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Low-Frequency Waves in the Ligurian Sea During December 1977

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Observations of low-frequency waves in the Ligurian Sea in December 1977 are presented. From time series of thermal infrared images obtained by satellite NOAA 5, the mean wavelength and phase velocity are estimated. They are, respectively, 38 km and 18 cm s^{-1} . These waves are analyzed as large-amplitude baroclinic waves. Fairly good agreement is found with a two-layer model.

INTRODUCTION

The northwestern Mediterranean basin is characterized at all seasons by a large cyclonic circulation of surface water. This is shown in Figures 1 and 2, which show the dynamic contours and the velocities calculated at the surface from a hydrological cruise done by Tchernia in February-March, 1960 (H. Lacombe and P. Tchernia, unpublished data, 1965). This large-scale motion is mainly due to the inflow of surface water coming from the Atlantic Ocean through the Straits of Gibraltar, which compensates for the water lost by evaporation. In winter, strong convective motions occur in the center of the gyre, and deep water masses are formed by mixing over the whole depth [Gascard, 1978].

The Ligurian Sea is the eastern part of that region. It has been studied by many authors [Lacombe and Tchernia, 1972; Gostan, 1967a, b; Hela, 1963; Trotti, 1953; Tchernia and Saint-Guily, 1959; Dahme et al., 1971; Stocchino and Testoni, 1977, 1978]. Three different masses of water are found. In December, a surface layer of some 100 m in depth is observed. Its temperature is between 13.50 and 14°C, its salinity is between 38.05 and 38.20 ‰, and its density (σ_θ) is between 28.50 and 28.95. Between 100 and 650 m an intermediate water type of levantine origin is found. Its temperature is about 13.25°C, its salinity is about 38.52 ‰, and its potential density (σ_θ) is about 29.08. Below this, a deep water type is found with a potential temperature of 12.70°C, a salinity of 38.41 ‰, and a density (σ_θ) of 29.11. A typical density profile is shown in Figure 3.

The horizontal velocities extend from the surface to at least 500-600 m. The deep water is nearly quiescent. A vertical section of the velocities on the line Nice-Calvi in October 1963 is presented in Figure 4 (H. Lacombe and P. Tchernia, unpublished data, 1965). The velocities are calculated by the dynamic method from hydrological data. Velocities up to 50 cm s^{-1} are encountered at the surface. These velocities are smaller than those measured during the same period with a GEK (Figure 5). This could be due to the existence of a cyclonic barotropic current of a few centimeters s^{-1} .

From the above considerations, it appears that the Ligurian basin can be modeled as a two-layer ocean with a surface layer of a thickness H_1 of 200 m, a Brunt-Väisälä frequency N_1 of $4 \cdot 10^{-3} \text{ s}^{-1}$, and an internal radius of deformation $R_1 = N_1 H_1 / f = 8 \text{ km}$ overlying a deep layer of a thickness H_2 of

2000 m, a Brunt-Väisälä frequency N_2 of $0.4 \cdot 10^{-3} \text{ s}^{-1}$, and an internal radius of deformation R_2 also of 8 km (Figure 3).

The general cyclonic motion suggests cool water in the interior with warmer water at the periphery of the sea. In between, there is a thermal front with a variation of a few tenths of a degree across the front. This feature is clearly visible on the thermal infrared imagery given by the radiometer VHRR of the satellite NOAA 5 (Figure 6).

The aim of this note is twofold. First, we present observations of low-frequency waves propagating in the Ligurian Sea made by satellite NOAA 5 during December 1977. From these observations, some parameters specific to wave motion are estimated. Secondly, we examine the wave phenomenon in terms of the baroclinic instability mechanism and compare the observations with the rotating tank experiment of Saunders [1973] and with the model of Tang [1975]. It is found that the Ligurian Sea may be baroclinically unstable and that the wavelengths predicted by the baroclinic instability theory of Tang [1975] are in general agreement with our calculations.

