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The effect of low frequency winds on sea level and currents in the Gulf of Genova

Wind
Sea level
Currents
Genova
Model
Vent
Niveau de la mer
Courants
Gênes
Modèle numérique

A. J. Elliott
Saclant ASW Research Centre, Viale San Bartolomeo 400, 19026 La Spezia, Italy.

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ABSTRACT

The initial effect of a low frequency wind blowing onshore along the west coast of Italy is to cause a decrease of the coastal sea level near Genova combined with a flux of surface water past Elba into the Tyrrhenian Sea. This observational result is in qualitative agreement with the results from a depth-integrated model, suggesting that large-scale effects are important and that the flux of coastal surface water results from the coupling of the response between the Ligurian and Tyrrhenian Seas. Both the observational data and the numerical results suggest that the wind forcing produces a two-way flow through the channel between Corsica and the Italian mainland.

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RÉSUMÉ

Le niveau de la mer et les courants dans le Golfe de Gênes sous l'action des vents dominants

Un vent constant soufflant uniformément en direction des côtes ouest de l'Italie provoque initialement une diminution de niveau sur les côtes génoises et un flux d'eau superficiel à la latitude de l'Ile d'Elbe en direction de la mer Tyrrhénienne. Ces observations sont en accord qualitatif avec les résultats d'un modèle numérique intégré verticalement qui suggère l'influence de phénomènes à l'échelle spatiale supérieure avec un couplage entre la mer de Ligure et Tyrrhénienne, entraînant le flux des eaux côtières superficielles. Les observations et les résultats numériques indiquent que la tension du vent force deux courants opposés entre la Corse et l'Italie.

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INTRODUCTION

The Gulf of Genova, located in the northeastern part of the Ligurian Sea (Fig. 1), is a semi-enclosed basin that is bordered by the coastlines of France and Italy, and by the shallow water area that extends between the Italian mainland and Corsica near Elba. Water depths across the shelf near Elba are generally less than 200 m, especially to the east of Elba, while the deeper parts of this channel lie near the Corsican coast and have water depths approaching 500 m. In contrast the main part of the Ligurian Sea has depths greater than 2 000 m. Southeast of the Ligurian Sea lies the Tyrrhenian Sea, where the maximum depth exceeds 3 000 m.

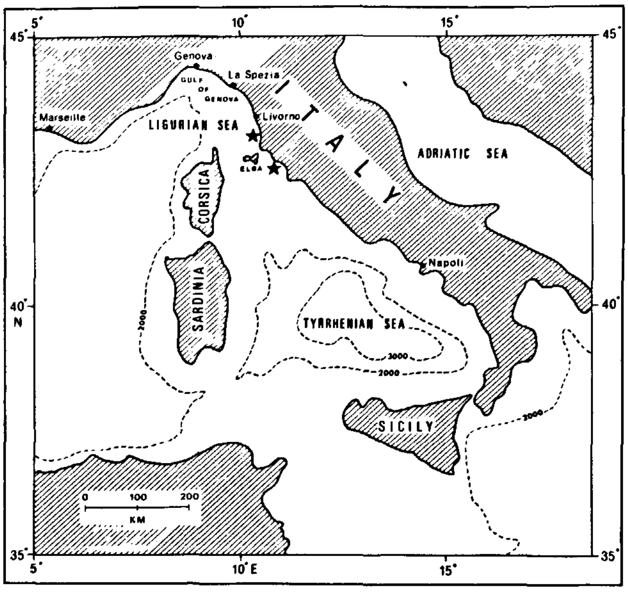

Figure 1
The Ligurian and Tyrrhenian Seas. Current meter observations were made at the two locations shown near Elba. Bottom depths are in metres.

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The tides are relatively unimportant in the Gulf of Genova and the surrounding coastal waters. For example, the M_2 component of the sea level variation at Genova has an amplitude of less than 10 cm. Consequently, the dominant sea level changes are meteorologically induced. The mean surface currents in the area are thought to follow the coastline in a cyclonic gyre around the Ligurian Sea with a mean speed of about 5 $\mathrm{cm.s^{-1}}$. Part of this surface flow originates in the Tyrrhenian Sea and flows past Elba into the Ligurian basin (Elliott, De Strobel, 1978).

