysis to force the whole Tyrrhenian Sea (e.g. Pierini and Simioli, 1998). A high-resolution model of the gulf of Naples could then be coupled with the large-scale model of the Tyrrhenian Sea. The approach adopted in this paper is rather different: here we develop a process study aimed at analyzing a variety of circulation patterns produced by simplified forcings which are however inspired by realistic considerations. Different scenarios will thus be available, each being associated with different meteorological and large-scale circulation conditions.

Pierini and Simioli (1998) have numerically studied the circulation in the Tyrrhenian Sea induced by both climatological and instantaneous “National Meteorological Center” momentum flux data. Fig. 6 shows vertically averaged currents taken at a point near the external boundary of the buffer zone (point P of Fig. 1). A prominent direction from (to) south-east and to (from) north-west is evident, corresponding to a flow approximately along x in the external buffer zone of our domain of integration. The climatological signal computed by averaging over the period 1980–1988 (Fig. 6a), shows north-westward currents (corresponding to an overall cyclonic

Tyrrhenian circulation) in all periods except in summer, when much smaller currents with episodes of reversal are evident. The instantaneous forcing shows how realistic barotropic wind-driven currents (Figs. 6b and c) can differ from climatological ones. During winter and autumn the prevailing direction is still toward north-west but the flow has a much larger temporal variability, with larger current values and several episodes of reversal. The climatological currents have values ranging from 0.1 to 0.8 cm/s and the instantaneous currents have an average winter value just below 1 cm/s, with peaks up to 2–3 cm/s.

In view of the previous discussion, and in order to develop a simple but fairly realistic process study, we considered a boundary-forcing corresponding to an external current flowing in the x -direction of the domain of integration. Following the preceding discussion, the external current is chosen as $u = 1$ cm/s at $y = 0$, i.e. very close to the point P (see Fig. 1) where the currents of Fig. 6 are evaluated. The variation of $u(y)$ along L_A and L_B is fixed by the requirement that the volume transport must be constant along these two lines (see Section 2 for details). As far as the time dependence is concerned, a two-day interval of north-westward flow (sufficiently long to allow for the local barotropic adjustment) is followed by a rapid linear transition to an opposite flux. These simple boundary conditions exemplify at a time, the main regimes of the climatological circulation of the Tyrrhenian Sea and also transient conditions that, as can be seen in the examples of Figs. 6b and c, are quite common in practice. In a first set of numerical experiments a spatially uniform wind stress is also imposed along x , with the same time dependence as the external currents, both in and out of phase with respect to them (maximum values of 5 m/s for the winds are chosen). Fig. 7 shows the two different forcings used. From the wind climatology (e.g. Pierini and Simioli, 1998) it is evident that north-westerly winds (corresponding to positive values of the wind in Fig. 7) are typical of the winter, but any phase is possible and any phase-lag with the external current is also admissible in principle. Each circulation pattern described below is representative of the corresponding external circulation, wind condition and temporal variability of the forcings summarized in Fig. 7.

Fig. 8 shows the induced circulation at different times in the case in which wind and boundary current flow in the same direction (see Fig. 7a). The circulation patterns shown in Figs. 8A and D represent almost symmetrical states that are virtually steady, corresponding to relatively stable weather conditions. Topographical gyres of opposite sign connected to the external circulation are evident in the two cases, both implying a significant renewal of waters and consequent dispersal of pollutants. A secondary circulation is evident in the Gulf of Castellammare (off the northern part of the Sorrento peninsula) where the river Sarno runoff can bring high pollutant concentrations: again this kind of circulation has a positive effect in diluting them. The circulation pattern of Fig. 8A represents correctly a dynamic scenario observed by De Maio et al. (1985) for similar meteorological and oceanographic conditions. Figs. 8B and C show transients connecting the two opposite steady states. They are not symmetrical, although the forcings are, because the variability is faster than the adjustment time. The state of Fig. 8B evidences a sensible weakening of the recirculation within the Tyrrhenian Sea (note also the strong anticyclonic topographic gyre over the canyon Dohrn) which is almost completely absent in Fig. 8C. These are conditions for which the circulation of waters of the gulf is virtually separated from the large-scale Tyrrhenian circulation. The transient circulation pattern of Fig. 8C corresponds well to a dynamic condition observed by De Maio et al. (1985) in connection with a rapid reversal of the external circulation (from northward to southward) associated with the passage of an atmospheric perturbation.

