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Barotropic oscillations of the Mediterranean and Adriatic Seas[1]

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ABSTRACT

The periods and structures of several of the lowest barotropic free modes of oscillation of the combined Mediterranean–Adriatic system are computed. The computations take account of the two-dimensional structure of the Mediterranean–Adriatic system, the actual bottom topography, and the earth's rotation. To separate the effects of each of these factors, calculations are carried out first for uniform depth, then for variable depth but no rotation, and then for variable depth and rotation. The results show that the effect of variable bottom topography is more important than rotation. The computed periods for the lowest four modes of the Mediterranean Sea are 38.5 h, 11.4 h, 8.4 h, and 7.4 h.

In addition, the periods and structures of several of the lowest modes of the Adriatic Sea are computed without rotation on a high-resolution grid. The location of the mouth of the Adriatic Sea is determined by the combined Mediterranean–Adriatic calculation. By imposing the mouth in the proper location, we found that the computed periods of the lowest modes agree with observed periods. The computed periods of the three lowest modes in the Adriatic Sea are 21.9 h, 10.7 h, and 6.7 h.

1. Introduction

This paper deals with a computation of the periods and structures of several of the lowest barotropic modes of oscillation of the combined Mediterranean–Adriatic Basin. The computations take into account the morphometry of the combined basin (excluding the Aegean Sea), the actual bottom topography and the earth's rotation.

Historically, studies on the oscillations of natural basins were done using the so-called "Channel equations", which are essentially one-dimensional in nature (in the longitudinal direction) and explicitly ignore the effects of the earth's rotation. These equations have been able to successfully account for the periods and structures of the lowest modes in several lakes and bays. (See Defant, 1961; Platzman and Rao, 1964.) However, the validity of the approximations involved in deriving the channel equations breaks down when a basin is not narrow and elongated. The channel theory also breaks down for higher modes of oscillations and, in particular, is incapable of describing transverse oscillations.

In recent years, several methods have been developed to attack the full two-dimensional quasi-static oscillations of large natural basins, including the effects of the earth's rotation (Platzman 1972, 1975, 1978; Rao and Schwab, 1976). In the case of the Mediterranean Sea, there do not appear to be any comprehensive calculations on the properties of its free oscillations using the entire basin. The purpose of this paper is to apply the two-dimensional methods to the Mediterranean and Adriatic Seas.

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2. Formulation of the problem

The problem deals with the small amplitude, free quasi-static oscillations of a barotropic sea on a rotating earth. The governing equations are the traditional shallow water equations:

$$\frac{\partial \mathbb{a}}{\partial t} = L\mathbb{a}, \tag{1}$$

where

$$\mathbb{a} = \begin{pmatrix} H \\ \mathbb{V} \\ \eta \end{pmatrix}$$

$$L = \begin{pmatrix} -f\,\mathbb{k}\,x & -gH\nabla \\ -\nabla & 0 \end{pmatrix}.$$

In the above equations, $\mathbb{v}$ is the horizontal velocity vector, η is the free surface fluctuation, and $H = H(x,y)$ is the equilibrium depth of the sea. The symbols defined in the spatial differential operator L have their conventional meaning. In the calculations for the Mediterranean Sea we consider it to be a completely enclosed water body. Hence, the appropriate boundary condition in solving eq. (1) is that

$$H\mathbb{v}\cdot\mathbb{n} = 0, \tag{2}$$

where $\mathbb{n}$ is a unit vector normal to the coast.

The normal modes of the sea are determined by seeking simple harmonic solutions of eqs. (1) and (2). That is

$$\mathbb{a} \sim \mathbb{A}e^{i\sigma t},$$

which on substitution into eq. (1) yields

$$L\mathbb{A} = i\sigma\mathbb{A}. \tag{3}$$

Hence the frequencies σ (multiplied by $i = \sqrt{-1}$) are the characteristic values of the operator L and the $\mathbb{A}$'s are the corresponding vectors. Each characteristic vector is a function of the horizontal coordinates and represents the spatial structure of the normal mode associated with a particular frequency σ.