OBSERVATIONS

In December 1977, the meteorological situation over the Ligurian Sea was atypical. From December 1 to December 20 the northern part of the Ligurian Sea was calm, but easterly winds were blowing continuously over the southern part. Their velocities were larger than 8 m s^{-1} on December 1, 2, 4, 15, 16, 18.

Seven cloud-free thermal infrared images were obtained during that period. The NOAA 5 satellite data were processed by the Centre de Télédétection et d'Analyse des Milieux Naturels (CTAMN). This included the following: computation of equivalent temperatures; smoothing by a two-dimensional spatial filter contrast enhancement; plotting of full thermal resolution maps; and, finally, a geometric correction for the earth's spin and the curvature of its surface.

The absolute values of temperature provided by the radiometer are not very accurate, but sea surface temperatures (SST) may be determined with an accuracy of 0.5°C at a 3-km resolution in this area [Albuisson et al., 1979; Wald and Nihous, 1980]. In order to make the images superposable ($\pm 1 \text{ km}^2$), they must be geometrically corrected on the basis of known landmarks.

One of the seven images of December 1977 is presented in

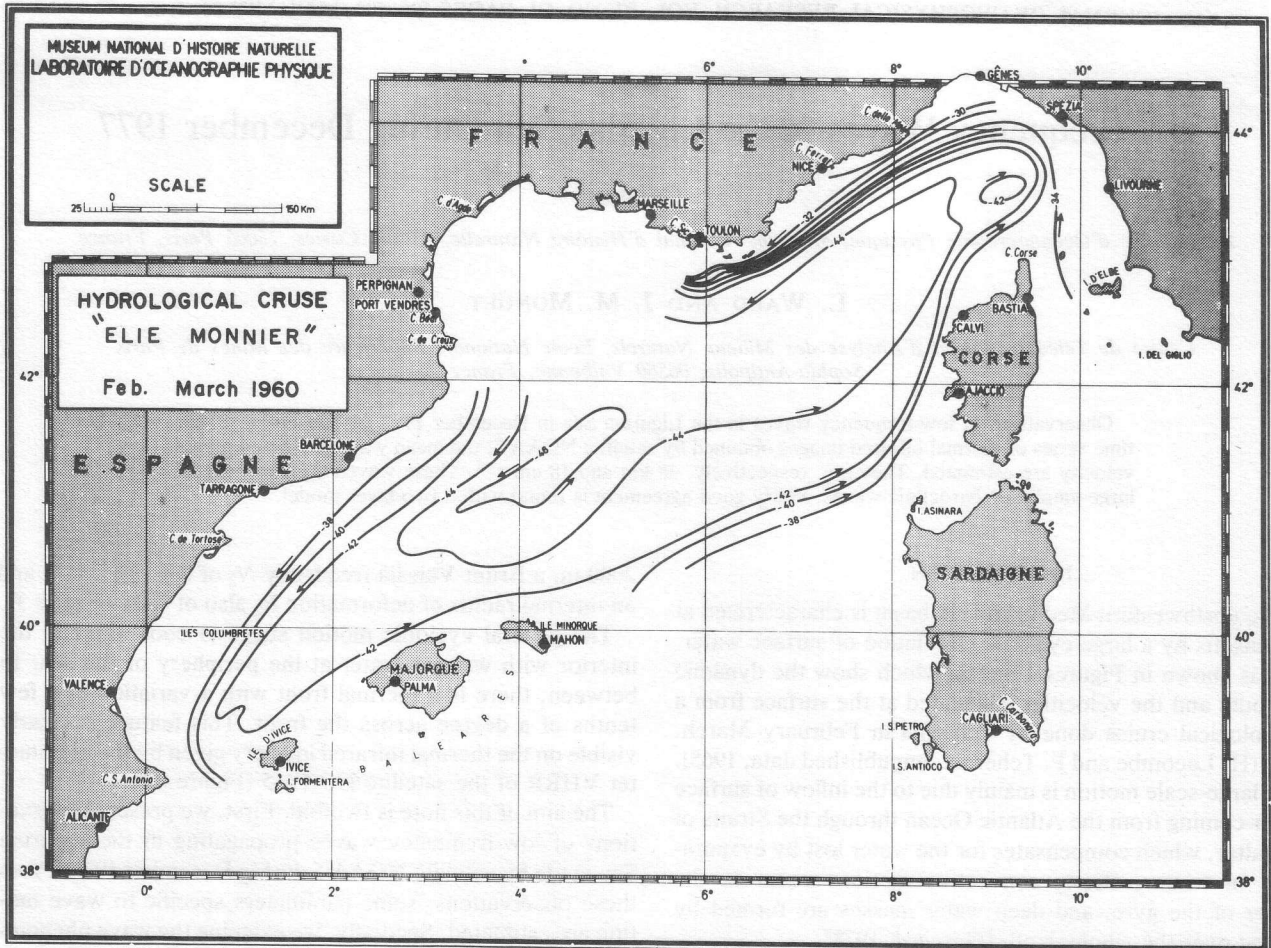


Fig. 1. Dynamic contours in centimeters at the surface in February–March, 1960. The zero-velocity depth is 500 m.