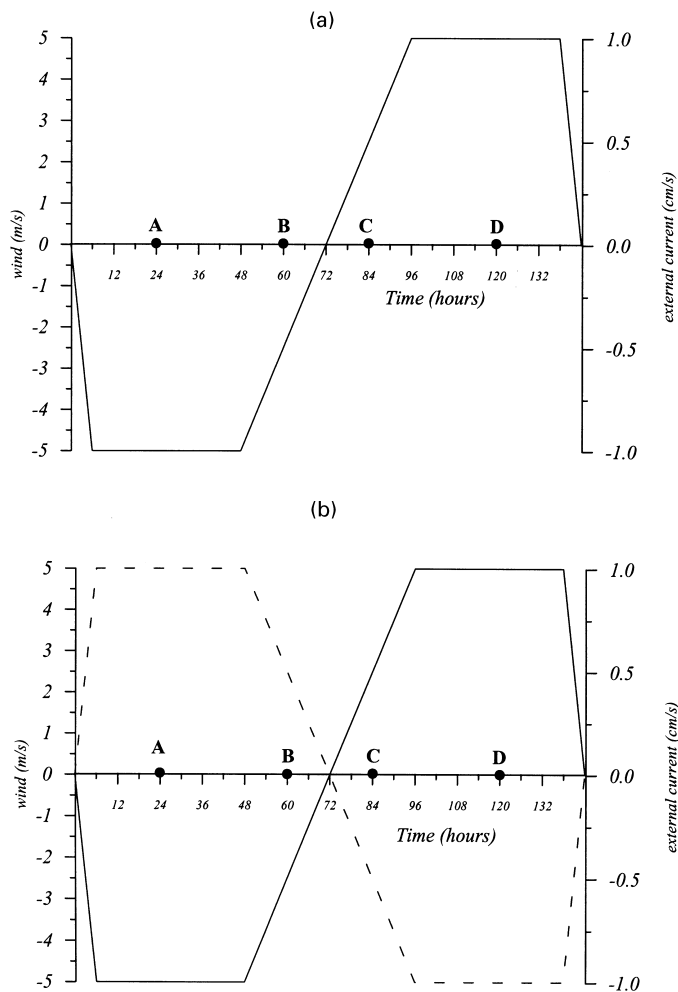


Fig. 7. Time dependence of the external current (solid line) and of the wind (dashed line) used to produce circulation patterns. In (a) solid and dashed lines are superimposed.

Fig. 9 shows the induced circulation at different times in the case in which wind and boundary current, flow in the opposite directions (see Fig. 7b). Also in this case the circulation patterns of Figs. 9A and D represent almost symmetrical states, and they differ from those of Fig. 8A and D in that the internal circulation is reversed. Another difference is that, now the recirculation at the level of the “bocca grande” follows more closely the canyon Dohrn bathymetry, with stronger currents near the Island of Capri. The transient state of Fig. 9C is qualitatively similar to the one of Fig. 8C while that of Fig. 9B yields a stronger internal–external path than the corresponding state with in-phase wind and external current.

Two further numerical experiments are carried out in order to analyze the effect of north-easterly and south-westerly winds on the circulation in the gulf. Upper panels of Fig. 10 give the response at times A and C to the forcing given by Fig. 7b but with the wind directed along y , while lower panels of Fig. 10 give the response at times A and C to the forcing given by Fig. 7a but,