In the continuum, the solutions to eq. (3) yield an infinity of normal modes. If the Coriolis parameter f and/or the equilibrium depth H vary as a function of horizontal coordinate(s), the spectrum of normal modes consists of two distinct species usually referred to as oscillations of the first class and oscillations of the second class. The former are the gravitational oscillations that, in the context of the full set of equations (1), are altered in their basic properties by the rotation of the earth both qualitatively and quantitatively. The oscillations of the second class are governed by the principle of conservation of potential vorticity and owe their existence to non-zero values of the horizontal gradient of basic state potential vorticity f/H. Again, in the context of eq. (1), the basic properties of the vorticity modes are modified by gravity and divergence effects associated with the free surface fluctuations.

The solution to eq. (3) is a formidable one even in the case of simple idealized geometries. When a real water body with irregular topography and horizontal plan form is considered, it is imperative to resort to discrete methods of solving the problem. Various alternatives in attacking this classical problem of solving for free oscillations were lucidly discussed by Platzman (1972). The method adopted here is based on a Galerkin procedure developed by Rao and Schwab (1976) and applied successfully to study the normal modes of the Laurentian Great Lakes of North America. We refer the reader to that paper for the details of the numerical treatment. We present here the results of the computations for the gravitational modes only since these modes are more easily detectable from analyses of water level records. The vorticity modes, on the other hand, tend to be quasi-non-divergent and would be more apparent in a long series of current meter data rather than water level data. In any event, we have not been able to obtain enough water level records to examine the spatial structures of the normal modes in any detail as, for example, was done for the Laurentian Great Lakes by Rao et al. (1976) and Schwab and Rao (1977). However, the present method was shown to work remarkably well in describing the properties of the gravitational modes in the above cases and we expect similar conclusions to hold for the Mediterranean Basin also.

The structures of the normal modes will be described in terms of the phase and amplitude of the free surface fluctuations $\eta\ (x,y,t)$. Because of the nature of the operator L, the simple harmonic solutions occur in conjugate pairs, $\mathbb{A}e^{i\sigma t}$ and $\mathbb{A}^*e^{-i\sigma t}$. The normal mode solution for η is the real part of either of these solutions and can be represented by

$$\eta = |A| \cos(\sigma t - \alpha(x,y)).$$

A convenient way to present the result is to map the distribution of the amplitude $|A|$ (co-range lines) and the phase α (co-tidal lines) as is commonly done in tidal charts. The co-tidal lines are drawn in equally spaced intervals in the range $0 \leqslant \alpha < 2\pi$ and the direction of propagation is in the direction of increasing α. In the absence of the earth's rotation, the gravitational modes in an enclosed sea will be standing oscillations with fixed nodal lines in the interior of the basin. The phase of oscillation changes discontinuously across the nodal line through an angle of π radians. However, when $f \neq 0$, each nodal line is no longer fixed in space, but instead rotates about a point called the amphidromic point at which the amplitude is always zero and the phase is multiple valued. The direction of rotation about an amphidromic point can be either positive (counterclockwise) or negative (clockwise).