During April and May of 1977 field measurements were conducted in the coastal waters near Elba (Fig. 1). The observations were made to determine the response of the shallow shelf waters to meteorological forcing and to determine the associated time scales (Elliott, 1979). Since the Ligurian Sea is a semi-enclosed basin a wind blowing towards the northeast might be expected to pile up water against the coast and cause an increase in sea level within the Gulf of Genova. However, the data show that the opposite happens: for low frequencies (periods longer than 10 days) sea level in the Gulf of Genova *decreased* when the wind was blowing onshore towards the northeast, and sea level *increased* when the wind blew offshore towards the southwest. Figure 2 shows the coherence and phase, computed from the two-month long records, between the barometrically adjusted sea level at Genova and the onshore component of the wind stress. The two records were coherent and out of phase at low frequency, i. e. a positive onshore wind was accompanied by a decrease in sea level. The sea level fluctuations at Genova and Livorno were highly coherent at the low frequencies (Elliott, 1979), suggesting that a wind induced set-up occurred along the entire Ligurian coast. Figure 3 shows the effect on sea level of a wind directed towards the northwest, i. e. blowing approximately parallel to the coastline. The coherent response again occurred at low frequency, when the two records were in phase; therefore, a wind towards the northwest resulted in an increase of sea level in the Gulf of Genova. Figure 4 shows an example, taken from the beginning of May, of the response to a relatively steady wind blowing onshore into the Gulf of Genova (i. e. towards the northeast). The figure shows the onshore component of wind stress, the barometrically adjusted sea level at Genova, and the alongshore current measured near Elba. The data, which had been low pass filtered to remove the fluctuations with periods shorter than 30 hours, illustrate that the sea level decreased and the near-shore coastal current flowed from the Ligurian Sea into the Tyrrhenian Sea as a result of the onshore wind. In the following discussion a numerical model is used to investigate the effect of wind forcing on the coastal sea level, showing that the response can be explained by the coupling between the Ligurian and Tyrrhenian basins and an exchange of surface water across the shallow region near Elba.

THE MODEL

As a first step towards resolving the effects of wind forcing, bottom topography and rotation, a depth-integrated model was applied to the region shown in Figure 5. The two-dimensional equations, integrated between the surface and bottom, take the form:

$$\frac{\partial \eta}{\partial t} = -\frac{\partial}{\partial x_1}[\mathrm{H}u_1] - \frac{\partial}{\partial x_2}[\mathrm{H}u_2],$$

$$\frac{\partial}{\partial t}[\mathrm{H}u_1] = \frac{\partial}{\partial x_1}\left[\mathrm{HN}\frac{\partial u_1}{\partial x_1}\right] + \frac{\partial}{\partial x_2}\left[\mathrm{HN}\frac{\partial u_1}{\partial x_2}\right] - ku_1(u_1^2+u_2^2)^{1/2} + f\,\mathrm{H}u_2 - g\mathrm{H}\frac{\partial \eta}{\partial x_1} + \mathrm{F}_1,$$

and

$$\frac{\partial}{\partial t}[\mathrm{H}u_2] = \frac{\partial}{\partial x_1}\left[\mathrm{HN}\frac{\partial u_2}{\partial x_1}\right] + \frac{\partial}{\partial x_2}\left[\mathrm{HN}\frac{\partial u_2}{\partial x_2}\right] - ku_2(u_1^2+u_2^2)^{1/2} - f\,\mathrm{H}u_1 - g\mathrm{H}\frac{\partial \eta}{\partial x_2} + \mathrm{F}_2,$$

where η is the surface elevation above mean water level, u_1 and u_2 are the components of horizontal flow, f is the coriolis parameter (assumed constant), N represents the horizontal eddy viscosity (set equal to $10^6.\mathrm{cm^2.s^{-1}}$) and H is the total water depth. The components of surface stress, F_1 and F_2, were calculated using a quadratic drag law with a constant drag coefficient of 1.3×10^{-3}. The bottom stress was also assumed to be quadratic, the drag coefficient being 2.5×10^{-3}. Consequently the equations form a basically linear system with the exception of the quadratic friction term.