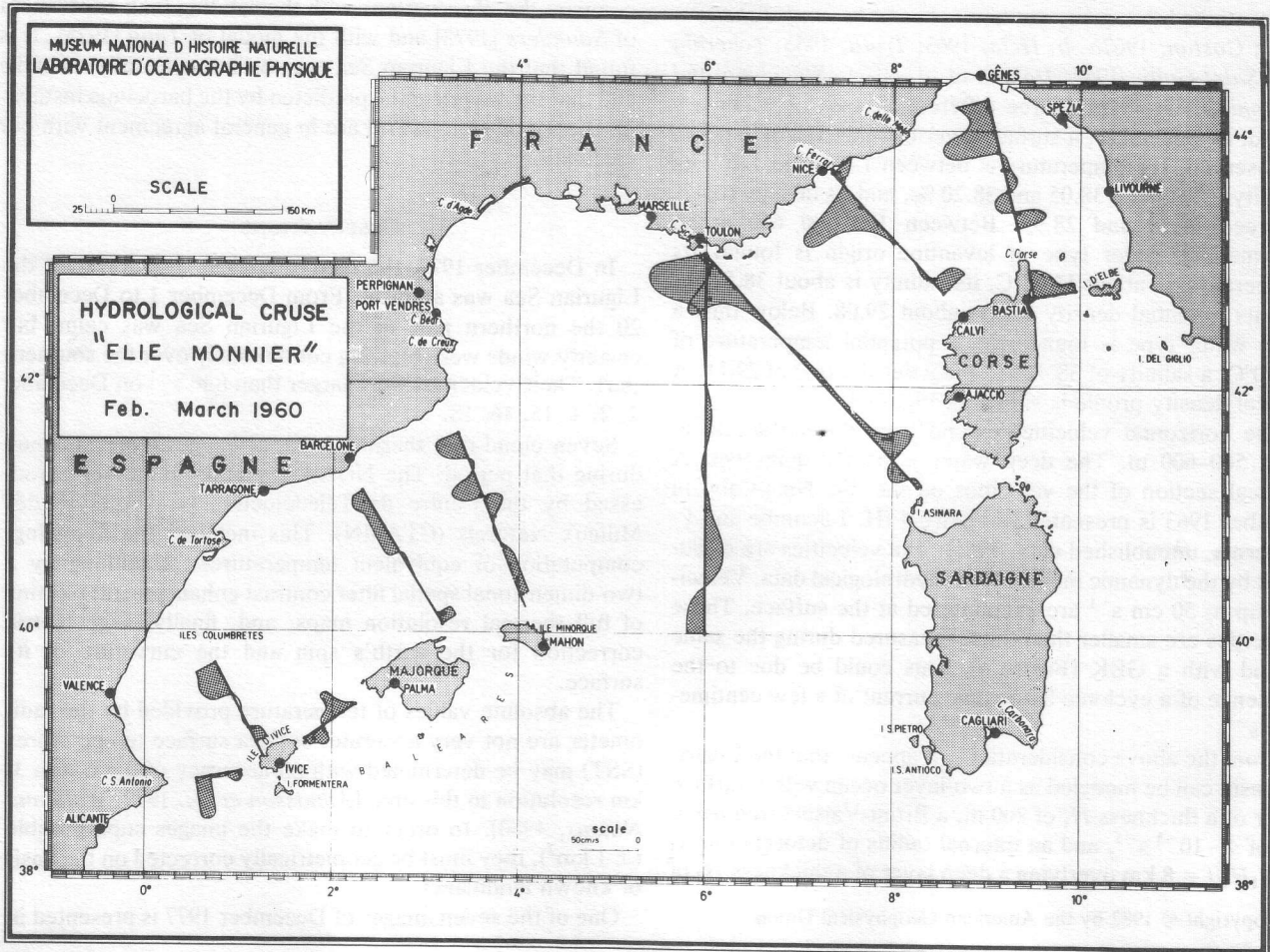


Fig. 2. Surface velocity in February–March, 1960.

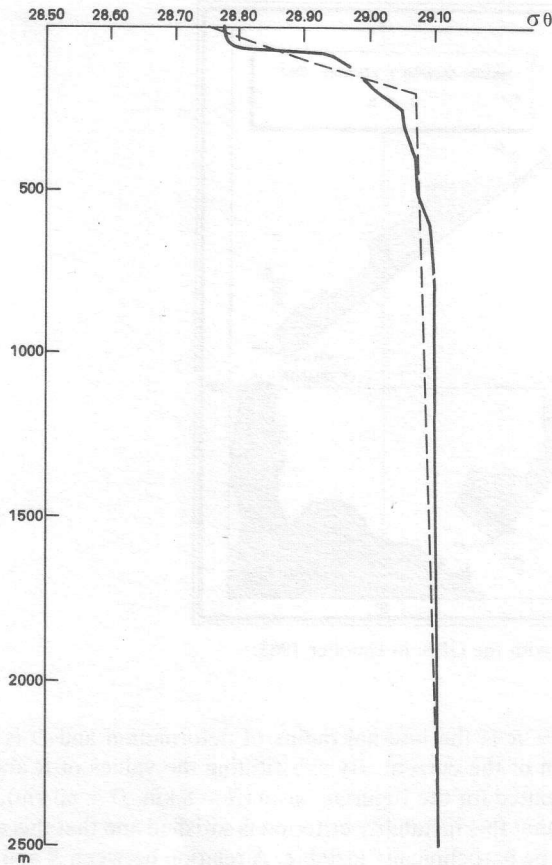


Fig. 3. Typical density profile in December 1960 (after *Gostan* [1967a]) (solid line) and its schematic representation (dotted line), fitting the Tang model.

Figure 6. The seven images exhibit large meanders of the thermal front. The horizontal SST gradients are the strongest we have ever seen on satellite images in this region; they are of the order of $0.05^{\circ}\text{C}/\text{km}$. Observations of the wave motion over 24-hour sequences are possible for December 3 and 4 and December 17, 18, 19, and 20, 1977. Meanders may also be followed, but less clearly, on the images of January 5, 6, and 7, 1978.

In Figure 7 we present meanders of two frontal isotherms (solid and dotted lines) on December 3 (thick lines) and 4 (thin lines). Waves apparently propagate around the central eddy in the cyclonic direction. At any particular time the meanders are of different shapes along the front, but a particular meander keeps the same shape during its propagation. This shape preservation allows measurements of wavelengths and phase speeds.

The mean values of wavelength and of phase speed, computed from 30 measurements, are, respectively, 38 km and 18 cm s^{-1} , with rms values of 10 km and 2 cm s^{-1} . The phase speed is in the same direction as, but smaller than, the mean current off Nice, which is about 50 cm s^{-1} . The period is 2.5 days and is greater than the inertial period $2\pi/f$ (about 17.30 hours). These quantities are remarkably constant during the period of observation.

