Long-period oscillation in the Ligurian Sea

Mediterranean Sea
Ligurian Sea
Barotropic planetary waves
Mer Méditerranée
Mer Ligure
Oscillations planétaires barotropes

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ABSTRACT

From hydrological data collected along the Nice-Calvi transect in the Ligurian Sea, a 4-month periodic oscillation in density was identified out at all depths. This oscillation, found also in the atmospheric pressure, can be explained in terms of barotropic planetary waves.

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RÉSUMÉ

Oscillation de longue période en Mer Ligure

Les observations hydrologiques effectuées sur la radiale Nice-Calvi (Mer Ligure) ont permis d'isoler une oscillation de 4 mois en densité. Cette oscillation, rencontrée également dans la pression atmosphérique, peut être interprétée comme une onde planétaire barotrope.

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INTRODUCTION

In recent years, the importance of long-period changes and eddies in the ocean has become more and more evident. Most investigations have mainly concentrated on the analyzes of the structure of mesoscale eddies, in particular the warm water eddies (50 to 300 km in diameter) associated with the Gulf Stream (*e.g.* Cheney, Richardson, 1976). Atmospherically-forced eddies have been detected in the North West Pacific (Willmott, Mysak, 1980) and in the Atlantic Ocean (Willebrand *et al.*, 1980).

The frequent occurrence of meso- and small-scale eddies in the Mediterranean Sea is also evident from satellite imagery (Philippe, Harang, 1982). Their generation mechanisms are not completely known, but it seems that eddies can be generated by a baroclinic instability process (Gascard, 1978) or can have a topographic planetary origin (Garzoli *et al.*, 1982).

In the Ligurian Sea, the existence of a cyclonic circulation is well known, and has been studied by means of satellite images (Wald, Nihous, 1980), dynamic methods (Stocchino, Testoni, 1977) and objective analysis (Nyffeler *et al.*, 1980). Moreover, the Ligurian Sea exhibits a high spatial variability that sometimes overcomes the general cyclonic circulation. Eddy-like structures and patches of warm and cold water reported by Hela (1963), Dahme *et al.* (1971), Stocchino and Testoni (1977), are due to wind effects and to local topography (Hela, 1963) or to climatic variations (Wald, Nihous, 1980). Their evolution is known only approximatively, since advances in the knowledge of long-period variations have unfortunately been hindered by the lack of long-term current and TS records.

One exception relates to the hydrological data collected along the track Nice-Calvi (Hydrokor Cruises, 1973; 1975; Fig. 1), which permitted Bethoux *et al.*, (1982) to evaluate the fluxes through the section. The circulation is stronger in the northern part because of the concentration of fluxes from both sides of the Island of Corsica (Bethoux *et al.*, 1982).

