OCEANOLOGICA ACTA 1981 - VOL. 4 - N° 1

Low frequency current variability off the West coast of Italy

Coastal
Currents
Sea level
Wind
Dynamics

Côtier
Courants
Niveau marin
Vent
Dynamique

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Received 5/5/80, in revised form 26/6/80, accepted 5/7/80.

ABSTRACT

Month-long current measurements were made during the spring of 1978 at three coastal locations and at a deep location off the West coast of Italy. The data from two of the shallow moorings, located near La Spezia and Civitavecchia, have been analysed to investigate the role played by meteorological forcing. Two different methods, evaluating the terms in the momentum equation directly from the observations and contructing a simple Ekman model of the shelf, both suggest that the dynamic balance is different at the two locations. Near La Spezia the effect of bottom friction is small, and a good estimate of the alongshore flow can be obtained by simply integrating the alongshore wind stress. In contrast, the effects of bottom friction are significant near Civitavecchia where the alongshore flow cannot be reproduced without the inclusion of friction into the dynamic balance.

For locations within a few kilometres of the coast the flow is constrained to follow the local bathymetry, and can therefore be adequately reproduced by a model that considers only the alongshore dynamics.

Oceanol. Acta, 1981, **4**, 1, 47-55.

RÉSUMÉ

Variabilité basse fréquence des courants au large des côtes ouest d'Italie.

Des mesures de courants pendant des périodes de l'ordre du mois ont été effectuées au cours du printemps 1978, à trois stations côtières et à une station par plus grande profondeur au large de la côte ouest d'Italie. Les données provenant de deux des mouillages situés près de La Spezia et de Civitavecchia ont été analysées afin de connaître le rôle joué par les forces d'origine météorologique. Deux méthodes différentes, l'une faisant l'évaluation directe à partir des observations des termes intervenant dans les équations dynamiques, l'autre s'appuyant sur un modèle d'Ekman simple de la zone côtière, suggèrent toutes les deux un équilibre dynamique différent pour chacune des stations. Près de La Spezia, l'effet de frottement sur le fond est petit, et une estimation correcte de l'écoulement parallèle au rivage peut être faite simplement en intégrant la tension du vent dans la même direction. Par contre, les effets du frottement sur le fond sont significatifs près de Civitavecchia, station pour laquelle une bonne estimation de l'écoulement parallèle au rivage ne peut être réalisée en l'absence de termes de frottement dans l'équation d'équilibre dynamique. Pour les stations situées à quelques kilomètres du rivage, l'écoulement doit suivre la bathymétrie locale, et peut donc être représentée de manière correcte par un modèle prenant en considération la dynamique côtière.

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INTRODUCTION

The shallow shelf waters that lie along the West coast of Italy are receiving an increasing amount of oceanographic attention, mainly due to an awareness of the need to reduce the coastal pollution. For example, there is the need for a balanced program of port expansion at Genova and La Spezia, which lie along the Italian Riviera on the Ligurian coast of Northwest Italy (Fig. 1). Both of these ports are being expanded as oil and container terminals, yet at the same time are tourist centres and are situated near beaches where water quality must be maintained. Another example can be found further to the South in the Tyrrhenian Sea, along the coastline near Roma, where a power station at Civitavecchia uses the coastal water for cooling purposes. For all of these problems there is the basic requirement of a description of the nature and variability of the currents and hydrographic properties of the shallow and coastal waters.

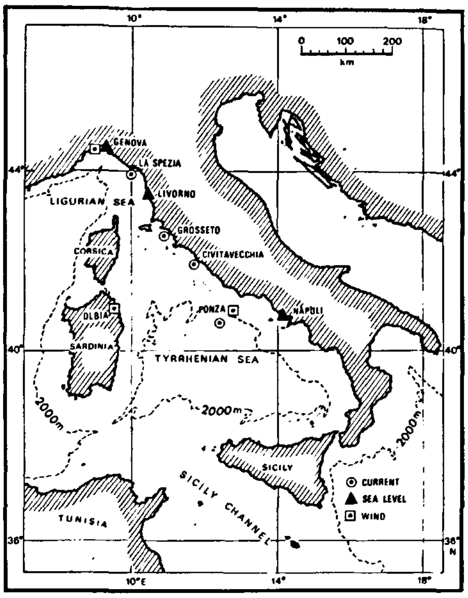

Figure 1
Locations of the moorings, and wind and sea level stations.

Earlier work tended to be concerned with indirect inferences about the mean coastal circulation, using geostrophic or isentropic analysis, as part of an analysis of the large-scale circulation within the Ligurian and Tyrrhenian Seas (e. g. Wust, 1961; Krivosheya, Ovchinnikov, 1973). In addition, some work has been done on tidal and higher frequency fluctuations in the sea level (e. g. Papa, 1977). However, since the tides are relatively unimportant in this area, for example the M_2 component of the sea level variation along the West coast of Italy is less than 10 cm, the dominant changes in sea level and the associated currents are mainly meteorologically induced. In contrast, the mean coastal currents are believed to be part of the large-scale thermohaline driven circulation of the western basin of the Mediterranean, and are thought to flow along the West coast of Italy towards the North-West, with a speed of around 5 cm . s^{-1} (Wust, 1961; Sankey, 1973).