We have examined the possibility that the phase velocity was due to the stroboscopic effect. This mechanism gave unrealistic values for the phase speed, and hence this was not considered further.

Five similar meanders were also observed between Nice and Marseille on one image from NOAA 6 on November 26, 1979. The distance between two adjacent crests ranged from 30 to 70 km. The lack of additional information prevented us from combining the observations of December 1977 and of

VERTICAL PROFILES OF CURRENTS ON THE LINE NICE-CALVI OCTOBER 1963

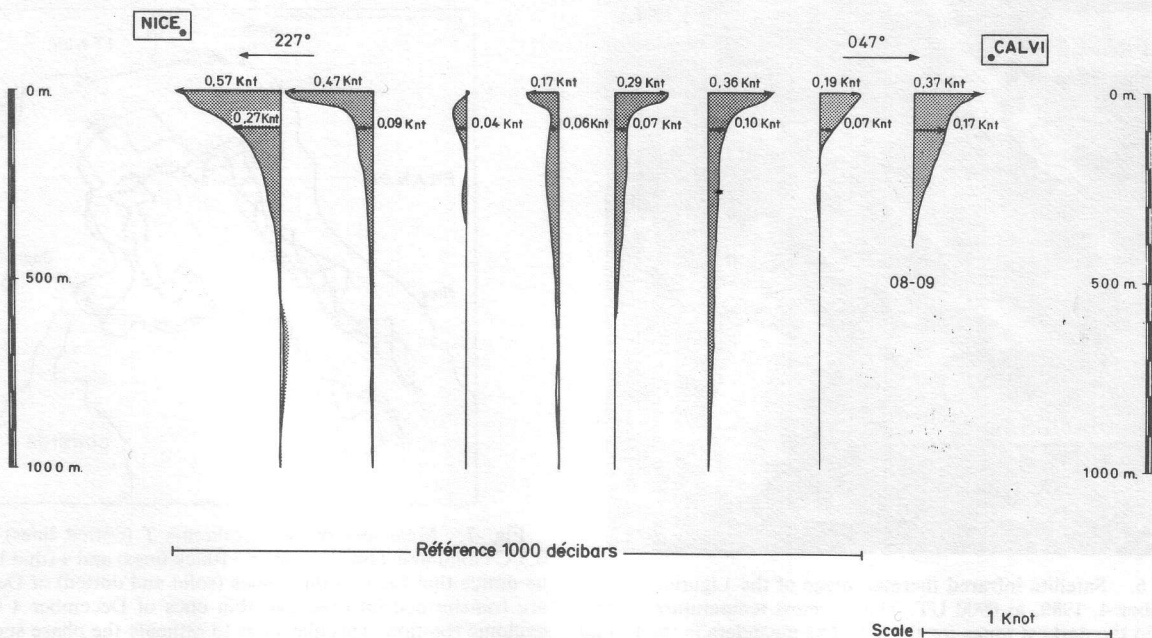


Fig. 4. Velocity profiles calculated by the Helland-Hansen method on the line Nice-Calvi in October 1963.