3. Description of the numerical grids

The calculations to determine the normal modes of the Mediterranean and Adriatic Seas proceeded in two steps. First we used the grid shown in Fig. 1 to find the normal modes of the combined Mediterranean–Adriatic system. The lateral boundaries and bottom topography are resolved on 1° squares on a Mercator (1° M) projection (1° M = 111.18 km at the equator). The basin extends on the Mercator map between 32° M (30.46° actual) and 50° M (44.65 actual). The islands of Corsica, Sardina, and Sicily are included. There are a total of 278 grid boxes, with a mean depth of 1442 m. The Aegean Sea was excluded from the grid because the 1° M resolution is insufficient for even a crude representation of the complicated topography there. The Straits of Gibraltar are closed for the same reason. These simplifications eliminate the possibility of a co-oscillating or Helmholtz mode for the entire Mediterranean Basin with a nodal line at the Straits of Gibraltar and preclude the determination of any Aegean Sea modes, but do not significantly affect the calculation of the other Mediterranean and Adriatic Sea modes. The results for the 1° M grid include both the normal modes of the Mediterranean Sea proper and several modes whose amplitudes are confined to the Adriatic Sea. Each of the Adriatic Sea modes has a nodal line separating the Adriatic from the Mediterranean, but the location of the nodal line, or mouth, is not known *a priori* and can change with each mode, as has been shown for Green Bay in Lake Michigan by Rao et al. (1976). Therefore, the results from the 1° M grid are used to locate the mouth of the Adriatic Sea and further calculations (without rotation) are carried out on a much finer grid covering the Adriatic Sea only. The fine grid is shown in Fig. 2. Grid squares are 0.1° M on a side. There are 2452 squares in the full grid, with an average depth of 459 m.

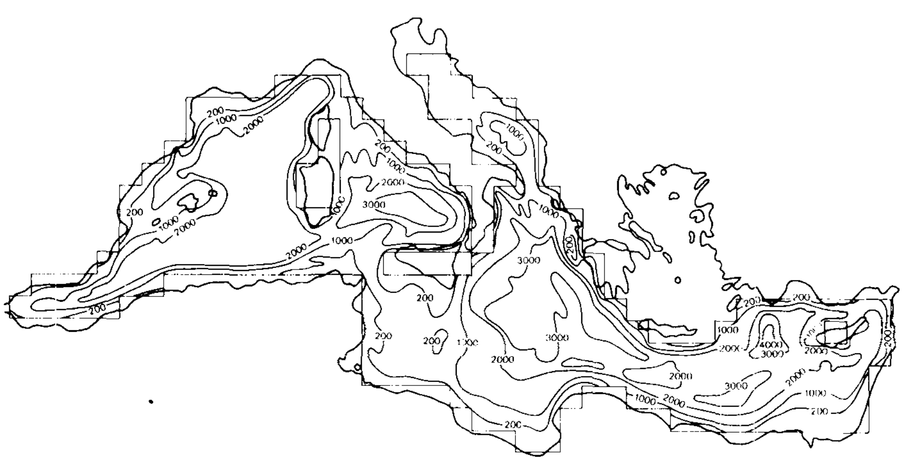

Fig. 1. Computational 1° Mercator grid and bathymetric contours (in meters) for the combined Mediterranean–Adriatic system.

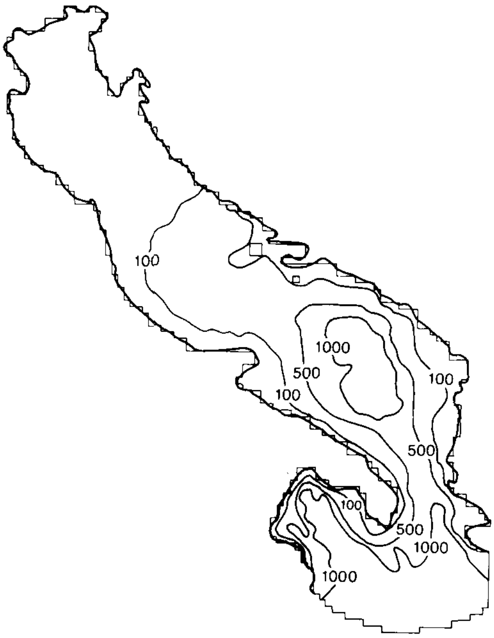

Fig. 2. Computational 0.1° Mercator grid and bathymetric contours (in meters) for the Adriatic Sea.