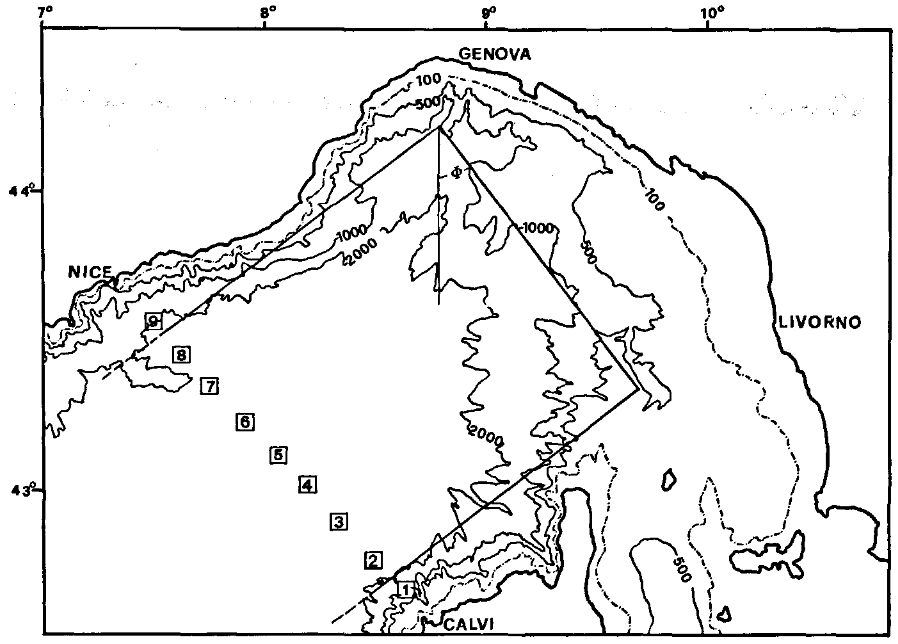

Figure 1
Ligurian Sea and the idealized basin. φ is the orientation angle; numbers in the squares indicate the hydrological stations.

Referring to average annual density profile and the atmospheric pressure, Gasparini and Manzella (1984) suggested that atmospheric oscillations can excite Rossby waves in the Ligurian Sea: the Nice-Calvi transect data provide a good opportunity to verify their existence. This is done by studying the spatial and temporal characteristics of those data and investigating both time- and length- scales involved in the dynamics of the Ligurian Sea at seasonal intervals.

THE *IN SITU* MEASUREMENTS

Monthly STD profiles were obtained from the data gathered during the years 1969-1973 at nine stations spaced at regular 10 mile intervals along the Nice-Calvi transect (Hydrokor Cruises, 1973; 1975). In order to obtain complete time evolutions of vertical profiles, we assembled the nine profiles into three sets (one near Nice, one situated centrally and one near Calvi), according to the Bethoux *et al.* (1982) analysis, which found strong geostrophic flows channelled into a coastal band 20 to 30 miles wide and a central zone in which the geostrophic flows are almost nul. The incoming geostrophic currents in front of Calvi sometimes present a reversal which is not detected in the current off Nice (Gostan, 1967); this notwithstanding, there exists a permanent circulation normal to the Nice-Calvi transect. This circulation is believed to have an annual cycle (Bethoux *et al.*, 1982), but a seasonal fluctuation of the flux off Nice has been hypothesized by Gostan (1967).

The time evolution of the density data shows a certain surface variability flattening progressively to a depth of 100-150 m, below which the density variations become quite homogeneous. Figure 2 shows density spectra of the central zone data; similar behaviour is encountered in the coastal zone data. An annual fluctuation is clearly present in the surface data, while the data below 100-150 m are characterized by a significant amount of energy, almost constant in the vertical at 3-4 cpy. This fluctuation is well evidenced in the data after the removal of annual oscillation (Fig. 3).

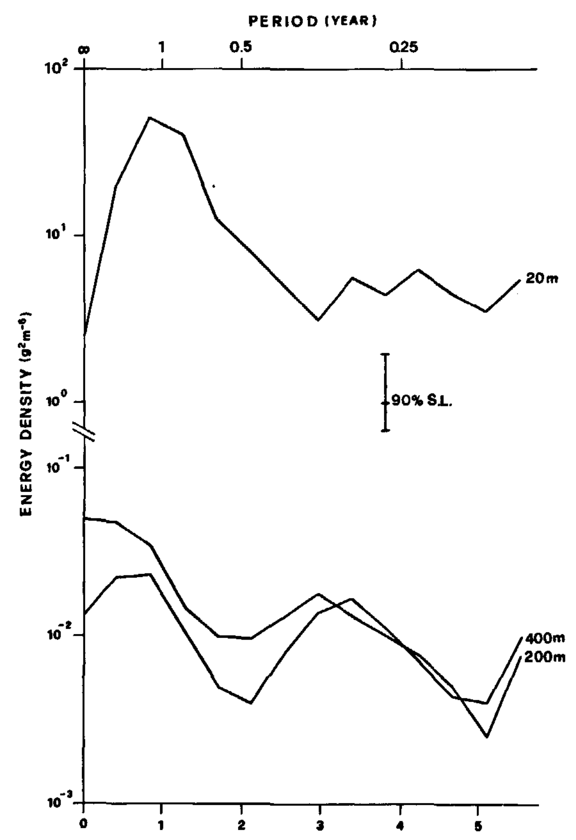

Figure 2
Spectra of density at 20, 200, 400 m. 90% confidence limits are included.

