Fluxes across the Corsica Channel and coastal circulation in the East Ligurian Sea. North-Western Mediterranean

Mediterranean Sea
Ligurian Sea
Corsica Channel
Fluxes across straits
Mer Méditerranée
Mer Ligure
Canal de Corse
Flux à travers les détroits

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ABSTRACT

Current measurements in the Eastern Ligurian Sea off La Spezia (Italy) permit the definition of the relationship between the fluxes across the Corsica Channel and the almost depth-independent shelf water movements. Hydrological fluxes computed by Bethoux *et al.*, (1982) and the present data both suggest a reference velocity of 3-6 cm/s for the surface layer flux through the Corsica Channel. The influence of external forcing is assessed during the period March-April, 1982.

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RÉSUMÉ

Flux à travers le canal de Corse et circulation côtière dans la Mer Ligure orientale, Méditerranée Nord-Occidentale.

Des mesures de courant dans la Mer Ligure orientale ont permis de définir les relations entre le flux traversant le canal de Corse et les déplacements des masses d'eaux côtières. Au large de La Spezia (Italie), ces derniers sont presque indépendants de la profondeur. Une comparaison avec les données hydrologiques (Bethoux *et al.*, 1982) a permis de calculer une vitesse barotrope de 3 à 6 cm/s dans les flux à travers le canal. On a établi l'influence des forces externes pendant la période mars-avril 1982.

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INTRODUCTION

In previous studies of the Mediterranean Sea, many efforts have been made to determine the fluxes across the straits (Fig. 1), since they control the general circulation. It is believed that the circulation across the Straits of Gibraltar, Sardinia and Sicily can be considered as a two-layer system that is baroclinically compensated. *i.e.* the surface inflow is compensated by the lower layer outflow (Lacombe, Richez, 1982; Garzoli, Maillard, 1979). The straits control the exchanges between Atlantic and Mediterranean waters and between Western and Eastern Mediterranean waters, the motion being controlled by the climate and the physical characteristics of the different basins (Bethoux, 1980) and in particular by the atmospheric pressure distribution (Garrett, 1983). The other straits of the Western Mediterranean have been less well studied. The circulation in the Straits of Messina is mainly related to the tides, which are capable of creating strong currents up to 3 m/s (Alpers, Salusti, 1983). Study of the Straits of Bonifacio has demonstrated that the water motion is mainly wind-driven (*e.g.* Bruschi *et al.*, 1980). The funnelling of the wind between Corsica and Sardinia is furthermore capable of strongly influencing the circulation in the North-West Tyrrhenian Sea (Moen, 1983).
As a result of oceanographic expeditions carried out

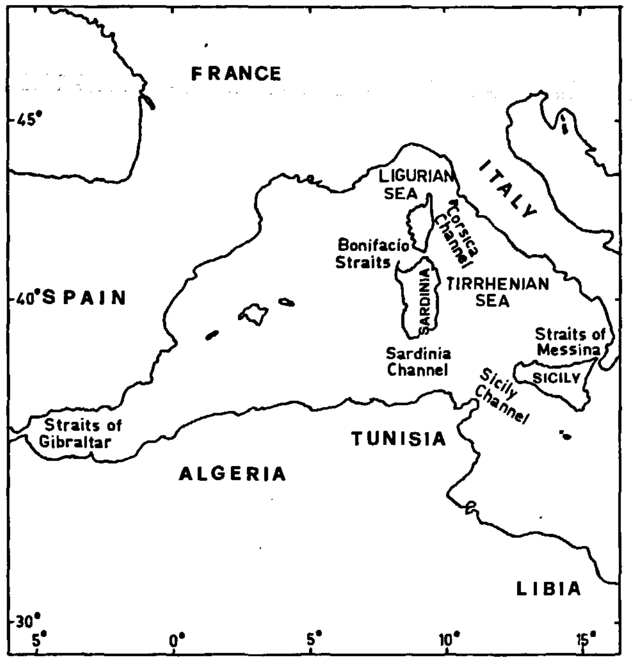

Figure 1
The Western Mediterranean Sea and the Straits.