4. Results

4.1. *Normal modes of the Mediterranean Basin*

The numerical calculations required to evaluate the derivatives and integrals involved in the Galerkin procedure are computed on a single Richardson lattice as described in Rao and Schwab (1976). In this procedure, we compute two sets of numerical orthogonal functions, ϕ's and ψ's, which are then used as basis functions in computing the normal mode periods with rotation. From our representation of the Mediterranean–Adriatic Basin using 1° M grids, we obtain a total of 278 ϕ functions and 186 ψ functions. In the final calculations, however, we found that 50 functions of each kind were sufficient to yield well-converged values for the periods and structures of the modes. In the technique described in Rao and Schwab's (1976) paper, the Coriolis parameter f was treated as a constant. The validity of the technique is not in any way restricted to the case of a constant f. The inertia period in the Mediterranean–Adriatic Basin varies locally from a value of about 24 h at the southern end to about 15.7 h at the northern end (average value for the mean latitude is 19.6 h). In view of this large change, the Coriolis parameter was taken as a variable $f(y) = 2\Omega \sin \theta(y)$ in the calculations. Here Ω is the angular speed of rotation of the earth and θ is latitude.

In order to assess the influence of the variable topography and the earth's rotation on the periods of oscillation, we have included the periods of several of the lowest gravitational modes under different conditions in Table 1. Column 1 is simply an enumeration of the modes arranged in order of decreasing periods. In column 2, we have given a tentative identification for each mode as belonging primarily to an oscillation of either the Mediterranean Sea (modes with prefix M) or the Adriatic Sea (modes with prefix A). Column 3 gives the non-rotating periods, assuming a uniform mean depth for the entire Mediterranean–Adriatic Basin (taken as 1442 m) but allowing for the actual shape. The non-rotating periods with actual topography and shape are given in column 4. The periods computed with a constant value for $f = 2\Omega \sin \theta_0$ ($\theta_0 = 37.75°$) are presented in column 5. Column 6 lists the periods with variable f.

Table 1. *Periods (in hours) of the lowest gravitational modes of the Mediterranean–Adriatic basin using 1° Mercator squares*

Mode	Identification	H = constant $f = 0$	H = variable $f = 0$	H = variable $f = 2\Omega \sin \theta_0$	H = variable $f = 2\Omega \sin \theta$
1	M1	23.1	42.5	38.2	38.5
2	A1	13.1	20.0	20.0	20.1
3	M2	8.9	11.3	11.4	11.4
4	A2	7.6	9.3	9.3	9.3
5	M3	5.6	8.4	8.4	8.4
6	M4	4.7	7.3	7.4	7.4
7	A3	4.2	6.8	6.8	6.8

It is clear from Table 1 that the most significant effect on the periods of the Mediterranean modes is due to the variable topography of the basin. Inclusion of the real topography altered the period of the fundamental mode of the Mediterranean by almost 84%. This is mainly because of the significant reduction in the depth of the Sicily Strait in the variable depth grid, restricting the flow between the eastern and western basins and increasing the period. The effect of rotation was not as significant as the topographic effect. Rotation reduced the fundamental period M1 from 42.5 h to 38.2 h when f was a constant and to 38.5 h when f was treated as a variable. The reduction of period with rotation is in contrast to the results for the fundamental mode in ideal rectangular basins or circular basins (Rao, 1966) and will be discussed further below.

a. *The first Mediterranean mode—38.5 h* (Fig. 3). The structure of the fundamental oscillation of the Mediterranean Basin consists of a single positive amphidromic system that spans the Sicily Strait. The near uniformity of amplitude distribution in the western and eastern basins (with the eastern basin amplitude about half that of the western basin) gives this mode the character of an oscillation between two basins connected by a canal. (See Defant, 1961.) The earth's rotation affects this mode in a manner similar to the Helmholtz mode in a bay, i.e., decreasing the period over the no-rotation case and transforming the fixed nodal line into a positive amphidromic system. Although we are not aware of any clear observations of this oscillation, currents from the Sicily Strait or water levels from the edges of the western basin should reflect this periodicity.