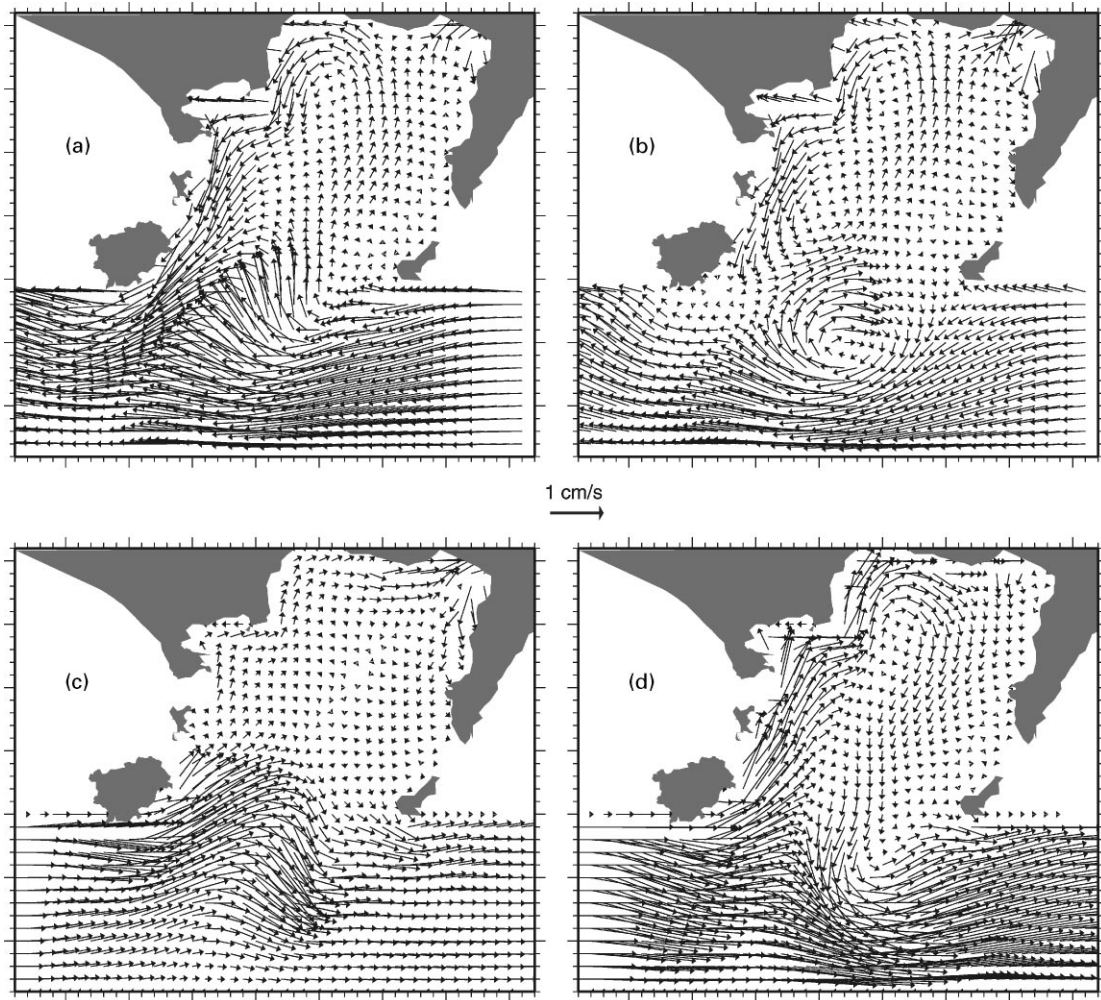


Fig. 8. Depth-averaged currents corresponding to the forcing shown in Fig. 7a at times indicated by A, B, C, D.

again, with the wind directed along y . The response to south-westerly winds given by Fig. 10A, upper panel, is in terms of an anticyclonic circulation inside the gulf which is similar to that observed in Fig. 9A (that refers to the same boundary forcing at the same instant but with north-westerly winds). In this case, however, a broader current distribution is evident along with a shift of the anticyclonic structure towards the Sorrento peninsula. The response to north-easterly winds (Fig. 10A, lower panel) evidences relatively intense coastal currents flowing toward the interior of the gulf along both the islands of Ischia and Procida on one side and along the Sorrento peninsula on the other side, accompanied by a recirculation inside the gulf.