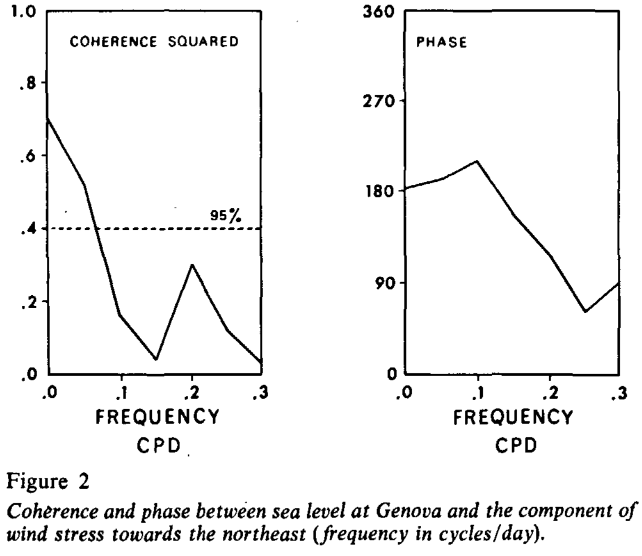

Figure 2

Coherence and phase between sea level at Genova and the component of wind stress towards the northeast (frequency in cycles/day).

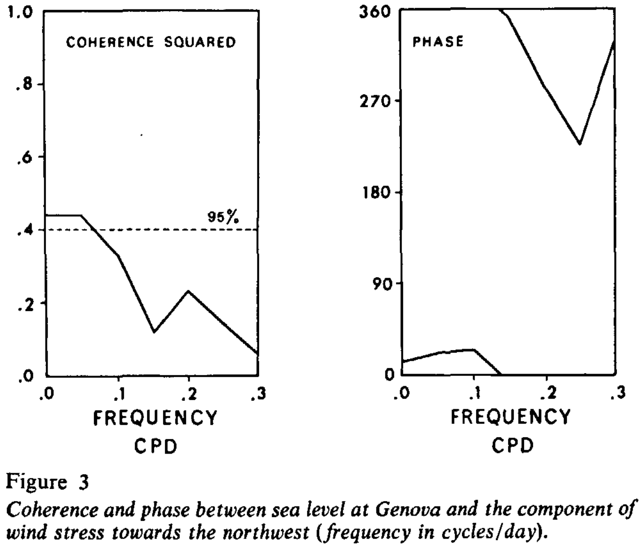

Figure 3

Coherence and phase between sea level at Genova and the component of wind stress towards the northwest (frequency in cycles/day).

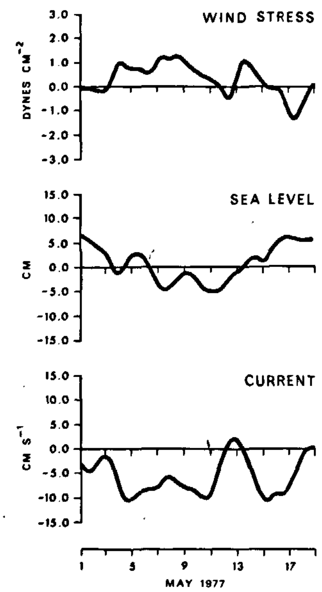

Figure 4

The component of wind stress directed towards the northeast, the barometrically adjusted sea level at Genova, and the alongshore current measured near Elba during a period of onshore wind.

The equations were solved explicitly in a standard manner using a leap-frog scheme with centred space differences on a regular grid. The variables were spatially staggered on the grid so that surface elevation, density and depth were specified at the centre of each rectangular element while the two velocity components were specified at the mid-points of adjacent sides of the grid elements (Tee, 1976; Pingree, Maddock, 1977).

For the boundary conditions there was assumed to be no flow through the Straits of Messina (between Sicily and the Italian mainland). In addition, a surface radiation condition was applied to the open boundary to the west allowing wave energy to pass out of the region. This took the form $\eta = u(g/H)^{-1/2}$ where u was the flow directed outwards along a normal through the boundary (Heaps, 1974). Since the model was developed for coastal application time was measured in tidal cycles.