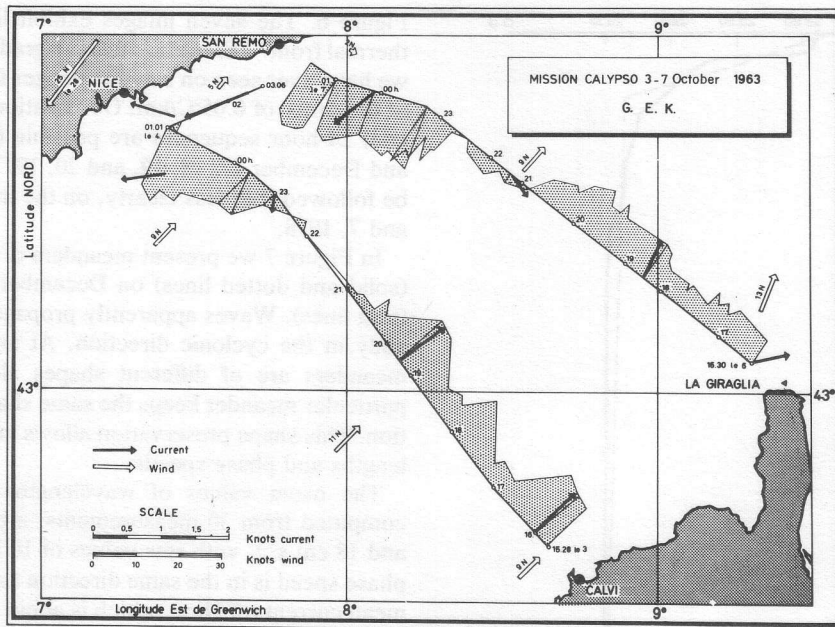


Fig. 5. Velocities at the surface calculated with the GEK in October 1963.

November 1979. In fact, it seems that the Ligurian current is particularly unstable at the end of November and in December. Unfortunately, this period is the worst for satellite infrared imagery because of frequent cloud coverage.

DISCUSSION

The shape of the thermal front presented in Figures 6 and 7 looks very much like that of the *Saunders* [1973] experiment, which deals with the instability of a baroclinic vortex in a rotating tank. Using dimensional analysis, he found that the instability occurs when

$$1 \gg R^2/D^2$$

where R is the internal radius of deformation and D is the width of the current. By substituting the values of R and D computed for the Ligurian basin ($R = 8$ km, $D = 60$ km), we find that this instability criterion is satisfied and that this area may be baroclinically unstable. A relation between R and the number meanders m can be found:

$$m \approx 1.8 D/R$$

where an m is an integer.

For the Ligurian basin, we find $m = 13$, which is in rough agreement with the nine meanders observed in Figure 6 and 7.

The explanation of the above-mentioned phenomenon

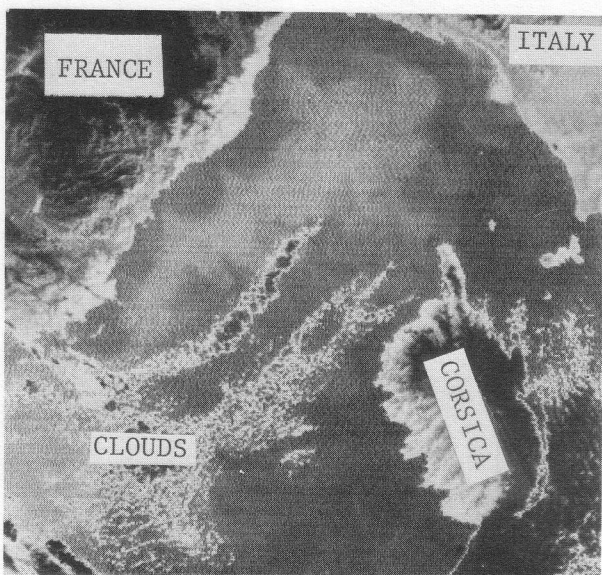


Fig. 6. Satellite infrared thermal image of the Ligurian Sea on December 4, 1980, at 0900 UT. The warmest temperatures correspond to the darkest tones for the sea. The meanders in the frontal zone are clearly visible.

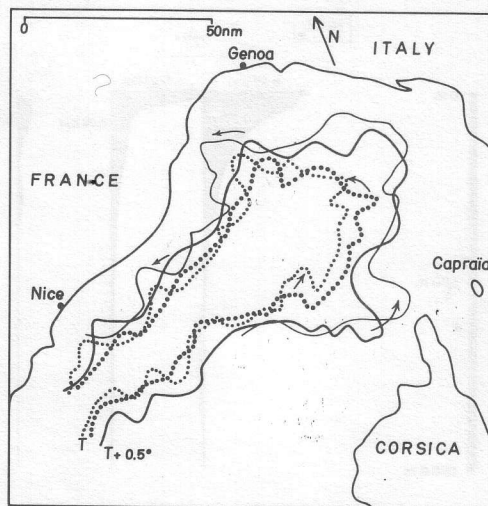


Fig. 7. Meanders of two isotherms T (dotted lines) and $T + 0.5^\circ\text{C}$ (solid lines) on December 3 (thick lines) and 4 (thin lines). Let us notice that the two thick lines (solid and dotted) of December 3 are transformed into the two thin ones of December 4 through a cyclonic rotation. This allows us to estimate the phase speed of the wave-like motion.