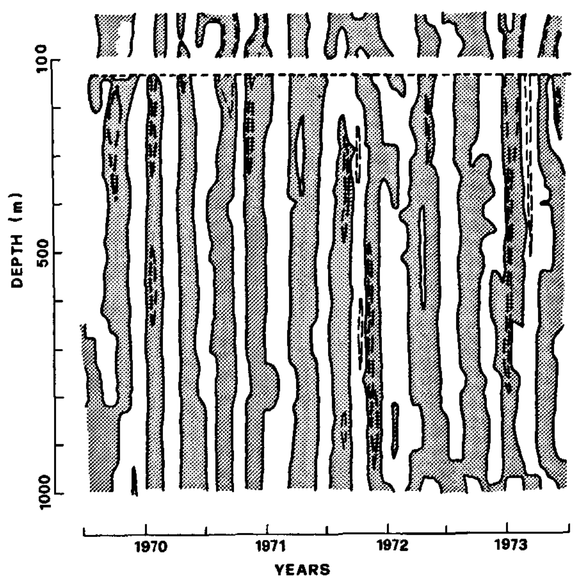

Figure 3
Vertical density anomaly time-evolution of the avereged central profile between 100 and 1000 m. Hatched areas are negative anomalies. The dashed contours should read 0.04 kg m^{-3}.

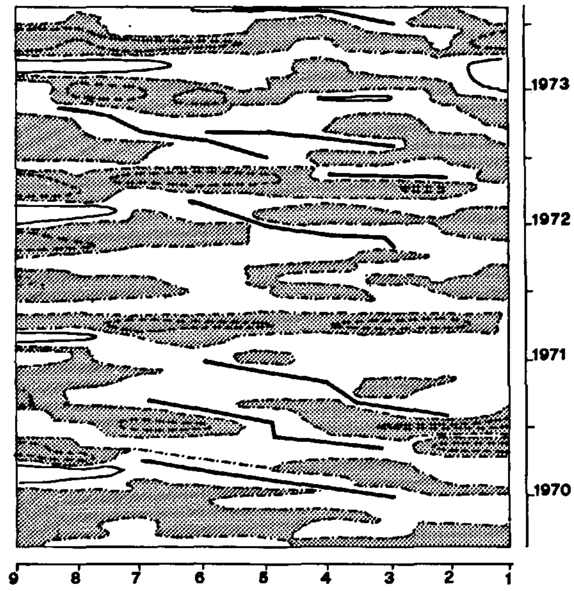

Figure 5
Horizontal density anomaly time-evolution at 150 m. Hatched areas are negative anomalies. The dashed contours should read 0.04 kg m^{-3}.

In order to investigate the time and spatial evolution of the density anomalies along the Nice-Calvi transect, we examine the data at 150 m depth because of data completeness at all nine stations. Also considering the restriction of the spectral analysis, wave number spectra were computed yielding 3 degrees of freedom (Fig. 4) indicating that most of the energy has wavelengths of 60-80 km.