During the spring of 1977 a series of direct measurements were made on the Italian shelf, current meters being deployed on two moorings, separated by about 100 km, on either side of the shallow water near Elba (Elliott, De Strobel, 1978; Elliott, 1979 *a*). The currents were analysed together with wind and sea level data to provide an insight into the exchange of surface water between the Ligurian and Tyrrhenian Sea past Elba. The analysis showed that the dominant winds over the area during the spring were directed towards the East and were coherent over the Tyrrhenian Sea, thus the wind measured at either Olbia or Ponza (Fig. 1) can be regarded as being representative of the large-scale wind. An analysis of the curl of the wind stress together with the atmospheric pressure showed that there was a persistent cyclogenic structure with a periodicity of around 5 days, and this was attributed to the depressions that tend to be centred over Genova and which have a characteristic time scale of around one week (Palmieri, 1968; Meteorological Office, 1962). The sea level changes at Genova and Livorno were highly coherent and were mainly due to a set-up caused by the semi-enclosed nature of the Ligurian sea. The Ligurian sea level rose when the wind was towards the North-East on time scales of 2-3 days; however, for periods longer than 10 days the wind and Ligurian sea level were out of phase, suggesting that either rotational effects or a larger spatial scale response was important (Elliott, 1979 *b*). The sea level at Napoli was raised by the alongshore wind, suggesting an Ekman type response; the highest coherence between sea level and wind was found at the 5-day time scale. A combined analysis of the currents, sea level and wind suggested that the coherent response near Elba was similar to that of a semi-enclosed region. The wind acted to set up surface slopes, and then the currents were driven by the relaxation of the surface set-up. The highest coherence between separate current records, and between the currents and the alongshore wind, was found at the 5-day time scale. This was attributed to the influence of the cyclogenesis, since the wind field has a coherent spatial structure during the development of each depression and the cyclones have a tendency to remain stationary over the Gulf of Genova and the Northern Tyrrhenian Sea.

This paper reports the results of observations made during 1978, the goals of which were to obtain current measurements over greater alongshore separations and also to resolve the vertical structure of the horizontal flow. Other goals were to examine the dynamics of the coastal currents and to give guidelines to those involved in developing water quality models for the coastal zone.

THE OBSERVATIONS

The data

During an approximately 30 day period in April and May of 1978 current measurements were made at coastal locations in the Ligurian and Northern Tyrrhenian Sea (Fig. 1). There was negligible stratification in the

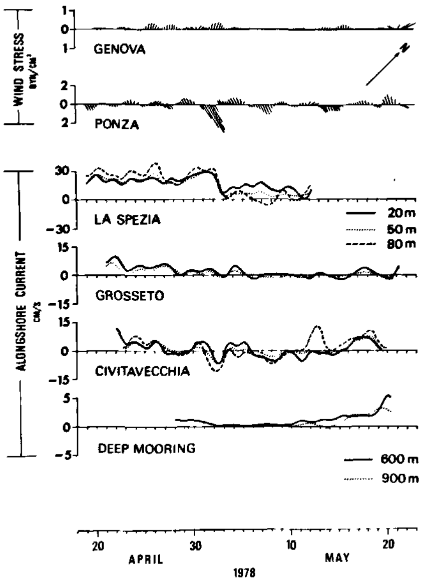

Figure 2*a*

Wind stress vectors at Genova and Ponza, shown with respect to an alongshore and offshore coordinate system (the arrow points North); alongshore components of the current at the three coastal locations and at the deep mooring.

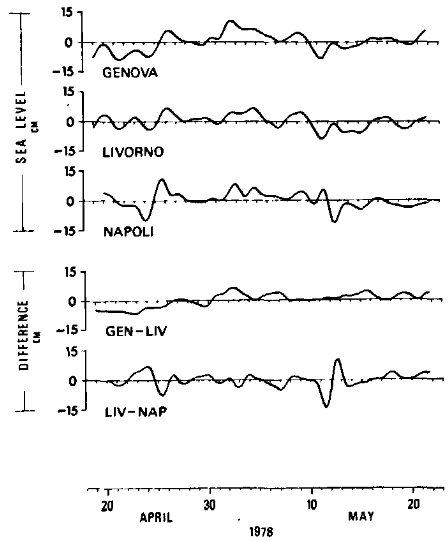

Figure 2*b*

Adjusted sea level at Genova, Livorno and Napoli, and the calculated sea level difference between Genova and Livorno, and between Livorno and Napoli.

coastal waters at the start of the measurements, the temperature was uniform along the coast at about 13.8°C, while the salinity varied from 37.8 ppt at La Spezia and Grosseto to 36.8 ppt near Civitavecchia. One month later, the salinity was essentially unchanged while the upper 10 m of the water column had warmed to around 16°C.