Finally, a circulation scheme observed by Moretti et al. (1977) and quite common in winter time deserves to be simulated. Convergence of an offbound flow was observed in the middle of the gulf in January 1973 in correspondence to persistent north-easterly winds. This was evidenced both from tracer trajectories and direct current measurements and the peculiar spatial structure of the

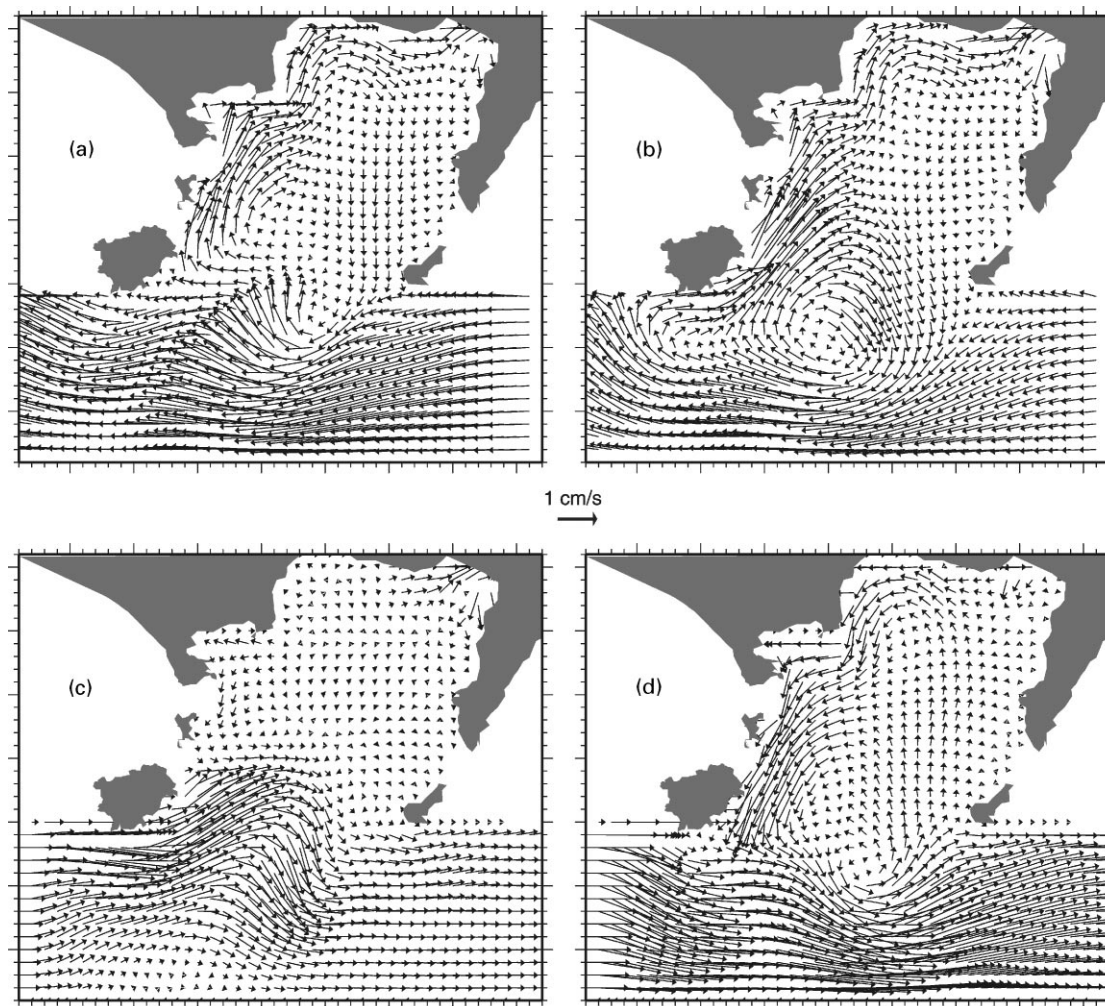


Fig. 9. Depth-averaged currents corresponding to the forcing shown in Fig. 7b at times indicated by A, B, C, D.

flow was attributed to the effect of volcano Vesuvius that shelters the central part of the gulf from the NE winds. In order to reproduce this situation, we forced the model with a wind of 5 m/s (~ 10 knots, which was the maximum observed wind speed) directed along the negative y -direction but confined outside a region (Fig. 11a) obtained as the shadow of the Vesuvius along the y -direction (in the shadow region the amplitude was taken with a sinusoidal profile along x , and along y in the final part). Moreover the typical winter Tyrrhenian current flowing toward north-west is also imposed at the buffer zone. The circulation thus produced is shown in Fig. 11b, where it appears that the water convergence in the centre of the gulf is well reproduced, accompanied by a cyclonic gyre off the Sorrento peninsula and an anticyclonic gyre at the “bocca grande”. It is interesting to compare Fig. 11b with Fig. 10A, lower panel, that refers to the same forcing but with a spatially uniform wind. The presence of the wind shadow generates two cells of intense anticyclonic and cyclonic circulation with a consequent intensified outflow in the centre of the gulf.