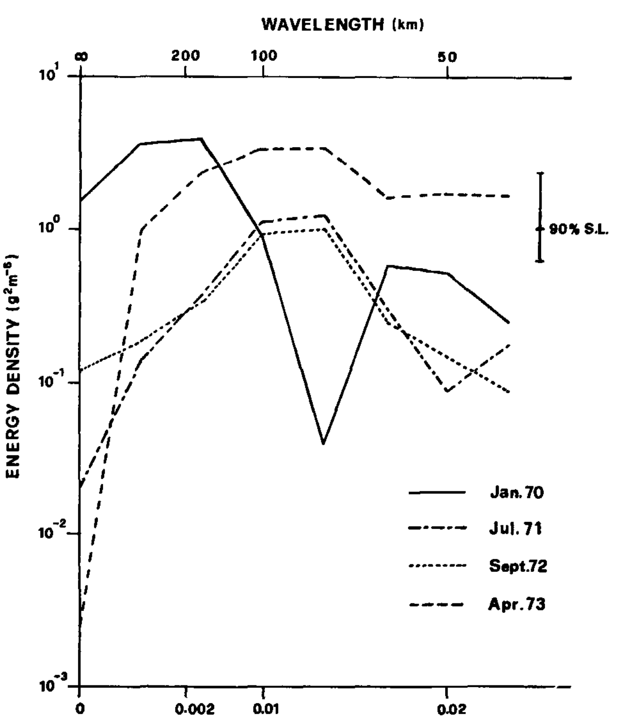

Figure 4
Wave number spectra at 150 m. 90% confidence limits are included.

From Figure 5, showing the lagged correlations among stations, one can see a westward propagation of the anomaly maximum values, even if there exists a certain amount of correlated and uncorrelated noise, which obscures that phenomenon. The sources of this noise may be found in instrument errors, subgrid variabilities or local dynamics. Nevertheless, from the linear regression of the non-negative lagged correlation for each pair of stations, it is possible to calculate an average speed of propagation of about 35 km/month (Fig. 6). In this computation the first station, particularly influenced by the complex dynamics present near Calvi, is neglected.

Since this oscillation is also present in the atmospheric pressure (Gasparini, Manzella, 1984) it is of interest to know whether it can be detected at the coastal sea level. Previous studies (Mosetti, Purga,

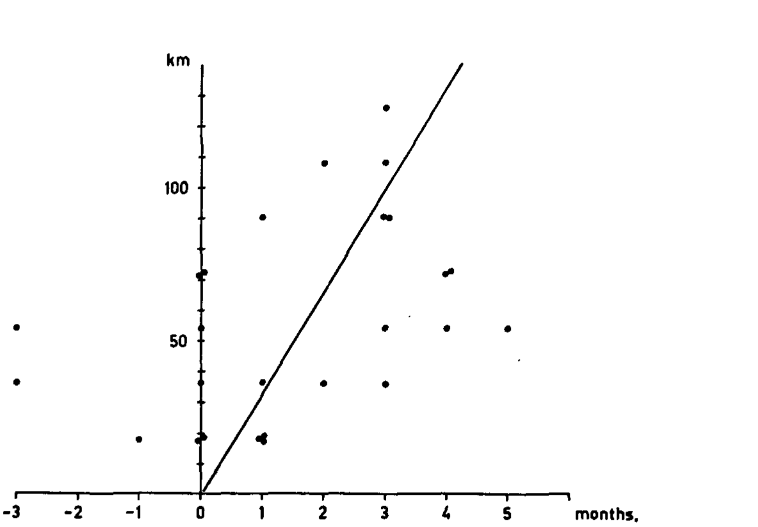

Figure 6
Lag time maximum correlation vs distance.

1982) have demonstrated the existence of annual and seasonal oscillations in the sea level along the Italian coasts. They were related to tidal forcings and in particular to climatic variations. An analysis of the monthly sea level at Genoa shows that there is a significant amount of energy at 3-4 cpy, but the coherence between the sea level and the atmospheric pressure (Fig. 7) is not well defined at that time scale, probably because near shore and shelf processes obscure the open sea signal. It is, however, interesting to note that atmospheric pressure and sea level, when coherent, are quite in phase.

Since from the data analysis some peculiar characteristics of barotropic Rossby waves appear, we are led to verify the extent to which a Rossby wave model fits the observations.