Three moorings were placed along the coast at distances approximately 10 km offshore and in water 100 m deep. These moorings were near La Spezia (at 44°00′N, 9°44′E), near Grosseto to the south-east of Elba (at 42°36′N, 10°52′E), and near Civitavecchia (at 42°07′N, 11°38′E). Each of these subsurface moorings supported two NBA current meters (model type DNC-2B) at depths of 20 and 50 m, plus an Aanderaa current meter at 80 m. In addition, data were obtained from a deep mooring that was part of a separate experiment; this mooring was in water nearly 3 000 m deep, and was located 40 km to the south-west of the island of Ponza (at 40°54′N, 11°51′E; see Fig. 1). On this mooring there were two VACM current meters at depths of 600 and 900 m. The recording intervals were 10 minutes for the shallow water meters and 15 minutes for the deep meters, and the data were averaged in blocks to extract hourly mean currents. Wind data were obtained from weather stations at Genova, Olbia and Ponza; these data were in the form of 10 minutes averages of wind speed and direction at hourly intervals. Wind stress vectors were then calculated using a quadratic relationship with a drag coefficient of 1.3×10^{-3} (Halpern, 1976). In addition, hourly values of sea level elevation were obtained from Genova, Livorno and Napoli; these were corrected barometrically. All the data were treated with a lowpass filter and then resampled at 6-hourly intervals; the filter had an amplitude response of near 100% at 50 hours (0.5 cycles/day), 50% at 29 hours (0.84 cpd) and 0% at 20 hours (1.2 cpd). The resulting time series are shown in Figure 2.

The coastal winds

Wind data were obtained for Genova, Olbia and Ponza since these three stations were sufficient for estimation of the curl of the wind stress and, in addition, could provide an indication of the structure of the large scale wind field (Elliott, 1979*a*). As expected, the wind was coherent between Olbia and Ponza, and therefore the Ponza wind is used as an approximation to the large-scale wind. The Genova wind is thought to be a more local feature, but one which may affect the currents along the coastline near La Spezia. Therefore both the Genova and Ponza wind records were used in the analysis. The spectra of the components of the wind stress at Ponza, and of the curl of the wind stress are shown in Figure 3. The wind variance was strongest in the E-W direction, the energy being contained at time scales of from 3 to 10 days with a pronounced maximum around 5 days. The curl also showed a maximum at around 5 days, with a secondary peak near 2.5 days; the 2.5 day signal is evident in the wind stress vectors shown in Figure 2*a*. The mean and standard deviation of the Eastward and Northward components of the Ponza wind stress were 0.2 ± 0.7 and 0.1 ± 0.3 dyn.cm^{-2}, respectively, while the curl had a corresponding value of $0.4 \pm 0.7 \times 10^{-8}$ dyn.cm^{-3}. The Genova wind was considerably weaker than the large-scale (Ponza) wind, and the eastward and northward components of stress were -0.1 ± 0.1 and

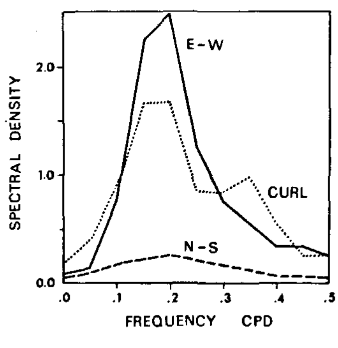

Figure 3

Spectral density of the eastwards and northwards components of the Ponza wind stress ($dyn^2.cm^{-4}/cpd$), frequency is in cycles/day (cpd). Dashed curve: spectral density of the curl of the wind stress ($\times 10^8$) ($dyn^2.cm^{-6}/cpd$).

0.0 ± 0.1 dyn.cm^{-2}, respectively. A strong wind event occurred at the beginning of May, when the wind over the Ligurian and Tyrrhenian Sea was directed towards the South-East at about 15 m.s^{-1}. This shows up in Figure 2 *a* as the negative alongshore wind stress of more than 3 dyn.cm^{-2} beginning at Ponza on May 1.

The currents

At all three of the coastal locations the flow was predominantly in the alongshore direction; the alongshore components of the flow are shown in Figure 2 *a*, and the mean statistics for La Spezia and Civitavecchia are given in Table 1. At La Spezia the currents were directed towards the North-West at about 25 cm.s^{-1} during the first half of the experiment, but they decreased to around 5-10 cm.s^{-1} following the strong wind event that occurred at the beginning of May. In contrast, the currents near Civitavecchia were significantly weaker, being generally less than 10 cm.s^{-1} and having a near zero overall mean. One particular feature was the reversal of the flow that took place in response to the strong wind event on May 2. A strong positive pulse of current was recorded by the instrument at 80 m on May 12 when the flow approached 10 cm.s^{-1}, however this event appeared to be uncorrelated with the wind. At both La Spezia and Civitavecchia the current records showed a significant amount of variability at the 2-3 day time scale; it is evident from Figure 2 *a* that these fluctuations were coherent throughout the water column and that they appear to be related to fluctuations in the Ponza wind record. The currents at Grosseto were less energetic than at the other two locations and, in particular, there seemed to be considerably less energy at the 2- to 3-day time scale. This location near Elba is one of the places where measurements were made during the earlier experiment in 1977, the data from which failed to produce convincing evidence for the existence of shelf waves (Elliott, 1979 *a*). The currents recorded at the deep mooring were also predominantly oriented parallel to the local isobaths, being directed towards the North-West with a speed of about 2-3 cm.s^{-1}. The 2- to 5-day variability, which is so apparent in the coastal data, was absent from the deep records. This suggests that the energy at these time scales is input directly into the surface layers by the wind, and that the deep water does not act as a source of energy for the shallow water variability at this time scale. The deep currents were extremely weak during the first half of May, but then increased in strength after May 10. If the 2- to 5-day variability is ignored it is possible to see a similar trend during May in the Civitavecchia currents; this suggests that the thermohaline component of the circulation may be coherent between the deep basins and the coastal water on time scales of 10 days or longer.