b. *The second Mediterranean mode—11.4 h* (Fig. 4). The structure of the second Mediterranean mode exhibits a negative amphidromic system in the western basin and a positive system in the eastern basin. A third system is present in the Adriatic Sea. The amphidromic systems divide the main Mediterranean Basin roughly into thirds with the eastern-most and western-most sectors oscillating with the same phase and the central sector with the opposite phase.

c. *The third Mediterranean mode—8.4 h* (Fig. 5). The third Mediterranean mode has three positive amphidromic systems in the main Mediterranean basin and one positive and one negative system in the Adriatic Sea. The amplitude is greatest at the Straits of Gibraltar and along the western coast of Italy. The amplitudes in the eastern basin are less than 10% of the maximum amplitude. This mode appears to be the fundamental oscillation of the western Mediterranean Basin, with antinodes at the Straits of Gibraltar and along the western coast of Italy and a nodal region running from the southern edge of the western basin through the islands of Sardinia and Corsica. If the Straits of Gibraltar were opened to the sea, a nodal line would be present at the Straits and the amplitude maximum of this mode would be moved somewhat eastward.

d. *The fourth Mediterranean mode—7.4 h* (not illustrated). The maximum amplitudes of this mode occur on the eastern shore of Tunisia with very little fluctuation in either the western or eastern Mediterranean basins proper. This mode would more properly be described as the fundamental oscillation of the Tunisian bight and so is not included in the figures.

4.2. *Normal modes of the Adriatic Sea*

The 1° M grid used for calculating the normal modes of the combined Mediterranean-Adriatic system provides only limited resolution of the Adriatic Sea. In order to better approximate the topography in the Adriatic Sea, the 0.1° M grid shown in Fig. 2 was used. The number of grid squares (2452) precluded application of the full Galerkin procedure used for the Mediterranean grid so the calculations were performed with $f = 0$. In this case, eq. (3) reduces to

$$\nabla \cdot H \nabla \eta = \frac{-\sigma^2}{g} \eta, \tag{4}$$

which can be solved by any of several standard numerical methods. We chose to use a Lanczos procedure (Platzman, 1975; Schwab, 1980; Rao and Schwab, 1981) that can determine the lowest eigenvalues and eigenvectors of eq. (4) even on a very fine grid.

The calculations on the 1° M grid produced a first approximation to the structures of the Adriatic Sea modes. They showed that the first and third modes had a nodal line just outside the narrowest part of the Strait of Otranto, roughly along the 1000 m depth contour. The second mode, however, had a nodal line much further out in the Ionian Sea, closer to the 2000 m depth contour. Therefore, in

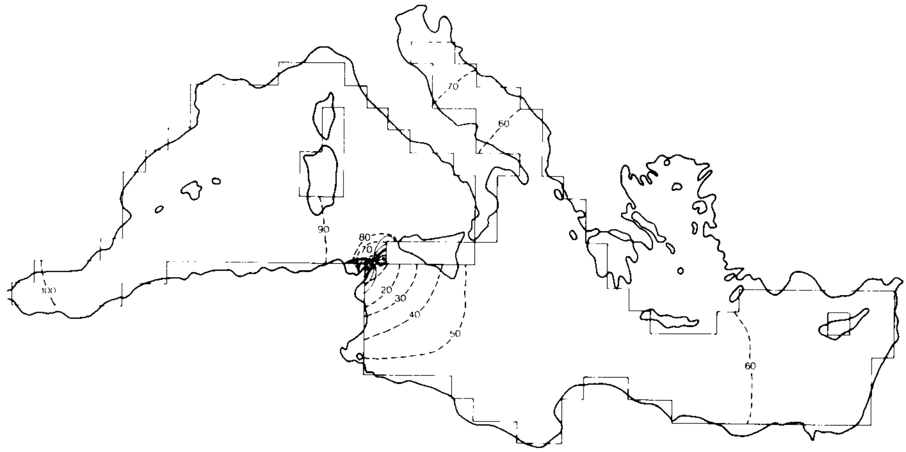

Fig. 3. Calculated structure of the first mode of the Mediterranean Sea with a period of 38.5 h. Solid lines are co-tidal lines in 30° increments with 0° indicated by an arrow indicating the direction of phase progression. Broken lines are co-range lines relative to a maximum of 100.

