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The response of the Ligurian Sea to large scale atmospheric fluctuations

Ligurian Sea
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ABSTRACT

Observation of the vertical structure of density and of low frequency atmospheric fluctuations over the basin permits examination of the response of the Ligurian Sea. Application of an analytical model which utilizes normal-mode decomposition reveals the importance of the barotropic and first baroclinic modes.

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RÉSUMÉ

Réponse de la Mer Ligure aux fluctuations atmosphériques à grande échelle.

A partir de l'observation de la structure verticale en Mer Ligure et des fluctuations atmosphériques à basse fréquence, on examine la réponse du bassin du point de vue des ondes planétaires. En appliquant un modèle analytique qui utilise la décomposition en mode normal pour fond plat, on met en relief l'importance du mode barotropique et des premiers modes baroclíniques.

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INTRODUCTION

Many processes may be responsible for Rossby waves in the ocean, including wind-forcing, storms, mean flow instabilities, topographic effects, and others. The response to these mechanisms may not be easily describable in terms of single-wave propagation (Killworth, 1979); moreover, the dynamics of the energetic low-frequency motions in the ocean at mid-latitudes are not well understood (Willmott, Mysak, 1980). However, linear barotropic and baroclinic Rossby waves account for most of the energy in this frequency band, at least where the North Atlantic and Pacific are concerned.

The oceanic response to time-dependent atmospheric forcings can either be trapped (vertically and horizontally) in the region that is forced, or may take the form of waves that propagate away from the region. Willebrand *et al.* (1980) have shown that at periods between a few days and a few hundred days, the response to large-scale forcing is essentially barotropic, while the response is baroclinic at greater periods.

This paper constitutes an analytical study of the response in the Ligurian Sea (Fig. 1) to fluctuating atmospheric forcing, in terms of propagating waves.

METHODS

This study of ocean waves is based on an idealization of the sea as a linear non dissipative mechanical system of uniform depth H. Solutions satisfying the top and bottom boundary conditions may be constructed by a normal mode representation, by separating the vertical and horizontal structures of the wave field. The theory of the possible solution of the vertical boundary value problem may be stated and solved using the Sturm-Liouville theory for a non-rotating fluid (however these results can readily be carried over to the rotating case; Gill, Clarke, 1974).

In the following, we utilize the Bryan and Ripa (1978) approach, and study a non-uniform stratified flat bottomed sea 2 000 m deep. We consider a Boussinesq fluid and the linearized form of the hydrostatic β-plane

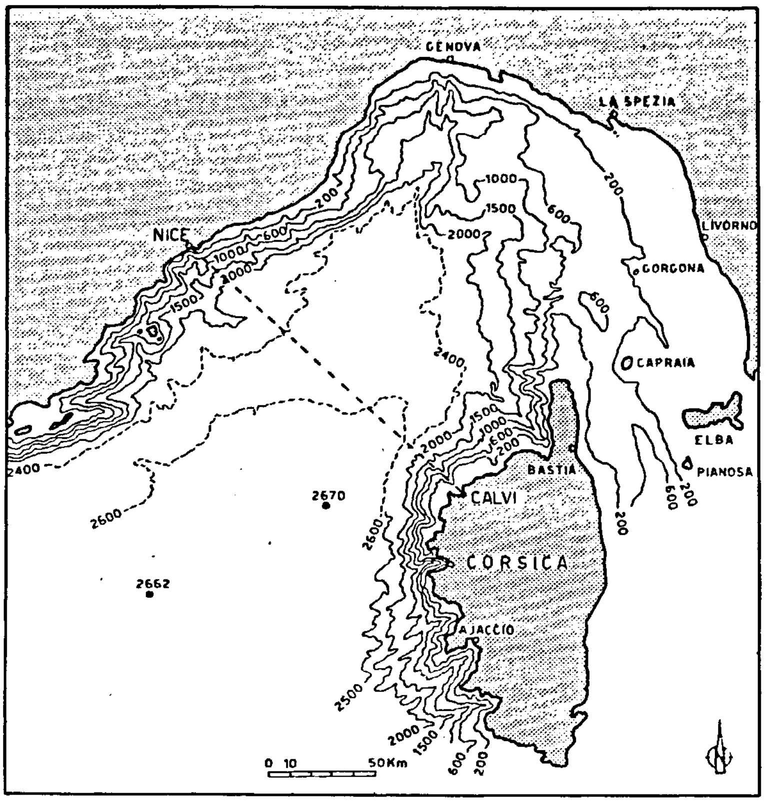

Figure 1
The Ligurian Sea area.