The method of empirical function analysis (Kundu *et al.*, 1975) was used to determine the vertical modal structure of the flow; the results for La Spezia and Civitavecchia are shown in Table 1. In the alongshore direction about 90% of the current variance was associated with a barotropic response, and the remaining 10% was due to a shear mode that had a minimum amplitude at mid-depth (the vertical modes have been normalised to represent the components of a unit vector; to obtain the corresponding current fluctuations at a particular depth it is necessary to multiply by the standard deviation of the current). For La Spezia the mean alongshore flow was around 16 cm.s^{-1} and independent of depth, however the standard deviation varied between 6-12 cm.s^{-1}. The mean alongshore flow at Civitavecchia was of the order of 1 cm.s^{-1} and the standard deviation between 3-5 cm.s^{-1}. The larger signal in the current fluctuations at 80 m with respect to the shallower meters is thought to be due to the different characteristics of the two types of current meter used (NBA meters at 20 and 50 m,

Table 1
Mean statistics and vertical structure of the alongshore and offshore components of the flow near La Spezia and Civitavecchia.

La Spezia	Alongshore flow					Offshore flow				
			Vertical structure (variance explained)					Vertical structure (variance explained)		
Depth (m)	Mean (cm.s^{-1})	S.D. (cm.s^{-1})	1 (92.1%)	2 (7.4%)	3 (0.5%)	Mean (cm.s^{-1})	S.D. (cm.s^{-1})	1 (61.2%)	2 (32.1%)	3 (6.7%)
20	16.7	6.6	0.56	0.77	−0.31	0.5	1.8	0.66	0.34	−0.67
50	14.4	8.7	0.60	−0.12	0.79	−0.3	1.3	0.70	0.05	0.71
80	17.0	12.8	0.57	−0.63	−0.53	0.5	2.1	0.28	−0.94	−0.20

Civitavecchia	Alongshore flow					Offshore flow				
			Vertical structure (variance explained)					Vertical structure (variance explained)		
Depth (m)	Mean (cm.s^{-1})	S.D. (cm.s^{-1})	1 (85.5%)	2 (13.2%)	3 (1.3%)	Mean (cm.s^{-1})	S.D. (cm.s^{-1})	1 (55.9%)	2 (34.5%)	3 (9.6%)
20	0.8	3.8	0.54	0.78	−0.31	0.3	2.1	−0.03	−0.98	−0.22
50	1.1	3.0	0.62	−0.11	0.78	−0.1	0.6	0.71	−0.17	0.69
80	1.4	5.2	0.57	−0.62	−0.54	−0.4	1.2	0.71	0.14	−0.69

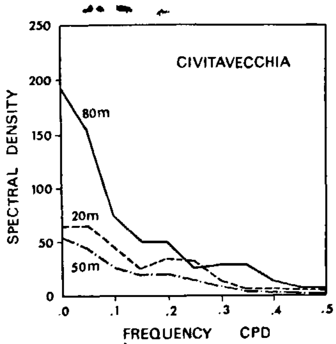

Figure 4 *a*
Spectral density of the along-shore current recorded near La Spezia ($cm^2.s^{-2}/cpd$).

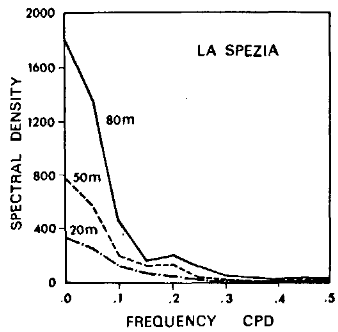

Figure 4 *b*
Spectral density of the along-shore current recorded near Civitavecchia ($cm^2.s^{-2}/cpd$).

Aanderaa meters at 80 m). Previous measurements that had used Aanderaa meters at both 20 and 80 m had found the current variability to be of comparable magnitude at the two depths (Elliott, 1979 *a*); therefore it is likely that the Aanderaa meters overestimate the variability due to the response characteristics inherent in the use of a savonius rotor (Karweit, 1974; Beardsley *et al.*, 1977). The shear mode was more pronounced in the cross-shelf direction, where approximately 60% of the current variance was in a barotropic mode and 30% in the shear mode (Table 1). At both locations the mean onshore flow had a magnitude of only 0.5 $cm.s^{-1}$ with a standard deviation of around 2 $cm.s^{-1}$. Figure 4 shows the spectra of the alongshore flow. Both data sets showed evidence for a 5-day periodicity, and the Civitavecchia data also showed a near-bottom variability on a 2.5- to 3-day time scale. These periodicities were also present in the wind data (Fig. 3).

The sea level

Adjusted sea level records (corrected for the inverse barometer effect) are shown in Figure 2*b*. The two Ligurian Sea levels, recorded at Genova and Livorno, were highly coherent and in phase, and dissimilar to the Napoli record. The two computed sea level difference records, representing the slopes along the Ligurian and Tyrrhenian coasts, were incoherent; this agrees with the earlier results which showed that only a fraction of the sea-level disturbances within one basin will propagate into the other across the shallow shelf area near Elba. The 3-day variability, which was evident during the first part of the Genova and Livorno records, does not appear in the alongshore slope record. This suggests that it was due to on/offshore effects, which would be enhanced by the semi-enclosed nature of the Ligurian sea.