in the Corsica Channel, the temperature and the salinity distributions in that area are rather well known (Le Floch, 1963). From geostrophic calculations and measurements with profiling current meters, Le Floch (1963) and Stocchino and Testoni (1968) proposed outlines of the circulation in the Corsica Channel, but these outlines have not been completed and verified by means of long-term current measurements. It is interesting to note that the summer surface circulation given by Furnestin and Allain (reported in Le Floch, 1963) shows a southward flux in the Capraia Channel. More recently Elliott (1979 *b*) modelled the Ligurian and Tyrrhenian dynamics and obtained a flow from the Ligurian Sea to the Tyrrhenian Sea related to a wind blowing toward the Italian coast and a corresponding lowering of the coastal sea level.

For average conditions the surface water of the Ligurian Sea is fresher and cooler than the Tyrrhenian Sea (Trotti, 1954), the higher temperature and salinity differences being ~ 2°C (December-October) and ~ 0.2‰ (March). From density differences and variation of salinity it is possible to compute an average flux across the Corsica Channel of 0.65 Sv (Bethoux, 1980). Thermohaline currents of ~ 5 cm/sec are thought to exist between the island of Elba and the Italian mainland (Elliot, 1979 *a*). This flux of 0.025 Sv is only 4% of the Bethoux computation, thus it can, essentially be ignored. The overall circulation in the region reveals high speeds but not well defined streams (Esposito, Manzella, 1982). North of the Corsica Channel, a front appears at the limit between the cold core of the cyclonic Ligurian Sea circulation and the warm waters running laterally to it (Philippe, Harang, 1982). Salinity and temperature distributions (Trotti, 1954; Le Floch, 1963) show that the northward flow is not uniform across the Corsica Channel and off North-West Italy, but that there is a flow of "Tyrrhenian" water into the Ligurian Sea close to the coast. Local upwelling, probably induced by topographic waves, appears to stop the surface currents (Astraldi, Manzella, 1983).

In 1981-1982, during the Mediterranean Alpine Experiment (MedAlpEx), moorings were maintained at different times in the Capraia Channel (mooring C, 43°01′40″E 9°42′40″N), in the neighbothood of the Elba Channel (mooring E, 42°54′12″E 9°54′24″N, both channels are referred to here as the Corsica Channel) and along the coast of North-West Italy (moorings S, 44°13′34″E 9°22′49″N, and V, 43°42′24″E 9°58′54″N). A meteorological buoy (ODAS-I-1) moored on the 500 m isobath provided the wind data, while sea level and air pressure were gathered in La Spezia harbour (Fig. 2).

In this note a study of the current fluctuations in the Capraia and Elba channels and their relationships with the coastal circulation off North-West Italy is presented. The data analysis was performed by means of modal decomposition, correlation, coherence and spectral analysis. Modal decomposition, involving empirical orthogonal functions (EOF), can be a powerful method in some circumstances. The method is used to formally separate the velocity field in the vertical into its modal components. It was used to analyse the coastal circulation in the Ligurian and Tyrrhenian Seas by Elliott (1979) who isolated the barotropic response of the coastal circulation.

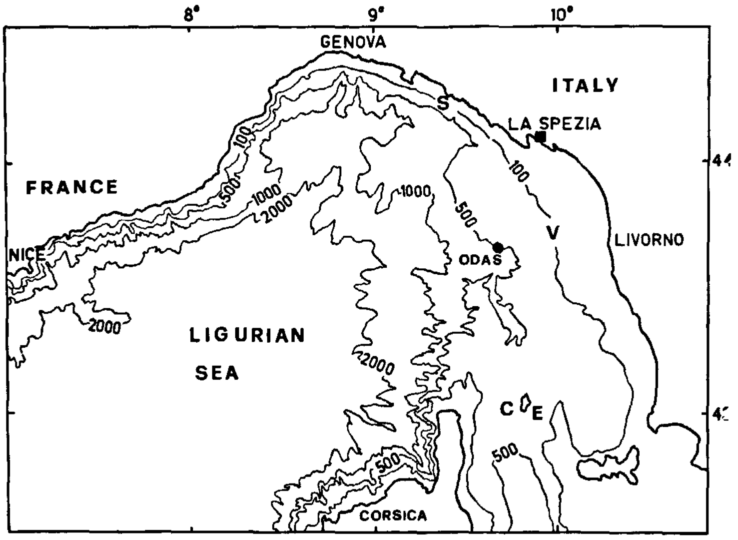

Figure 2
The Ligurian Sea. The letters denot current meter moorings, the meteo buoy Odas-I-1 and the tide gauge station are indicated. Depth in metres.