RESULTS

Tests were made to determine the effect on sea level of a steady wind of 16 $m.s^{-1}$, equivalent to a wind stress of 4 $dyn.cm^{-2}$. Four separate runs were made, corresponding to winds blowing parallel and perpendicular to the mean orientation of the Italian coast (Fig. 6). Each test was run to simulate 20 tidal cycles (about 10.4 days), the system being taken at rest initially. To damp out the transient motions the bottom friction was initially increased by a factor of 10^3 and then decreased exponentially, reaching the normal value at the end of the third tidal cycle; this value being retained during the remainder of the run. (This is equivalent to allowing the wind to increase exponentially in strength.) The distributions shown in Figure 6 were then obtained by averaging the results calculated during the final tidal cycle of each test. A steady state had not been reached at the end of 20 tidal cycles; during the final tidal cycle the elevations and currents changed by about 2%.

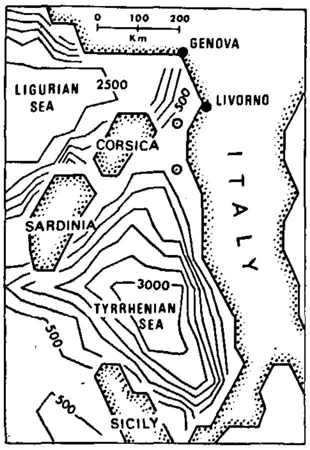

Figure 5

Bottom topography used in the model, depths are given in metres; the grid spacing was 20 km. The circles show the positions that correspond to the mooring locations given in Figure 1.

Figure 6 shows the predicted wind-driven currents within the Tyrrhenian Sea and the Gulf of Genova; the currents have not been shown in the western parts of the basin where conditions were influenced by the open boundary. However, since the Tyrrhenian Sea is semi-enclosed then the circulation within it should not have been unduly affected by the open boundary. The arrows on the figure represent the depth-mean currents, in addition regions of relative maxima (H) and minima (L) in sea level are shown. The region in which sea level remained unaltered from mean level is denoted by the dashed line. Thus for a wind blowing onshore into the Gulf of Genova (test B) sea level decreased in the Gulf of Genova and increased in the Tyrrhenian Sea. The rise in sea level was greatest near the centre of the Tyrrhenian basin and near the Straits of

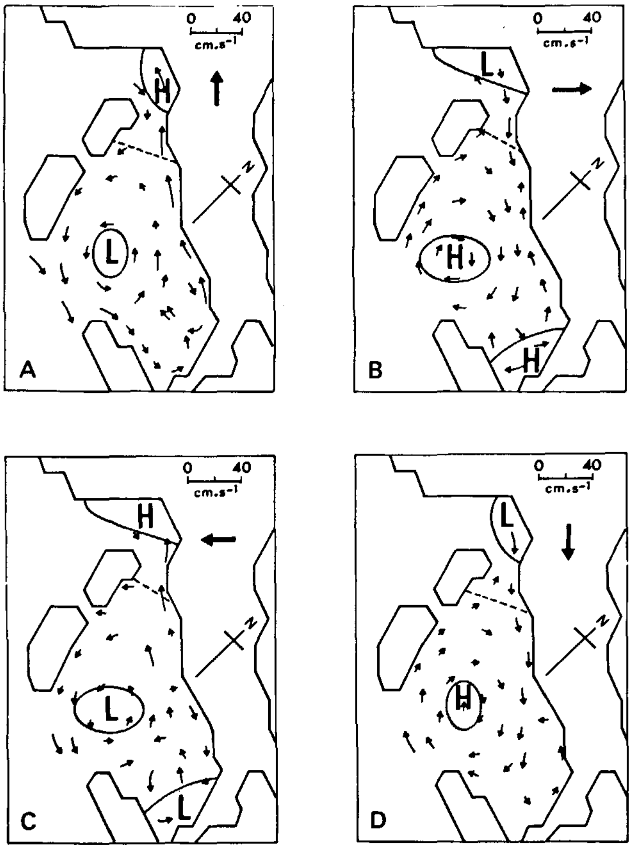

Figure 6

The computed wind-driven currents and the regions of maximum change in sea level after an elapsed time of 10 days. The large arrows show the direction of the steady wind that was assumed constant over the entire region.