THE ALONGSHORE DYNAMICS

A diagnostic analysis

If we consider a co-ordinate system in which x denotes the alongshore direction (positive with the coast to the right) and y is the offshore direction, then the linear depth integrated alongshore momentum equation can be written as

$$\frac{\partial u}{\partial t} = fv - g\frac{\partial \eta}{\partial x} + \frac{\tau_x}{h} - \frac{ku}{h} + \varepsilon, \qquad (1)$$

where τ_x is the alongside component of the wind stress, and the bottom friction has been written in terms of a linear relationship with a drag coefficient, k. The final term on the right hand side of equation (1), ε, represents the error which arises both through the neglection of terms (for example, the non-linear acceleration terms), and also through errors in the measurements themselves (for example, inaccuracies in the data and errors in the calculation of the stress terms due to an imprecise knowledge of the drag laws). The first five terms in the equation were calculated directly from the observations, and the ε term was determined by requiring both sides of the equation to balance. The resulting time series are shown in Figure 5.

A linear bottom friction was used since the high frequency fluctuations had been removed by filtering (Hunter, 1975). The best fit values for the friction coefficient were calculated by a method similar to that used by Winant and Beardsley (1979), who assumed a balance between the bottom and surface stresses and estimated the drag coefficient by regression, i. e. by assuming a balance of the form $\tau_x = ku$. In the present case a response analysis was used and the drag coefficient estimated by averaging the magnitude of the response function over the time scales at which wind forcing was important. For the La Spezia current the calculation was made for both the Genova and Ponza wind stress components, giving bottom drag coefficients

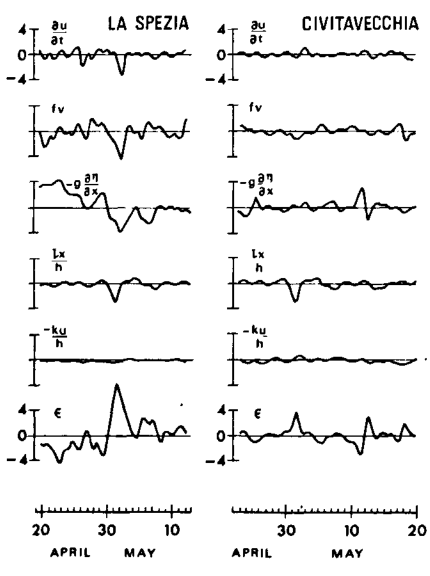

Figure 5
Calculated time series of the terms in equation (1).

in the range of 0.01-0.02 and 0.02-0.10, respectively, in cgs units. The Civitavecchia current, taken with the Ponza wind stress, gave a value in the range 0.20-0.30. Consequently, the friction terms shown in Figure 5 were calculated using a drag coefficient of 0.01 for the La Spezia balance, and a drag coefficient of 0.10 for the Civitavecchia balance. Further evidence of this difference in the frictional behaviour at the two locations will be given in a later section.

As shown by Figure 5, each term in equation (1) has a typical value of around 10^{-4} (cgs). However, the largest of the terms was the error series, ε, which suggests that either important terms have been neglected or that the measurements contained significant errors. For the La Spezia balance the shape of the error series is comparable to the reflection of the alongshore slope term, $-g\,\partial\eta/\partial x$, evaluated using the sea level at Genova and Livorno. This supports the conclusion, made during the sea level analysis, that the changes in the Ligurian sea level are mainly due to on/offshore effects which mask the alongshore differences. In the Civitavecchia balance the error appears to be due both to the alongshore slope term and also to the wind stress term. At both locations, therefore, a significant error will be made if the alongshore current is estimated by integrating directly the first four terms on the right hand side of equation (1). It appears that most of the error would arise through imprecise estimation of the alongshore slope, $\partial\eta/\partial x$, and that better current prediction may be obtained if this term is neglected.

The method of empirical orthogonal function analysis, used in an earlier section to determine vertical modes, was applied to the time series of the first five terms in equation (1). If the error time, ε, is neglected then the other five series can be used to construct five orthogonal time series (Wallace, Dickinson, 1972). The orthogonal functions can then be correlated with each of the original series in the momentum equation, and in this way the forcing mechanisms can be isolated. This is similar to the method by which forcing mechanisms were isolated in a set of estuarine data (Elliott, 1978). The advantage of the method is that since it gives results in terms of regression coefficients (i. e. it determines the percentage of the variance in each of the data series that can be predicted using the orthogonal functions as linear predictors), then the results are independent of the scaling of the input variables. This is particularly important in the present circumstances when the exact values of the surface and bottom drag coefficients are imprecisely known. The method is therefore only dependent upon the relative shapes of the dynamic time series shown in Figure 5.