DATA AND METHODS

Current and temperature measurements were obtained using Aanderaa, NBA and General Oceanic

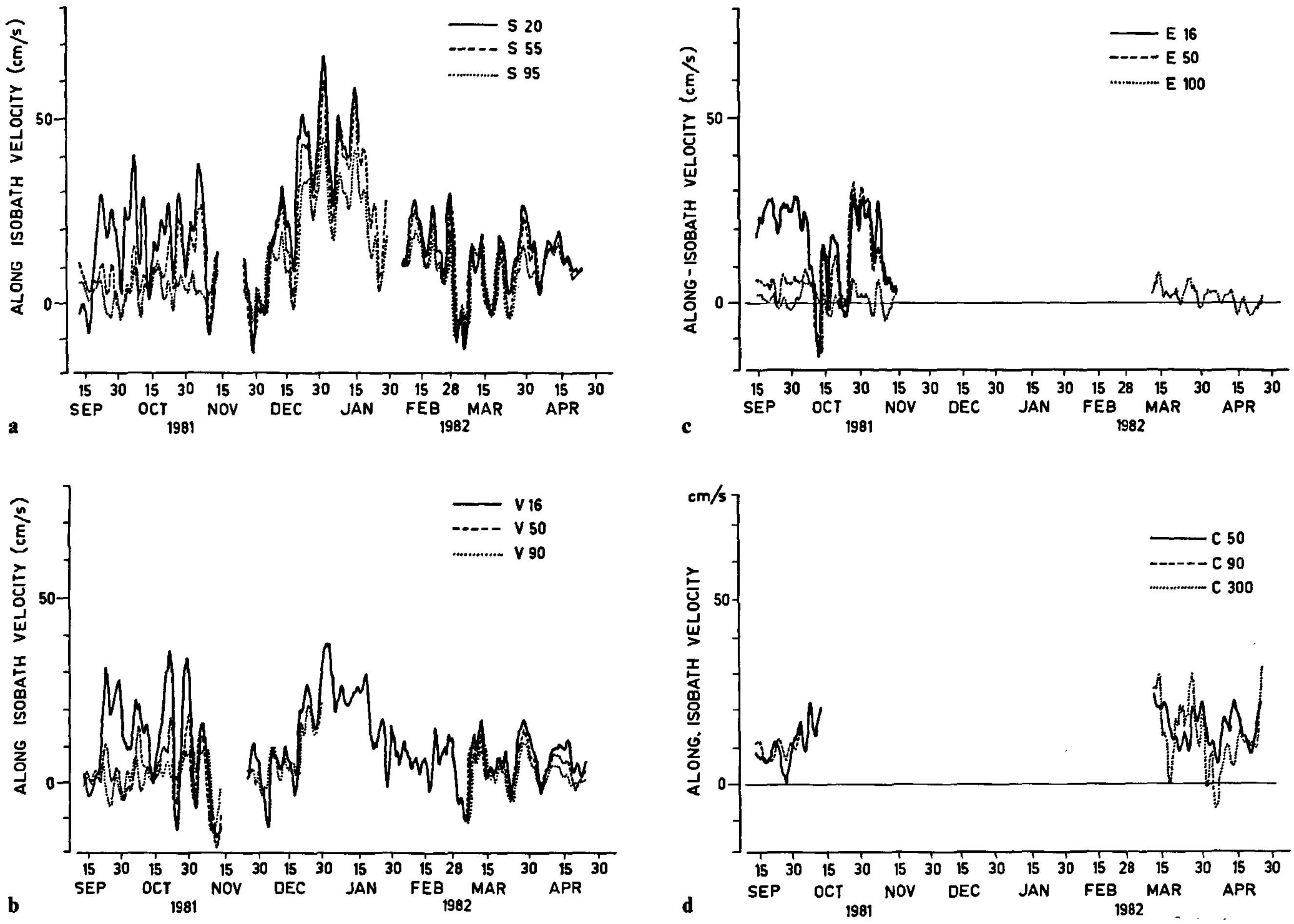

Figure 3
Along-isobath current components at position S (a), V (b), E (c) and C (d).