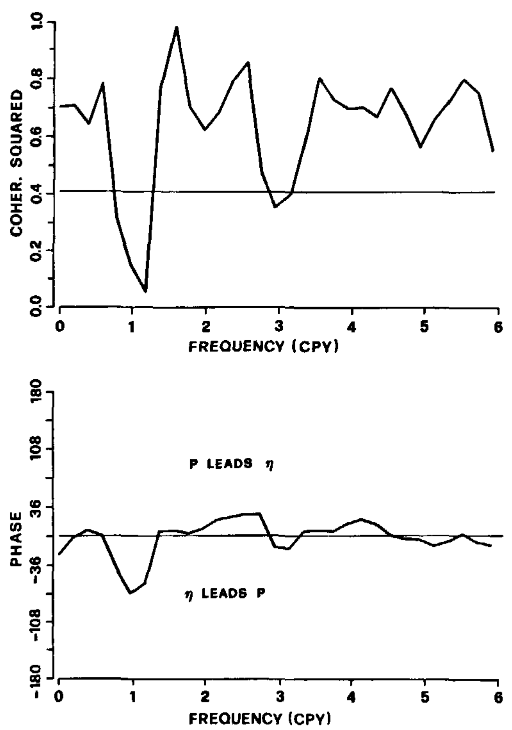

Figure 7
Coherence and phase between sea level and atmospheric pressure at Genoa.

ROSSBY WAVE FORMULATION

The response to atmospheric fluctuations of an idealized flat rectangular basin not zonally aligned and open towards the south-west is examined (Fig. 1) and studied in terms of barotropic planetary waves. In particular, the role of multiple reflections that planetary waves can undergo from the side boundaries of the semi-enclosed region, is examined. The planetary wave equation is

$$\nabla^2\eta_t - \frac{1}{R_0}\eta_t - \beta \sin\varphi\, \eta_y + \beta\cos\varphi\,\eta_x = \text{FORCING},$$

Table
Adimensionalisations and values of constants

Adimensional variables		
$x, y \sim L(x, y)$	$t \sim t/(\beta L)$	$p \sim p^* p \quad \eta \sim \eta^*\eta$
Values of parameters		
D	Length of the basin	150 km
L	Length scale	50 km
H	Total depth	2 km
x_0, y_0	Forcing position	75 km
g	Gravity	9.81 m s^{-2}
f	Coriolis parameter	1.03 × 10^{-4} s^{-1}
β	Beta parameter	1.6179 × 10^{-11} m^{-1} s^{-1}
η^*	Characteristic sea level	1 cm
p^*	Mean pressure	10^3 kg m^{-1} s^{-2}
φ	Rotation angle	37°
$2\pi/\omega$	Period of atmospheric forcing	.33 year
$R_0 = (gH)^2 f^{-1}$	Rossby radius	1360 km
ρ_0	Reference density	10^3 kg m^{-3}

where the basin rotation from the North axis (φ = 37°) is taken into account, φ being the surface sea level and R_0 the Rossby radius. The wave equation used is the same as that adopted by Willebrand *et al.*, (1980). In fact we can transform the surface elevation η into the stream function ψ by means of the relation

$$\eta = \frac{f_0\psi}{gH} - \frac{P}{\rho_0 g},$$

where P is the atmospheric pressure.

By introducing the carrier wave transformation

$$\eta\,(x, y, t) = \tilde{\psi}(x, y) \exp\left\{i\left(\frac{\beta}{2\omega}\cos\varphi\, x - \frac{\beta}{2\omega}\sin\varphi\, y - \omega t\right)\right\}$$

the surface displacement equation, in terms of dimensionless variables (*see* the Table), can be reduced to the non-homogeneous Helmholtz equation

$$\nabla^2\tilde{\psi} + \left(\frac{1}{4\omega^2} - \frac{L^2}{R_0^2}\right)\tilde{\psi} = -4\pi Q,$$

where

$$Q = \frac{i}{4\pi}\frac{1/fP^*}{\omega\rho_0\, g\,\eta^*} F(x,y) \exp\left\{-i\left(\frac{\cos\varphi}{2\omega}x - \frac{\sin\varphi}{2\omega}y\right)\right\}.$$