Messina. The changes in sea level were accompanied by a flux of surface coastal water from the Ligurian basin into the Tyrrhenian Sea past the island of Elba. For a wind blowing offshore from the Gulf of Genova (test C) the sea level changes and currents were reversed. The figure also shows the computed effect of a wind blowing parallel to the mean orientation of the Italian coast (test A). This component of the wind caused an increase of sea level at Genova and drove the coastal flow towards the northwest, from the Tyrrhenian into the the Ligurian basin. Consequently the calculated distributions shown in Figure 6 are in qualitative agreement with the observed characteristics of the Genova sea level shown in Figures 2 and 3. (The results shown in Figure 6 were redrawn from the computer plots to show schematically the main features of the response. Since the model was basically linear a reversal in the wind direction reversed the sign of the solution; the discrepancies between the solution pairs shown in the figure are mainly due to the redrawing.)

In order to make a quantitative comparison, the two-month long observational data were used to compute the magnitude of the response function between the wind and Genova sea level, and between the wind and the coastal currents measured near Elba (Fig. 1). Predictions based on field data could then be made for the effects of the steady winds shown in Figure 6 by averaging the results at low frequency. As shown by Table 1, the magnitude and direction of the predicted alongshore currents near Elba were in fair agreement with the observed values. The predicted sea level changes, however, only reached 20%-50% of the observed variation.

Some comments can be made on the manner in which the observational and computational results were obtained: The observational data were analysed by cross-spectral analysis and the response function between pairs of variables was estimated at the low frequencies. For each pair of variables (e. g. wind stress and sea level elevation) the amplitude of the response function was then averaged over the low frequencies so that a ratio between the two variables could be derived. The low frequency response of sea level or alongshore current could then be estimated for a given wind stress (Table 1). Thus it was implicit in the analysis that the wind field should have a harmonic character, generating a harmonic response in the coastal water. In order to make a comparable calculation with the model it would be necessary to apply a harmonic wind stress (of periodicity of at least 10 days) and to run the model for a time that would be long compared to the period of the forcing. Then a cross-spectral analysis could be made between the time series of wind stress and computed elevation or current. In this way analogous results could be obtained to those derived from the field data. This, however, is not a practical method since the amount of computer time required would be considerable (the calculations to produce a 50 day time series would require more than 130000 time steps). Therefore the elevations and currents, generated from rest by a steady wind after an elapsed time of 10 days, were calculated; this was considered as being an approximation to the effect of a harmonic wind with a 10 day period. Note that it would not be correct to run the model to steady state under the influence of a constant wind and to compare the results obtained in this manner with the field data. (Some tests were made in which the model was allowed to run towards a steady state under the influence of an onshore wind, similar to that shown in test B of Figure 6. The steady state solution was for an increase of sea level along the entire west coast of Italy and for a lowering of sea level near the open boundary to the west. This suggests that the coastal waters never approach steady conditions but are constantly adjusting to the influence of the variable winds. By restricting our attention to the spin-up phase of the numerical calculations we obtain a better prediction of the actual response.)

Table 1

Comparison between the field data and the model calculations on the effect of a steady wind of 4 dyn.cm^{-2}. (u is the alongshore current near Elba and ΔSL is the sea level change at Genova.)

Data	Model
Alongshore wind (tests A and D)	
$u = 14$ cm.s^{-1}	$u = 12$ cm.s^{-1}
ΔSL = 12 cm	ΔSL = 6 cm
On/offshore wind (tests B and C)	
$u = 12$ cm.s^{-1}	$u = 15$ cm.s^{-1}
ΔSL = 16 cm	ΔSL = 3 cm

The results will have been influenced by the choice of both surface and bottom drag coefficients. Heaps (1977) used a surface drag coefficient, which was dependent upon the wind speed, that varied from 0.5×10^{-3} to 2.5×10^{-3}. The value used in the present calculations was 1.3×10^{-3}, lying in the middle of this range; if, however, we compute the stress coefficient that corresponds to a wind of 16 m.s^{-1} (4 dyn.cm^{-2}) then we obtain a value of 2.1×10^{-3}. This represents an increase of 60% in the surface drag coefficient and will cause a corresponding increase in the sea level variation. However, increasing the surface drag coefficient would also increase the magnitude of the computed currents; therefore, the bottom drag coefficient would need to be increased in order to maintain realistic predicted currents.