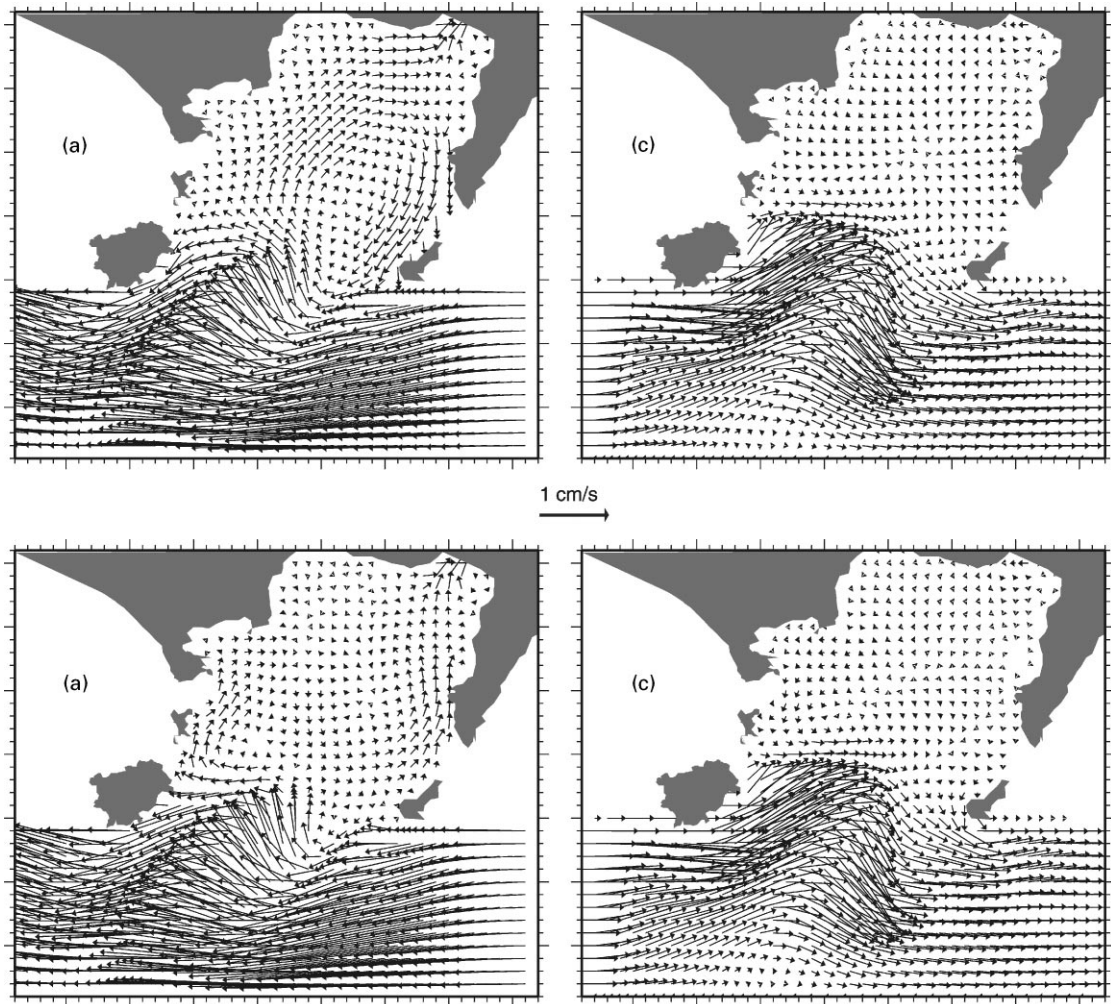


Fig. 10. Upper panels: depth-averaged currents corresponding to the forcing shown in Fig. 7b (with the wind flowing along y) at times indicated by A and C. Lower panels: depth-averaged currents corresponding to the forcing shown in Fig. 7a (with the wind flowing along y) at times indicated by A and C.