η^* and P^* are characteristic values of the surface displacement and of the atmospheric pressure. In defining the shape of the forcing Q some considerations have to be made. As has been pointed out by many authors (*e.g.* Willebrand *et al.*, 1980), the forcing can be caused by the wind stress, pressure fluctuations or buoyancy fluxes at sea surface, the nature of the oceanic response depending only on the space and time scales. Although the wind stress curl is generally believed to be more important than other forcings, it was not introduced because there is no information on its spatial distribution, and because in the Ligurian Sea it is controlled by the low-pressure cell evolutions. In fact the Ligurian Sea is a cyclogenetic area (Meteorological Office, 1962) where the atmospheric pressure plays a fundamental role in the evolution of the wind field. On the other hand because of the time (3-4 months) and spatial (50 km) scales involved in the oscillations of the anomalies, only the gradient of the atmospheric pressure can be considered (Philander, 1978). This forcing is idealized in terms of a delta function and applied to the center (x_0, y_0) of the basin:

$$F(x,y) \simeq \sin\varphi\, P_x - \cos\varphi\, P_y \sim \delta(x-x_0)\,\delta(y-y_0)$$

The solution is given by:

$$\tilde{\psi}(x,y) = \iint_S Q(x_0,y_0)\, G\, dx_0 dy_0,$$

where S is the domain of integration and (x_0, y_0) is a concentrated forcing position. G is the Green Function that is obtained from the method of images, and is expressed in terms of zero-order Hankel functions of the second type. Details on the solution method can be found in Gasparini and Manzella (1983). For the previous considerations we chose $\omega = 3.3$ c.p.y. for the time frequency and $L = 50$ km for horizontal length scale. The Helmholtz equation was solved over a half period $0 < t < \pi/\omega$. Figure 8 shows the time evolution of the sea surface elevation plotted every 15 days, the predominant feature being a westward propagation corresponding to a phase speed of about 72 km/month, or 0.03 m/s, along the Nice-Calvi transect, a value quite consistent with the depth-independent density anomaly propagation found in the observed data. It is interesting to note that the wave propagation from Calvi to Nice is related to the basin orientation while a zonally aligned basin has an along-axis symmetric structure. The sea level variation is of the order of a centimeter, the amplitude increasing synchronously with the atmospheric pressure.

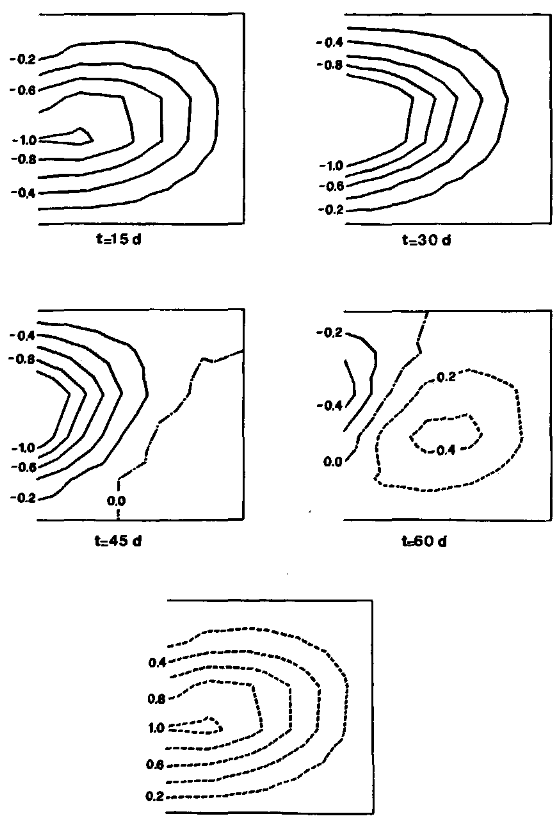

Figure 8
Model time-evolution of surface elevation.

DISCUSSION

The main points of this paper are the analysis of a low barotropic oscillation in the Ligurian basin in term of Rossby waves and the role played by the atmospheric oscillation on its generation. It has been shown how a simple linear model, considering the multiple reflection effects of the coastal geometry and the basin orientation and utilizing a very simple forcing, can reproduce the tendency of the wave to propagate from Calvi to Nice.