The results of the analysis are given in Table 2, which lists the total variance that can be explained by each of the orthogonal functions, and also gives the percentage of the variance that can be accounted for in each term of the momentum equation if the orthogonal functions are used as linear predictors (i. e. the table shows the correlation squared). Because the usual t-test cannot be used to test for significance, since the input series and the orthogonal functions are not independent, a value of the correlation squared of 0.20 has arbitrarily been taken to indicate significance. For the La Spezia balance, the first function could explain 34 % of the total variance, and in particular could account for 65 % of the acceleration variance. However, the friction term, $-ku/h$, was not correlated with the first function, which suggests a coupling between acceleration, rotation, surface slope and wind stress. In contrast, most of the friction term variance was related to the second function, as was 40 % of the slope variance. The acceleration term, however, was not related to the second mode. The third function suggested a direct coupling between the acceleration and the wind stress, but only 20 % of the acceleration variance was related to this response. Consequently, the dominant response near La Spezia involved the acceleration, rotation, wind stress and surface slope. Of the slope variance, only 35 % was linked to this response, while 40 % was related to a second mode that was not coupled to the acceleration. In particular, the frictional term had near zero correlation with the first function, and therefore was not related to the acceleration.

The results obtained using the Civitavecchia data (Table 2) differed in that it was the frictional term, and not the surface slope term, that was related to the first mode. The dominant response at Civitavecchia, therefore, involved the acceleration, rotation, wind stress and friction. If modes 1 and 2 are combined then they involve a total of 75 % of the acceleration variance and 70 % of the frictional variance. Consequently, in contrast to La Spezia, friction appears to play a significant rôle in the dynamic balance at Civitavecchia. As noted previously, these results and conclusions are independent of the value taken for the bottom drag coefficient.

Table 2

Empirical orthogonal function analysis of the terms in equation (1). The values show the percentage of the total variance that can be explained by each orthogonal function, and the correlation squared between each function and the individual terms in the alongshore momentum equation (excluding the error term, ε).

La Spezia

Function	Total variance (%)	Variance explained				
		$\partial u/\partial t$	fv	$-g\,\partial\eta/\partial x$	τ_x/h	$-ku/h$
1	33.9	0.65	0.67	0.35	0.31	0.02
2	27.4	0.01	0.04	0.40	0.06	0.86
3	20.3	0.20	0.11	0.13	0.55	0.01
4	6.8	0.07	0.13	0.04	0.02	0.08
5	5.6	0.08	0.04	0.08	0.05	0.03

Civitavecchia

Function	Total variance (%)	Variance explained				
		$\partial u/\partial t$	fv	$-g\,\partial\eta/\partial x$	τ_x/h	$-ku/h$
1	41.5	0.50	0.45	0.10	0.79	0.23
2	27.1	0.23	0.06	0.59	0.00	0.47
3	13.4	0.16	0.44	0.02	0.04	0.01
4	12.0	0.00	0.04	0.29	0.01	0.26
5	6.0	0.10	0.00	0.00	0.16	0.03

A numerical shelf model

The linear two-dimensional depth-integrated momentum and continuity equations for water of uniform density can be written as:

$$\frac{\partial u}{\partial t} = fv - g\frac{\partial \eta}{\partial x} + \frac{\tau_x}{h} - \frac{ku}{h}, \tag{2}$$

$$\frac{\partial v}{\partial t} = -fu - g\frac{\partial \eta}{\partial y} + \frac{\tau_y}{h} - \frac{kv}{h}, \tag{3}$$

and

$$\frac{\partial \eta}{\partial t} = -h\frac{\partial u}{\partial x} - h\frac{\partial v}{\partial y}. \tag{4}$$

If these equations are applied to a point at a distance D offshore on a flat straight shelf of width L, then neglecting all variations in the alongshore direction they become

$$\frac{\partial u}{\partial t} = fv + \frac{\tau_x}{h} - \frac{ku}{h}, \tag{5}$$

and

$$\frac{\partial v}{\partial t} = -fu + \frac{\tau_y}{h} - \frac{kv}{h} - \frac{2\alpha gh}{D(2L-D)}\int v\,dt. \tag{6}$$

The cross-shelf slope term, which has been multiplied by a factor α $(0 \leq \alpha \leq 1)$, was estimated by assuming that the cross-shelf motion was a simple seiche with $\eta = 0$ at the shelf edge, and by using continuity to relate the cross-shelf slope to the cross-shelf flow [with $(\partial/\partial x) \equiv 0$]. For $\alpha = 0$ the equations reduce to those appropriate to an open sea (e. g. Pollard, Millard, 1970). The coupled equations (5) and (6) were solved using centered finite differences, the Coriolis term being treated semi-implicity. Initial tests, made using a time step of 1 hour, were unstable due to a cross-shelf seiche that had a period of order $2L(gh)^{-1/2}$. For a shelf geometry with L = 20 km and $h = 100$ m, this period is of the order of 20 minutes. Therefore a time step of 10 minutes was required for stability. In addition, the output from the model was filtered to remove the inertial oscillations that were generated by the wind and which had a period of around 18 hours. The low-pass output was then resampled at 6-hour intervals so that it could be compared directly with the observed currents. The only inputs required by the model were the time series of the alongshore and offshore components of the wind stress. This simple model, therefore, permits an investigation into the relative importance of rotation, friction and shelf geometry. The main features that need to be explained are the significantly stronger currents at La Spezia than at Civitavecchia, and the response of the coastal currents to the strong wind event of May 2. For all of the computational tests, the initial values for the alongshore and offshore components of the current were set equal to 25 cm.s^{-1} and zero, respectively.

The currents predicted using the Genova wind as input did not agree with the observations. The alongshore component of the Genova wind stress was always positive (Fig. 2 *a*), and its integral, therefore, increased with time. In addition, there was no feature of the Genova wind that could explain the current response observed at the start of May. Consequently, although the Genova wind may influence locally the Ligurian sea level, it does not influence the general coastal flow. The Ponza wind, which has been taken as an indicator of the large-scale wind, was found to be a better predictor of the coastal flow and is used in all of the following tests.