meters. The use of different instrument poses the question of data compatibility. While there were few problems with the Aanderaa and NBA (even though we know that the use of the Savonious rotor in the Aanderaa current meter enhances the fluctuations with respect to the NBA meter), more questions arise from the use of the General Oceanic meters. However these instruments were used at moorings V and E where the currents did not exceed 55 cm/s so that there was an almost linear response of the instruments to the current fluctuations. Furthermore, there were few instantaneous reversals so that careful checking allowed us to extract the spurious data. The samplings were 6 data per hour for Aanderaa and NBA meters, 32 data per hour for the General Oceanic meters. The sea level and air pressure were measured by means of a Paroscientific quartz sensor. The data were checked for errors and the current vectors resolved into E-W and N-S components, then a data set was formed by averaging the data every three hours. Gaps due to servicing, if shorter than one day, were filled by a time series whose spectral characteristics were determined from the end of the previous record and the beginning of the following one. To obtain fluctuations with frequencies lower than 1 c.p.d., the averaged data were low-pass filtered by calculating the running means over 16 readings (48 hours) and resampling every 12 hours. At a later stage the data were rotated to local coordinate systems with the y-axis along the isobaths. As a consequence, the coordinate systems were rotated 57° anticlockwise at S and 41° anticlockwise at V. By means of these rotations the total current variances were almost completely in the along-isobath direction (Fig. 3-4). The variability due to the use of several kinds of instruments did not pose serious problems, since (apart from the spectral analysis) both the correlations and the modes were normalized to represent unit vectors. The ODAS-I-1 wind data, proved by courtesy of Istituto Automazione Navale CNR, contained numerous gaps and showed high frequency noise. At lower frequency (> 0.5 cpd) they seemed quite good and in accordance with the sparse data collected by commercial ships. The wind data were treated in the same way as the current data; frequent gaps, however, made it impossible to fill out the complete record.

Current analysis

The previous studies by Elliott (1979 *a*; *b*; 1981) and Astraldi and Manzella (1983) were based on current measurements in front of La Spezia, south of the island of Elba and at the current meter station S, in 100 m of water. The main conclusion of these papers

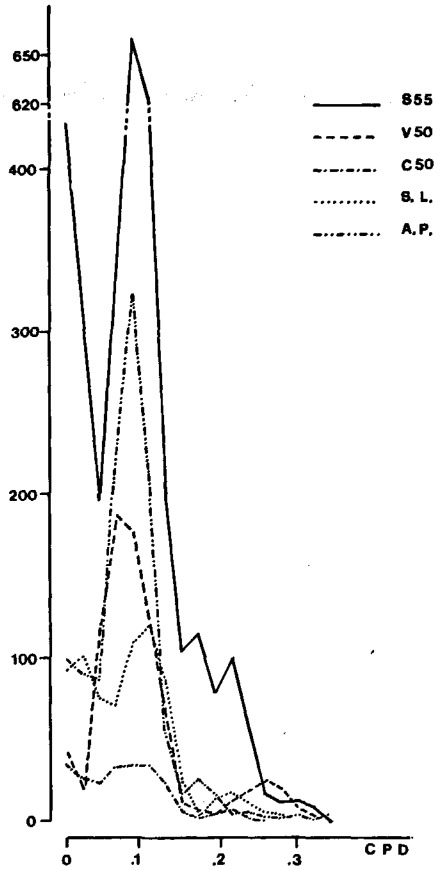

Figure 4
Energy distribution during the SOP of the low pass along-isobath currents (S55, V50, C50), non-adjusted sea level (S.L.) and air pressure (A.P.). Current spectra are expressed in $(cm/s)^2/(cycle/day)$, the sea level and air pressure spectra in $(mbar)^2/(cycle/day)$.

was that the dynamics of the coastal currents are driven by the large scale wind.