The computed wind driven currents shown in Figure 6 suggest a two-way flow through the channel between Corsica and the Italian mainland. The currents in the shallow water (near the mainland) flow in the direction of the alongshore wind, and flow to the right of the on/offshore wind. In the deeper water near Corsica the currents were directed in the opposite sense. From the observations we can estimate that a wind stress of 4 dyn.cm^{-2} will cause a maximum reduction of sea level of about 20 cm in the Gulf of Genova; this implies a loss of surface water from the area of about 12×10^{8}.m^{3} over a time scale of about 10 days, corresponding to a flux of 1.4×10^{3}.m^{3}.s^{-1}. Both the observations and the model results suggest that this surface water flows past Elba into the Tyrrhenian Sea. However, from the current observations we can estimate that the same wind stress will cause an alongshore flow near the coast of about 10 cm.s^{-1}. If this flow is assumed to be uniform across the section between Italy and Corsica then it implies a flux of about $1.3 \times 10^6 . m^3 . s^{-1}$, which is three orders of magnitude larger than the flux required by the change in volume. Consequently, in order for the surface waters to be in balance, continuity suggests that the flow cannot be uniform across the section and that there will be a return flow into the Ligurian Sea to compensate for the coastal transport. The model results suggest that this return flow occurs near the coast of Corsica.

DISCUSSION

The purpose of this study has been to seek a qualitative explanation of the sea level fluctuations recorded at Genova and to gain insight into the mechanisms that influence the transport of the surface and shallow coastal waters. As a first step towards this goal encouraging results have been obtained through a depth-integrated model and the assumption of a spatially uniform steady wind. This has shown that the low frequency sea level changes near Genova occur as a result of the coupling between the response of the Ligurian and Tyrrhenian basins, and that the coastal currents near Elba are influenced by the exchange of surface water between the two basins. The response could only be isolated in the data at the low frequencies (time scales longer than 10 days) suggesting that either rotational or large-scale effects are important. Both the model calculations and the observational data suggest that there would be a wind-driven counter current of surface water near the coast of Corsica. Although the model has not isolated the mechanisms that lead to the reduction of sea level at Genova when there is an onshore wind, results obtained for the Great Lakes (Birchfield, Hickie, 1977) suggest that topographic oscillations may be important. It should be stressed that the reduction in sea level is only a transient effect and that the steady state solution is for an increase of sea level at the coast when the wind blows onshore. In practise, however, the wind does not remain steady long enough for this to be observed and the coastal waters will be constantly responding to the changes in the wind stress.

Calculations have been made for a steady wind that was assumed to be uniform over both basins. However, the analysis of wind data from several coastal locations (Elliott, 1979) has shown there to be considerable variability in both the strength and direction of the low frequency winds, and that there is significant cyclonic energy with a periodicity of about 5 days. This suggests that future modelling effects should include a more realistic wind stress distribution, possibly by interpolating the coastal winds over the interior of the model and allowing the winds to be time dependent. In addition, the present observational data were collected during the spring of 1977 when the coastal water was vertically well-mixed (Elliott, De Strobel, 1978), consequently the use of a depth-integrated model may be appropriate for a preliminary analysis into the dynamics. Throughout the summer months, however, stratification in the coastal water will influence the response and either two-layered (e. g. Creegan, 1976) or multi-layered (e. g. Simons, 1978) models would need to be developed. Finally, the accuracy of the predictions made by a numerical model can be no better than the accuracy of the observational data used for its calibration. By necessity this implies that greater effort should be directed towards the collection of reliable long-term current observations in the Gulf of Genova and the surrounding coastal waters if accurate prediction is to be made of the coastal response.

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