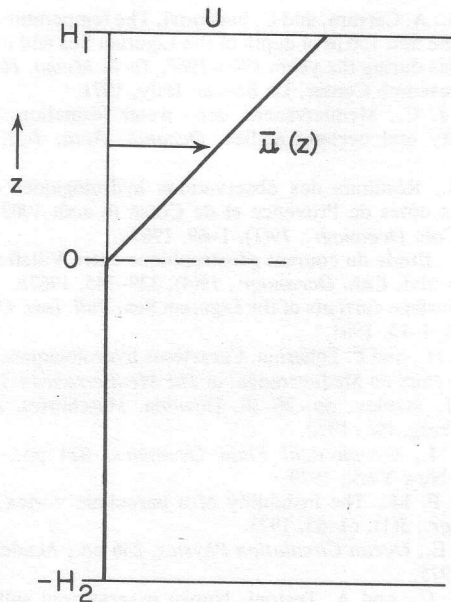


Fig. 8. Schematic representation of the velocity profile of the model: layer with constant shear on top of quiescent layer (after Tang).

may be sought through theories of large-amplitude baroclinic waves and, in particular, of baroclinic instability. These baroclinic waves could have been initiated by the wind blowing in the southern part of the region, which generated cross-current perturbations. Among the baroclinic models fitting geographical and observational conditions, the two-layer model of Tang [1975] is pertinent to this study. This analytical model deals with small perturbations of a mean current. A similar model was successfully employed by Gascard [1978] in the Medoc area, where Mediterranean deep water formation occurs.

The linearized versions of the quasi-geostrophic vorticity equation and of the continuity equation for small perturbations are

$$\left(\frac{\partial}{\partial t} + \bar{u} \frac{\partial}{\partial x}\right) \nabla^2 \psi' = f \frac{\partial}{\partial z} w' \quad (1)$$

$$\left(\frac{\partial}{\partial t} + \bar{u} \frac{\partial}{\partial x}\right) \frac{\partial \psi'}{\partial z} - \frac{\partial \psi'}{\partial x} \frac{\partial \bar{u}}{\partial z} + \frac{N^2}{f} w' = 0 \quad (2)$$

where ψ' denotes the perturbation of the stream function, w' denotes the perturbation of the vertical velocity, N is the Brunt-Väisälä frequency (assumed to be constant), and \bar{u} is the mean zonal velocity in the x direction.

Let us assume the solution to be of the form

$$\begin{pmatrix} \psi' \\ w' \end{pmatrix} = \text{Re} \left[\begin{pmatrix} \psi \\ w \end{pmatrix} e^{ik(x-ct)} \sin ly \right] \quad (3)$$

where Re denotes the 'real part of,' $\psi(z)$ and $w(z)$ are the complex Fourier coefficients, $k = 2\pi/L$ (where L is the wavelength in the x direction), $l = \pi/D$ (where D is the distance between the nodal surfaces in the y direction) and c is the complex phase speed.

Let us consider the two-layer fluid mentioned in the introduction. Let us assume that \bar{u} is uniform with y , varies linearly with z in the upper layer (i.e., $\bar{u} = u$ at $z = H_1$ and \bar{u}

= 0 at $z = 0$), and is equal to zero in the lower layer (Figure 8).