The MedAlpEx data (Fig. 3) are quite consistent with these previous measurements; one must note in Figure 3 *a*, however, greater variability at 2-6 days than in the observations reported by Astraldi and Manzella (1983). The mean values and the standard deviations of the along-isobath current components are reported in Table 1, where a dominant northward circulation can be seen (see also Fig. 3). Where records at three depths were available, a modal decomposition was performed. From the nature of the current fluctuations at different depths, the large part of the along-isobath current variations reveals a predominant depth-independent behavior (Fig. 3), with a vertical shear which is not greatly variable in time. In the first period of measurements at S, V and E (September-November, 1981, *see* Figures 2, 3 and Table 1), there were depth-independent currents (whose variances were 57-75%) with a significant contribution to the variance of the second empirical mode (20-30% of the total variance). This can be explained by the thermocline deepening and partial isolation of the bottom currents (Elliott, 1979). In March-April, 1982, because of vertical homogeneity, the barotropic mode accounted for ~ 95% of the variance both at S and V moorings. The current statistics (Table 1) show an almost constant mean current across the Capraia Channel, however in March-April the fluctuations near the bottom were more pronounced than at 50 m. This suggests that there is a barotropic component superimposed on the reputed baroclinic flow across the channel.

The correlation between the along-isobath currents at the same depths but at different mooring were significant (r = .20 − .40) having a 95% significant level of .15, but not coherent, except at 5 day periodicities. I will show that these oscillations are related to the sea level and air pressure fluctuations.

The current response

During the MedAlpEx "Special Observing Period" (SOP) March-April, 1982, the flux across the Capraia Channel was measured by means of two current meters at 50 and 300 m. There was no coherence at all between the along-isobath currents at C; the surface current fluctuated at the storm time scale (2-20 days) with a large amount of energy around 10 days (Fig. 4), while the bottom current spectrum had its maximum at longer time scales. This fact may be be related to the existence of a stratified system (Lusetti, Stocchino, 1979). The effects of one-dimensional topography and stratification on the circulation has been extensively studied (*e.g.* Csanady, 1982), however the effects of two-

Table 1
Statistics of the along-isobath current components. Mean currents and standard deviation (S.D.)

Mooring-Depth		Total		September-November		March-April	
		Mean	S.D.	Mean	S.D.	Mean	S.D.
S	20	18.28	15.54	16.67	11.70	11.59	7.08
S	55	15.29	14.16	8.82	7.08	10.19	6.69
S	95	10.81	11.21	3.23	3.48	7.75	5.83
V	16	10.45	10.99	10.88	13.67	6.37	6.23
V	50	4.05	6.54	3.09	7.78	5.17	4.43
V	90	3.94	5.48	2.00	4.75	3.80	3.35
E	16	15.93	10.95	16.18	10.99		
E	50	8.12	9.16	8.21	9.25		
E	100	8.62	2.07	0.63	2.67	11.19	2.68
C	50	13.26	5.57	10.40	5.43	15.11	5.89
C	95	9.15	2.36	9.15	2.36		
C	300	12.56	8.76			12.56	8.76

dimensional topography require elucidation, especially for the case of stratification. Theoretically barotropic and baroclinic modes could be allowed (Csanady, 1982) and both shelf and second class waves can coexist (Mysak *et al.*, 1979), but it is not possible to obtain more insights into the dynamic at C with the present data.

Linear regression was used to determine the relationship between the along-isobath components of wind stress and surface current; the results are shown in Table 2. It may be noted that wind stress and surface currents are positively correlated. Although the correlation is significant, an examination of the time series (Fig. 5) shows several instances where there were changes in current which were not related to the local wind. For example, the strong current at C during April, and similar events at S and V, are not explained by the local wind stress, but are probably due to advective processes (Esposito, Manzella, 1982). In order to understand better the role of atmospheric forcings on the circulation, one must refer to the weather circulation during the SOP as described in Kuettner (1982). During March, 6 cases of cyclogenisis, which are indicated by dots in figure 5, induced different responses of the sea at the various measurement sites (Fig. 5). For example one can see several reversals in the current measured off Sestri Levante and Viareggio, but not in the Capraia Channel.