Figure 6 *a* shows the results, with f and α set to zero, on the effects of varying the friction coefficient, k. For low friction (k less than about 0.010) the alongshore current

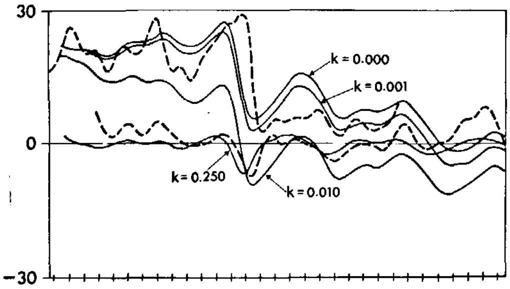

Figure 6 *a*

Computed currents for different values of the friction coefficient. The alongshore components observed near La Spezia and Civitavecchia are shown by the dashed curves: the time axis is marked in days.

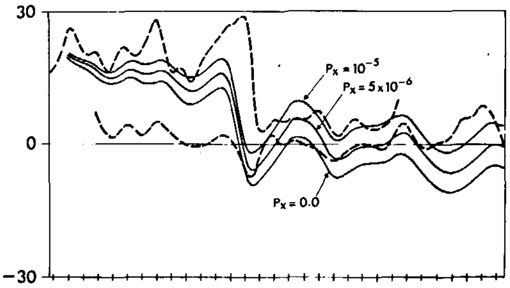

Figure 6 *b*

The effect of including a term, P_x, representing a constant alongshore pressure gradient ($k = 0.010$, wind driving included).

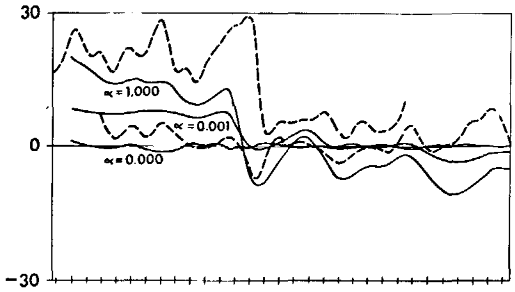

Figure 6 *c*

The effect of varying the shelf effect parameter, α (equivalent to considering locations at different distances from the coast).

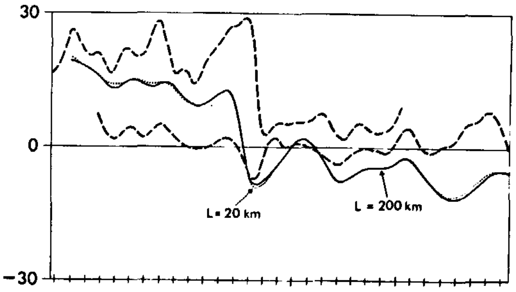

Figure 6 *d*

The effect of varying the effective shelf width, L.

was comparable in character to that observed near La Spezia. The predicted current, however, responded more rapidly to the strong wind event at the beginning of May, leading the observed current by about 1 day. As the friction coefficient was increased, the initial velocity was rapidly damped out, and the predicted current started to show similarities to the flow observed at Civitavecchia. With $k=0.250$, the response to the strong wind event was reproduced fairly well in terms of the magnitude of the current, although the prediction led the observed current by about 18 hours. This particular value of the friction coefficient is the one that has been used for storm surge prediction (Heaps, 1969), when attention is directed towards reproducing the effects of strong winds. However, it underestimated the current response during weaker wind events, suggesting that the wind stress may have been better represented by a linear relationship with the wind, or by making the drag coefficient a function of wind speed. The cross-shelf flow was not adequately modelled when rotation and shelf geometry were neglected, since integrating the onshore wind stress resulted in an onshore flow of the order of 30 cm.s^{-1}.

A difference in the thermohaline induced pressure force at the two locations may have been partly responsible for the dissimilarity in the observed currents. To test this possibility an extra term, P_x, was added to the right hand side of equation (5) to represent a constant alongshore pressure gradient. The results of varying P_x are shown in Figure 6 *b*, and they suggest that a constant pressure gradient cannot explain the difference between the two locations. Addition of the pressure force tended to increase the alongshore flow during the second part of the simulation, when the computed current was less than 10 cm.s^{-1}, but during the first part of the test the effect was reduced by the friction associated with the higher current speeds.

The results were sensitive to the shelf effect parameter, α. Decreasing α has the same effect as increasing D, the distance from the coast, and $\alpha=0$ is equivalent to an open ocean situation. In this case most of the wind forcing went directly into inertial oscillations, and when these were filtered out the remaining alongshore flow was of the order of a few cm.s^{-1} (Fig. 6 *c*). Increasing α caused the alongshore component of the flow to increase, and the cross-shelf flow to decrease to a realistic value due to the effect of the induced cross-shelf surface slope. The results were not sensitive to the value taken for the effective width of the shelf, L (the distance from the coast at which $\eta=0$). Figure 6 *d* shows the results for L=20 and 200 km, the predicted alongshore current being almost the same in both cases.