equations which describes small amplitude motions about the hydrostatic equilibrium state:

$$
\begin{aligned}
&u_t - fv + \rho_0^{-1} p_x = X_z \rho_0^{-1},\\
&v_t + fu + \rho_0^{-1} p_y = Y_z \rho_0^{-1},\\
&\rho g + p_z = 0,\\
&u_x + v_y + w_z = 0,\\
&\rho_t + w \rho_z = 0,
\end{aligned}
\qquad (1)
$$

X and Y being tangential stresses.

We also assume that ρ_0 is a constant reference density taken to be the value within surface mixed layer ($-h < z < 0$) in the equilibrium state of the form:

$$
\rho = \begin{cases} \rho_0, & -h < z < 0, \\ \rho_0 + \dfrac{\rho_0}{\gamma g}(e^{-\gamma h} - e^{-\gamma z}), & -H < z < -h, \end{cases} \qquad (2.1)
$$

h and $\tilde{H}$ being respectively the thermocline and bottom depth. The Brunt-Vaisala frequency takes the form:

$$N^2(z) = N_0^2\, e^{-\gamma z}\, \tilde{H}(-z-h), \qquad (2.2)$$

where $\tilde{H}$ is the Heaviside step function (Bryan, Ripa, 1978).

There exist eigenfunctions Γ_n (z) and F_n (z) and eigenvalues c_n by means of which u, v, w, p can be expanded. For the barotropic mode ($n=0$), they can be approximated by (Gill, Clarke, 1974):

$$\Gamma_0 = z + H, \qquad F_0 = 1, \qquad c_0 = \sqrt{gH}.$$

For the remaining baroclinic modes ($n = 1, 2, \ldots$), the vertical variation of the field variables can be determined from the solution of:

$$\Gamma_n''(z) + (N^2(z)/c_n^2)\,\Gamma_n(z) = 0. \qquad (2.3)$$

This equation must satisfy homogeneous boundary conditions, and at the thermocline h must satisfy continuity conditions; we then can calculate the eigenvalues c_n, the speeds of planetary wave propagation (Willmott, Mysak, 1980).

The governing equation for the horizontal dependence of the pressure field for planetary waves is:

$$\nabla^2 p_{nt} - (f^2/c_n^2)\, p_{n_t} + \beta p_{n_x} = Q_n, \qquad (2.4)$$

where $Q_n(x, y, t) = q_n(x, y)\, e^{-i\omega t}$ is a forcing function. The introduction of this function is not essential for our purposes, but it is maintained since the atmospheric periodicities will be compared with the cut-off periods. The forcing function is given by the curl of the tangential stress, taking the form of the wind stress curl at the ocean surface. In the following paragraphs, reference will be made to atmospheric pressure, since there are indications that it is related to the wind stress curl at low frequencies ($\omega > 0.5$ c. p. d.; Elliott, 1979). The β effect was written down for a zonally aligned basin; this is not really correct for the Ligurian Sea, however the basin orientation is not needed for our purposes.

By introducing the horizontal plane wave solution:

$$p_n(x, y, t) = \psi_n(x, y)\, e^{i(K_1 x + K_2 y - \omega t)},$$

we obtain:

$$\left[\nabla^2 + \left(\frac{\beta^2}{4\omega^2} - \frac{f^2}{c_n^2}\right)\right] \psi_n = \bar{q}_n(x, y), \qquad (2.5)$$

where $(f/c_n)^{-1} = R_n$ is the baroclinic radius of deformation for the n-th mode. The Helmholtz equation (2.5) admits travelling wave solutions, provided that:

$$\left(\frac{1}{\beta R_n}\right)^2 < \frac{1}{4\omega^2},$$

for each mode there is an upper cut-off frequency given by:

$$\omega_c = \frac{\beta R_n}{2}.$$

OBSERVATIONS

Much literature has been written on the physical oceanography of the Ligurian Sea (*e.g.* Trotti, 1954; Hela, 1963; Gostan, 1967; Stocchino, Testoni, 1977).