Table 2
Regression coefficients ($V = a\tau + b$) between the along-isobath currents at 50 m and wind stress. The 95% significance level for the correlation coefficient was calculated 0.15.

V	(Depth)	a	b	r
S	55	3.43	8.56	0.19
V	50	2.46	4.39	0.22
C	50	3.32	0.10	0.29

The energy was quite evenly distributed in the vertical (considering the obvious differences due to the current amplitude decreasing with depth, Fig. 3), the only exception being the energy distributions of currents at C. The spectra of currents at 50-55 m are shown in Figure 4 with the non-adjusted sea level and air pressure spectra. All variables had enhancement in energy at 3-6 and 10 day periods, the first enhancement being related (Elliott, 1979) to events of lee cyclogenesis and to pre-existing cyclones simply crossing the area (*i.e.* on March, 29). Figure 6 presents the coherence from high resolution spectra with 6 degrees of freedom (spectra with higher degrees of freedom showed the same pattern although considerably smoothed). The coherence between the non-adjusted sea level and local atmospheric pressure was high near 3-day periods, but the phase of 30° suggest a non-hydrostatic response of the sea level at this periodicity (Elliott, 1979 *a*). The coherence between sea level and alongshore current was significant at 2.5 and 5 days (Fig. 6). Because

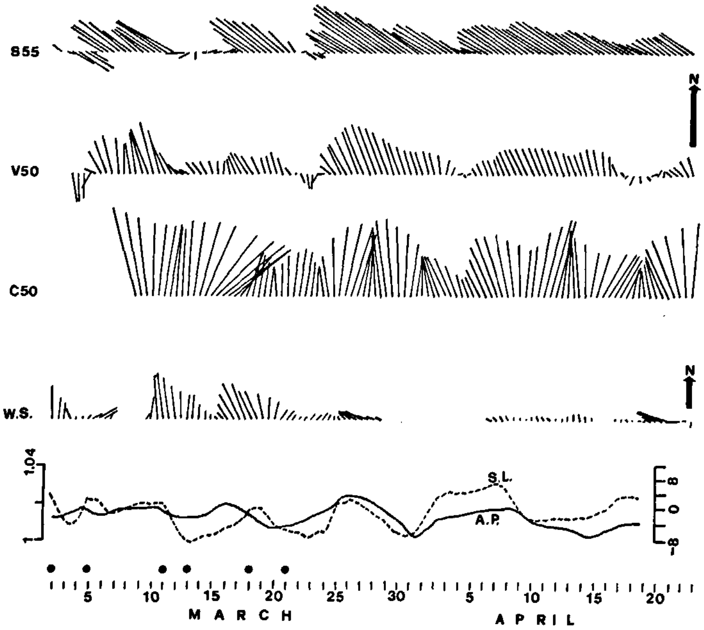

Figure 5
Low-passed stick vector plots from the current meters on S55, V50 and C50, wind stress (W.S.) and low-passed sea level variations with respect to the mean value (S.L., scale on the right in cm) and air pressure (A.P. scale on the left in bar) during the SOP (March-April, 1982). Arrows point North and their lengths correspond to a current speed of 10 cm/s (upper arrow) and a wind stress of 1 dyn/cm² (lower arrow).

of the numerous gaps in the wind record it is not possible to check the coherence between currents and wind stress. However Elliott (1979 *a*) found evidence that the wind field is spatially coherent at the cyclogenetic period of 5 days, which also when the coherence between both the sea level and the currents and along-shore wind stress reaches its highest value. The coherence between the surface current at C and the sea level was significant at 2-3 days, when the sea level is raised by eastward winds (Elliott, 1979 *a*), suggesting that the wind induced set-up in mean sea level along the eastern Ligurian coast constitutes a forcing mechanism on the coastal current.