5. Conclusions

In this paper a process-oriented numerical study based on the shallow water equations has been carried out in order to analyse two distinct aspects of the dynamics in the Gulf of Naples: (a) the gravitational normal modes of the basin and (b) the circulation induced by both wind and external currents in the gulf. As far as the seiches are concerned, their periods have been determined by analysing the spectra of the sea-surface elevation in selected points of the basin produced as a consequence of the setup relaxation. The structure of each seiche has then been analyzed by studying the response of the system to a monochromatic wind forcing having the same frequency

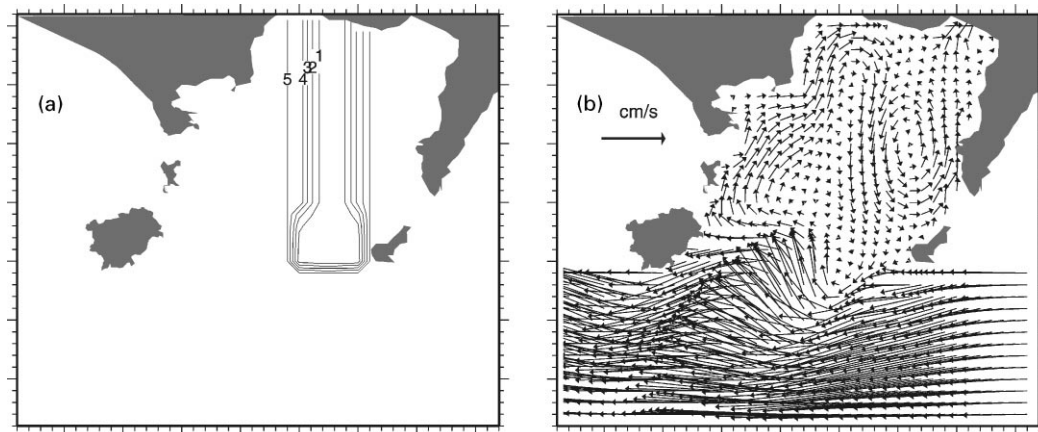


Fig. 11. (a): Isolines of the amplitude of the wind forcing directed along the negative y -direction (nearly north-easterly); (b): depth-averaged currents corresponding to the forcing shown in Fig. 7a (with the wind flowing along y and with the amplitude reported in (a)) at time A (compare with Fig. 10A, lower panel, that refers to the same forcing but with a spatially uniform wind).

of the seiche. Good agreement is found when comparing these modelling results with tide gauge records.

As for the circulation, a study has been carried out on the depth-averaged currents induced in the gulf directly by the wind and “remotely” by the large-scale Tyrrhenian circulation. External boundary conditions have been chosen on the basis of realistic modelling of the wind-driven circulation in the Tyrrhenian Sea (Pierini and Simioli, 1998). Simple idealized local wind forcings have also been considered. Both quasi-steady and transient forcing have been taken into account, so that a series of circulation schemes are obtained representing typical dynamic scenarios in the Gulf of Naples. The results are compared with observations and good agreement is generally found.

This process-oriented approach can complement realistic modelling for which reanalysed air–sea fluxes obtained by meteorological operational analysis and more sophisticated mathematical models are required. The role of this simple approach is to provide a series of dynamic information that can be easily and clearly associated to the given meteorological and oceanographic conditions, while in a more realistic approach this is often more difficult to obtain. Finally, we note that the methodology used in this paper, i.e. the spectroscopic analysis performed on the relaxation of a wind setup used to study the seiches and the imposition of external currents across lateral boundaries of a buffer zone used to study the circulation in the gulf, can be applied to different semi-enclosed areas of the world ocean.

Acknowledgements

We wish to thank A. De Maio, M. Moretti, E. Sansone and G. Spezie for useful discussions on hydrological and current meter observations in the Gulf of Naples.

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