Figure 7 *a* compares the results from the coupled equations (5) and (6), including rotation and the shelf geometry, with the result of integrating directly the alongshore component of the wind stress. It shows that if only the alongshore current is of interest then there is little to be gained by solving the coupled equations. The observational positions were so close to the coast that the dominant component of the flow was constrained to be parallel to the coast, and the on/offshore motion was balanced by the induced cross-shelf surface slope so that

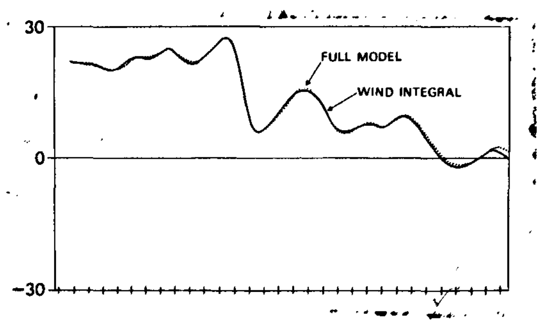

Figure 7 *a*
Comparison between the results obtained with the full model, including rotation and shelf geometry, and by considering only the alongshore dynamics.

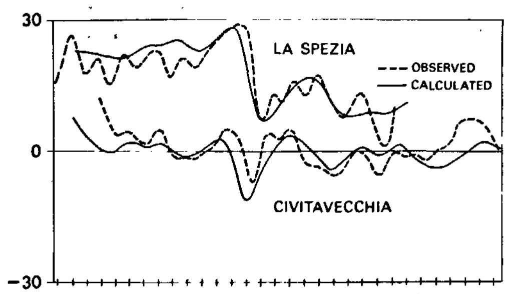

Figure 7 *b*
Comparison between the best fit calculated currents and the observed components of the alongshore flow at 20 m.

it had little effect on the alongshore flow. Consequently, an adequate model of the alongshore flow near the coast would be

$$\frac{\partial u}{\partial t}=\frac{\tau_x}{h}-\frac{ku}{h}. \qquad (7)$$

The output from this model, for different values of the friction coefficient, *k*, were shown in Figure 6 *a*. The best fit, resulting from applying this model to the currents observed at 20 m, is shown in Figure 7 *b*. A good prediction of the flow near La Spezia was obtained simply by integrating the alongshore wind stress and delaying the output by a lag of 18 hours. This gave a good fit to the response to the strong wind event and to the increase in current speed immediately afterwards. The best predictor of the Civitavecchia current was obtained by taking $k=0.10$ (Fig. 7 *b*).

The main difference between the observed and calculated currents shown in Figure 7 *b* is the absence of the 2- to 3-day variability in the calculated flow. Since all the alongshore gradients were neglected in the model it is not possible to reproduce waves in the alongshore direction. Therefore, the difference between the observed and predicted currents shown in Figure 7 *b* is indicative of the amount of shelf wave activity at the two locations.

DISCUSSION

Two separate methods, empirical function analysis of the terms in the alongshore momentum equation and constructing a numerical model, have each produced evidence that the apparent bottom friction near

La Spezia is smaller than the value appropriate for the location near Civitavecchia. The linear friction coefficient used in numerical modelling is typically of the order of 0.250 (Heaps, 1977) while Pollard and Millard (1970) used a value in the range 0.005-0.010 to represent the interfacial drag acting at the bottom of the mixed layer. Winant and Beardsley (1979) compared different sets of shallow water observational data and estimated the linear drag coefficient to lie in the range 0.030-0.200. Therefore, the value that gave the best fit to the Civitavecchia data ($k = 0.100$) was consistent with other numerical and observational results. In contrast, the apparent friction near La Spezia was an order of magnitude smaller than the accepted values. This may be due to the omission from the momentum equation of important dynamic terms. For example, cross-shelf internal pressure forces have been neglected, and tests were only made for the effect of a steady alongshore pressure gradient. Baroclinic pressure gradients have not been estimated, and it is possible that they are responsible to some degree for the motions observed near La Spezia. The inclusion of a constant alongshore pressure gradient [following equation (5)] was unsatisfactory, and this is to be expected since strong atmospheric forcing such as occurred at the beginning of May will affect the distribution of water properties and hence the baroclinic pressure gradients. It therefore seems quite likely that the difference in the flow between La Spezia and Civitavecchia was due not to a difference in the bottom friction, but due to time varying baroclinic effects which were neglected in the analysis.

For the immediate purposes of water quality modelling a simple predictor of the alongshore flow such as equation (7) is probably sufficient; little is to be gained by solving the coupled equations (5)-(6), when interest is restricted to the flow within a few kilometres of the coast. Future work needs to be directed towards the larger scale circulation of the Ligurian and Tyrrhenian seas and its interaction with the coastal currents.

Acknowledgements

P. Giannecchini, E. Nacini and G. Tognarini contributed to the collection, analysis and presentation of the data. F. de Strobel assisted with the planning and execution of the field measurements, and supervised the mooring design and the translation of the current meter tapes. The data from the deep mooring in the Tyrrhenian Sea were provided by R. Molcard.

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La figure montre le nouveau planisphère avec une représentation simplifiée de la salinité de surface des océans. Il est intéressant de le comparer à la carte VI du traité de Sverdrup, Johnson et Fleming.

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The Figure shows the new world map with a simplified picture of the surface salinity of the ocean. It is worthwhile to compare it with chart VI of the textbook of Sverdrup, Johnson and Fleming.

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