The conclusions reached by the various authors are that: *a*) the mean circulation in the Ligurian Sea is cyclonic in the surface and intermediate layers, while the deep water is nearly quiescent (*see* also Lacombe, Tchernia, 1972); *b*) two superficial flows, coming from the eastern and western Corsican coasts, meet along the line Cape Corso-La Spezia; *c*) meanders and eddies were observed in that area by Hela (1963).

By examining historical data, Le Floch (1963) defined two different circulations:

1) In winter the flux coming from the Corsica channel is greater than the flux along the western Corsican coast;

2) Conversely, in summer when the Corsica channel flux is of the same order or lesser than the flux along the western Corsican coast.

All the circulation schemes agree on the existence of a water flux almost perpendicular to the line Nice-Calvi, along which routine hydrographic campaigns were established starting from 1969.

In order to study the response of the Ligurian basin to meteorological forcings, we examined the vertical structure along the Nice-Calvi transect (Hydrokor cruises, 1973). Annual mean thermocline depth ($h=20$ m) and Brunt-Vaisala profile were computed. Below 100 m, the water is quite homogeneous and with very little variability during the year. For the schematic Brunt-Vaisala representation (2.2) we found: $N_0=0.016\ s^{-1}$, $\gamma=4.6\times10^{-3}\ m^{-1}$ (Fig. 2) corresponding to a period $2\pi/N_0 \sim 7$ min and to an *e*-folding scale $\gamma^{-1} \sim 217.5$ m.

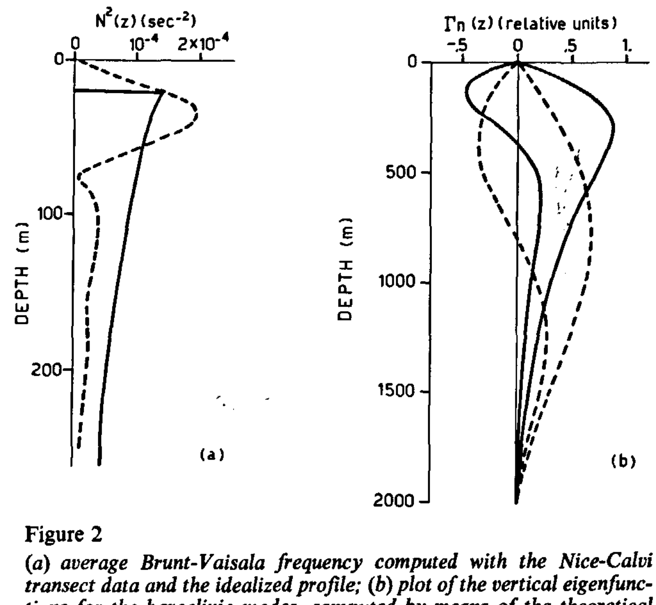

Figure 2

(a) average Brunt-Vaisala frequency computed with the Nice-Calvi transect data and the idealized profile; (b) plot of the vertical eigenfunctions for the baroclinic modes, computed by means of the theoretical (solid lines) and observed (dashed lines) Brunt-Vaisala frequencies.

The transfer of atmospheric perturbations to the sea depends on their scales and periodicities. The atmospheric pressure at frequencies greater than 2 days is coherent over the whole Ligurian area (Esposito, Manzella, 1982). From a spectral analysis of the montly pressure in Genoa from 1959 to 1978 (Fig. 3), with a 90 % significant level and 10 degrees of freedom, we found significant peaks at 0.33, 1.06 and 3.17 years, which can be considered as the lowest frequency atmospheric fluctuations affecting the Ligurian basin.

RESULTS AND DISCUSSION

From the vertical and horizontal equations (2.3; 2.5) the internal wave phase velocities, the baroclinic deformation radius and the cut-off periods for the idealized Brunt-Vaisala profile were computed. The latter was used for reasons of simplicity, and in order to have only analytical results. Moreover, we solved the eigenvalue problem (2.3) also with the real Brunt-Vaisala distribution to compare the results (Table, Fig. 2). The difference between the phase velocities computed with idealized and real Brunt-Vaisala frequencies is less than 6 %.