In spite of the encouraging results obtained, account is not taken of a number of effects which could also prove to be important, such irregularities in the topography which can transfer energy into smaller scales, and non-linear interactions with the mean flow. Also the coastal effects and the friction processes are neglected. Before many of these effects can be understood, however, it seems necessary to know more about such important aspects as the sea level evolution in the basin interior, and to obtain a more realistic forcing shape: only then will it be possible to evaluate effectively the role played by this wave in the dynamics of the basin.

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REFERENCES

Bethoux J.-P., Prieur L., Nyffeler F., 1982. The water circulation in the North-Western Mediterranean Sea, its relation with wind and atmospheric pressure, in: *Hydrodynamics of semi-enclosed seas,* edited by J.C.J. Nihoul, Elsevier, Amsterdam, 129-142.

Cheney R.E., Richardson P.L., 1976. Observed decay of a cyclonic Gulf Stream ring, *Deep-Sea Res.,* **23,** 143-155.

Dahme A., Carrara A., Pedenovi C., 1971. The temperature structure within the first 150 m of depth of the Ligurian Sea and its seasonal variations during the years 1960-1967, Tech. Memo. 165, Saclant ASW Research Center, La Spezia, Italy.

Garzoli S., Parisi V., Paschini E., 1982. On the effect of bottom topography to eddies in Sardinia and Sicily Straits regions, *Deep-Sea Res.,* **29A,** 77-86.

Gascard J.-C., 1978. Mediterranean deep water formation baroclinic instability and oceanic eddies, *Oceanol. Acta,* **1,** 315-330.

Gasparini G.P., Manzella G.M.R., 1983. A possible eddy generating mechanism in the Ligurian Basin, *Appl. Math. Model.,* **7,** 291-294.

Gasparini G.P., Manzella G.M.R., 1984. The response of the Ligurian Sea to large scale atmospheric fluctuations, *Oceanol. Acta,* **7,** 1, 49-52.

Gostan J., 1967. Études du courant géostrophique entre Villefranche-sur-Mer et Calvi, *Cah. Océanogr.,* **19,** 4, 329-345.

Hela I., 1963. Surface currents of the Ligurian Sea, *Bull. Inst. Océanogr. Monaco,* **60,** 3-15.

Hydrokor Cruises. Results of the N/O "Korotneff" cruises, 1973-1975, Cent. Rech. Océanogr. Villefranche-sur-Mer, fasc. 5, 16.

Meterological Office, 1962. Weather in the Mediterranean. Vol. 1, Her Majesty's Stationary Office, London, 362.

Mosetti F., Purga N., 1982. First results on long and mid period tide distribution in Italian Seas and their existence in the groundwater, *Il Nuovo Cimento,* **5C,** 143-158.

Nyffeler F., Raillard J., Prieur L., 1980. Le bassin liguro-provençal. Étude statistique des données hydrologiques, 1950-1973, CNEXO Rapp. Sci. Tech., 42.

Philander S.G.H., 1978. Forced oceanic waves, *Rev. Geophys. Space Phys.,* **16,** 15-46.

Philippe M., Harang L., 1982. Surface temperature fronts in the Mediterranean from infrared satellite imagery, in : *Hydrodynamics of semi-enclosed seas,* edited by J.C.J. Nihoul, Elsevier, Amsterdam, 91-128.

Stocchino C., Testoni A., 1977. Nuove osservazioni sulla circolazione delle correnti nel Mar Ligure, Ist. Idrogr. Mar., F.C. 1076, Genova, Italy, 39.

Wald L., Nihous G., 1980. Ligurian Sea: annual variation of the sea-surface thermal structure as detected by satellite NOAA5, *Oceanol. Acta,* **3,** 4, 465-469.

Willebrand J., Philander S.G.H., Pacanowsky R.C., 1980. The oceanic response to large scale atmospheric disturbances, *J. Phys. Oceanogr.,* **10,** 411-429.

Willmott A.H., Mysak L.A., 1980. Atmospherically forced eddies in the Northeast Pacific, *J. Phys. Oceanogr.,* **10,** 1769-1791.