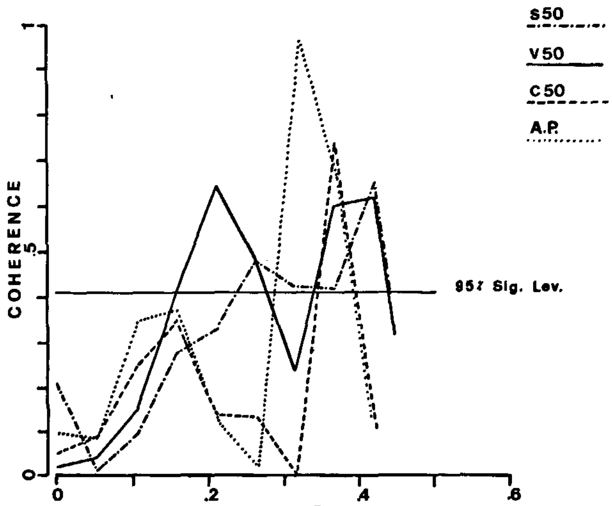

Figure 6
Coherence between sea level at La Spezia and along isobath currents S55, V50, C50 and air pressure A.P.

DISCUSSION AND CONCLUSIONS

The mean fluxes across the Straits of Capraia and Elba are presented in Table 3, together with the fluxes reported by Le Floch (1963) and Bethoux *et al.*, (1982) who computed the geostrophic fluxes off Calvi and off Nice and then assigned the difference to the Corsica Channel fluxes. The velocity was taken to be constant across the channels, and under this assumption one notes that the geostrophic method (Bethoux *et al.*, 1982) tends to underestimate the fluxes in the summer-autumn period. On average, the geostrophic currents contribute 35-75% of the observed fluxes. This fact can be partly explained by means of the approximations involved in the computations, and partly to the existence of a barotropic flow not considered by Bethoux *et al.*, which is capable of doubling the geostrophic circulation. Supposing that the barotropic contribution to the flux is given by the difference between Bethoux *et al.*, (1982) and actual observations, it is possible to estimate a reference velocity for the surface layer of 6 cm/s in summer and 3 cm/s in winter. The winter flux computed with the MedAlpEx data was between the Bethoux *et al.* and Le Floch calculations. The differences may in this case be attributed to density or wind interannual variability. A numerical model (Elliott, 1979 *b*) partly corroborates the idea that the wind determines the temporal evolution of the Eastern Ligurian Sea dynamics. A southward surface circulation, as depicted by Furnestin and Allain (reported *in* Le Floch, 1963), should be a rare event, since the low passed currents at C50 or C90 do not show reversals (Fig. 3), but only occasional stasis.

Table 3
Comparison between fluxes computed by: 1) Bethoux et al., *(1982); 2) Le Floch (1963) and the MedAlpEx data at C and E moorings.*

		Surface layer 0 200 metres	Intermediate layer > 200 metres
Annual	(1)	0.7	0.2
March	(1)	0.73	
Aug-Oct	(1)	0.25	
February	(2)	1.35	0.2
Sep-Nov	(C)	0.38	
Sep-Nov	(E)	0.3	
Total	(C+E)	0.68	
Mar-Apr	(C)	0.56	0.11
Mar-Apr	(E)	0.4	
Total	(C+E)	0.96	

Units in Sv = 1 million m^3/s

The common weather pattern for the Ligurian Sea is a depression moving eastward accompanied by winds veering from northward to southward. In this pattern, the wind first re-inforces the along-isobath current, then acts against the mean flow. The atmospheric depressions sometimes cover a large part of the North-Western Mediterranean so that uniform winds blow and generate an almost generally northward circulation in the area. The wind field produced by these atmospheric patterns is strongly influenced by the orography. A small scale wind circulation seems a typical aspect of the Ligurian area, the local wind being not capable of influencing the general coastal circulation (Elliott, 1981). This is supported by the fact that the events of Mistral (Kuttner, 1982) should be detected as eastward winds in the area. Figure 5 shows that this is not locally true because of the orography effects on the winds (Esposito, Manzella, 1982).

This paper can be briefly concluded with the following remarks.

1) Fluxes across the Corsica Channel cannot be completely explained in terms of baroclinic dynamics, but require the addition of a barotropic component.

2) Fluxes across the Corsica Channel would appear to depend on large scale atmospheric conditions.

3) Cyclogenesis strongly influences the coastal circulation, but the associated wind forcing has only a weakly noticeable effect on the Corsica Channel dynamics.

4) Coastal circulation, the Corsica Channel flux and sea level fluctuations are related at those time scales for which the basic weather situation permits a nearly eastward wind over the entire area.

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