Table

Real c_{rn} and theoretical c_n phase velocities, radii of deformation r_n and cut-off periods T_c for the barotropic and first three baroclinic modes.

Mode	c_{rn} (m/s)	c_n (m/s)	r_n (km)	T_c (year)
0	-	140.10	1360.0	0.0181
1	2.35	2.48	24.1	1.03
2	1.13	1.15	11.2	2.22
3	0.75	0.75	7.3	3.39

The processes of planetary wave formation are poorly understood at present, atmospheric disturbances being thought to be one of the generating mechanisms. By comparing the cut-off periods of the planetary wave (Table) with the atmospheric pressure periodicity, we can say that only the barotropic and the first two baroclinic modes will propagate. Obviously it is not possible to treat the barotropic problem as a local problem.

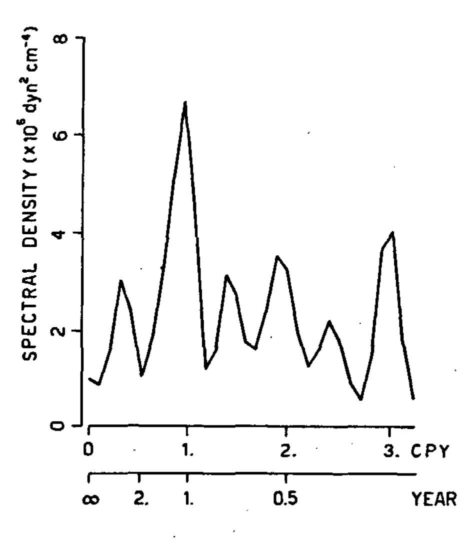

Figure 3

Spectral density of the monthly atmospheric pressure measured at Genoa from 1959 to 1978.

By considering the horizontal wavelengths equal to the dimension of the basin (L = 150 km), from the dispersion relation (Leblond, Mysak, 1978, p. 156), one obtains the period of the barotropic Rossby waves T > 25-30 days: the sea response for periods less than 25-30 days can be explained in terms of forced waves. We may go even further and following Willebrand *et al.* (1980), define, from equation (2.4), a time scale:

$$t = l\,\beta^{-1}\,(l^{-2} + R_n^{-2}),$$

where l is the horizontal length scale. The dynamic heights reported by Stocchino and Testoni (1977) show closed lines, whose length is about 50 km at all depths, configuring an essentially barotropic system. It is interesting to note that $l = 50$ km corresponds to a period of $T = 2\pi\, t = 0.25$ years, which is not far from the 0.33 years period shown in Figure 3.

For the first baroclinic mode, assuming $l = 50$ km, we obtain a period of T = 1.3 years, a value that can be compared to the 1.06 years of Figure 3. Finally at periods greater than 1 year, the barotropic problem may be approximated to a Sverdrup balance.

The solution of equation (2.5) with flat-bottom topography has been discussed in detail: the equation (2.5) holds as well for the barotropic as for the baroclinic modes. The solutions represent travelling waves with phase velocity c_n and amplitude modulated by Hankel functions (Willmott, Mysak, 1980).

In the case of a stratified sea with variations in bottom topography, bottom pressure torques are exerted on fluid columns creating interactions between the modes. On the other hand, the topography effect cannot be ignored, since it can be estimated equal to:

$$\beta' = \frac{f}{H}\frac{\partial H}{\partial x} = \frac{10^{-4}}{2000}\frac{200}{10^5} = 10^{-10} \gg \beta \sim 2\times 10^{-11}.$$

The topography influences the phenomena by reducing the time scales (as cut-off periods), and can support free waves whose frequency is $\omega \sim O(f\Delta H/H)$, where $\Delta H/H$ is the relative bottom change.

Since changes in depth act as a restoring mechanism of motion, it follows that for a fixed frequency they produce a decrease (increase) in the wavenumber magnitude for a decrease (increase) in the topography restoring force. This mechanism essentially generates a wavenumber whose phase moves with deep water to its left. When compared with the wavenumber generated by the planetary effect, this results in a change in the possible directions of phase propagation.

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