Equations (1) and (2) are applied to each layer. The general solution is

$$\psi_1 = A_1 \exp(K_1 z/H_1) + B_1 \exp(-K_1 z/H_1)$$

in the upper layer and

$$\psi_2 = A_2 \exp(K_2 z/H_2) + B_2 \exp(-K_2 z/H_2)$$

in the lower layer, where $K_1 = \mu H_1 N_1/f$, $K_2 = \mu H_2 N_2/f$, and $\mu = (k^2 + l^2)^{1/2}$. By using the above definition of H_1 , H_2 , N_1 , and N_2 , the following dimensionless parameters are computed.

$$K = \tanh K_2 / \tanh K_1 \quad M = N_1 / N_2$$

$$a = 2[(K_1/2) - \tanh(K_1/2)] / (K_1 - \tanh K_1)$$

$$b = 2[(K_1/2) - \coth(K_1/2)] / (K_1 - \tanh K_1)$$

Then, the phase velocity is written in the form

$$c = c_r + ic_i \quad c_i > 0$$

The solution of (1), (2) with the boundary conditions at the surface (rigid lid), at the interface (continuity of the motion), and at the bottom (vertical velocity equal to zero) leads to [Tang, 1975]

$$c_r = \frac{u}{2} \left[1 - \frac{MK \tanh K_1}{K_1 (1 + MK)} \right] \quad (4)$$

$$c_i = \frac{u}{2} \frac{K_1 - \tanh K_1}{K_1 (1 + MK)} [- (MK + a)(MK + b)]^{1/2} \quad (5)$$

The cutoff wavelength separating the short stable and long unstable waves is readily obtained by setting $MK + b = 0$ in (5). With the actual values of the physical parameters, one finds $L_c = 48$ km. The growth rate kc_i is drawn in Figure 9. Its maximum is obtained at $K_1 = 0.78$, which corresponds to the most unstable wave whose wavelength is 56 km. By substituting the numerical values in (4) and assuming that $u = 50$ cm s⁻¹, it is found that the velocity $c_r = 6$ cm s⁻¹. These values are roughly comparable to the observed wavelength of 38 km and velocity of 18 cm s⁻¹. It should be emphasized that the theoretical values are very sensitive to the physical parameters and to the model. Moreover, the

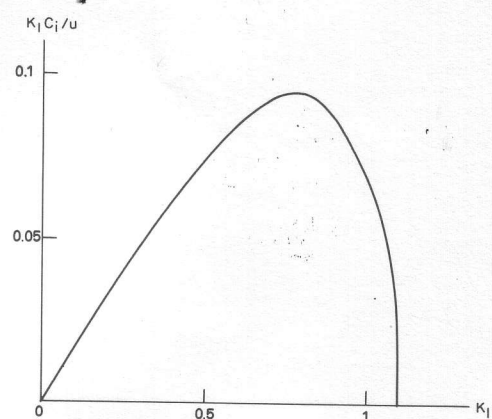


Fig. 9. Nondimensional growth rate $K_1 c_i / u$ with respect to K_1 for $H_1/H_2 = 1/20$.

baroclinic waves are really three-dimensional disturbances, whereas the observations are only the surface signature.

An explanation of the wave motion could be sought from theories of barotropic instability and of shelf waves. The width of the Ligurian current off Nice is about 60 km [Gostan, 1967b]. Because this width is much greater than the internal radius of deformation (8 km), the observed motion cannot be barotropically unstable [Stern, 1975; Pedlosky, 1979]. Shelf waves are not an explanation of the wave motion, since the shelf is too narrow and too steep to generate such waves.

CONCLUSIONS

Observations from NOAA 5 have suggested long waves propagating in the Ligurian Sea during December 1977. The estimated values of the wavelength, the phase speed, and the period are, respectively, 38 km, 18 cm s⁻¹, and 2.5 days. Hydrological data taken in that region during the month of December by previous authors show that baroclinic unstable waves can develop. The observed wavelength was, however, smaller than the theoretical ones.

This paper indicates the strength and weakness of satellite thermal images for quasi-instantaneous survey of vast areas. However, only relative values of superficial temperatures are obtained. Furthermore, our interpretation ignores the interior dynamics. Nevertheless, it is remarkable to obtain from a routine satellite survey quantities associated with wave propagation.

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