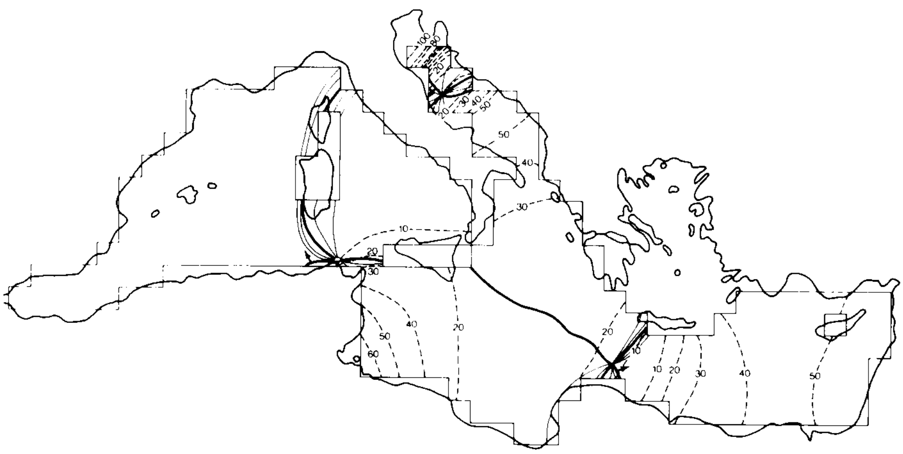

Fig. 4. As in Fig. 3, but for the second mode of the Mediterranean Sea with a period of 11.4 h.

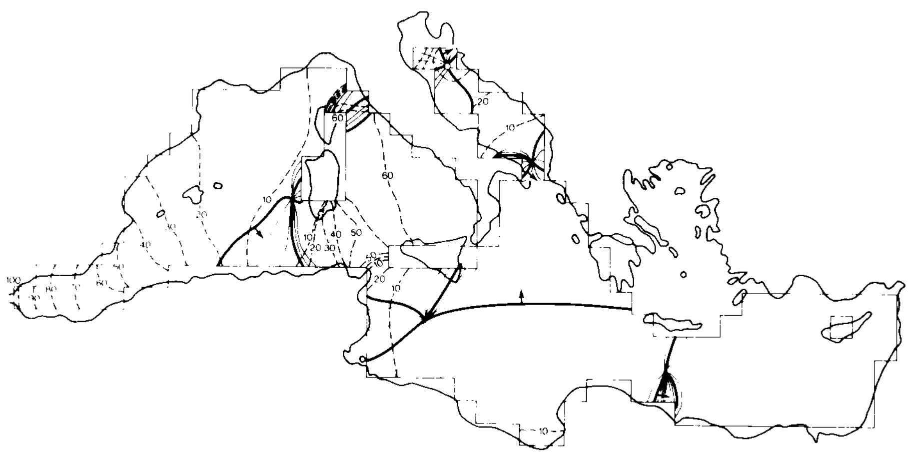

Fig. 5. As in Fig. 3, but for the third mode of the Mediterranean Sea with a period of 8.4 h.

the calculations for the Adriatic Sea normal modes, two grids were used, one with the boundary condition $\eta = 0$ imposed along the nodal line determined by the combined Mediterranean–Adriatic calculations for the first and third Adriatic nodes, and another with the boundary condition $\eta = 0$ imposed along the nodal line of the second mode. The results are presented in Table 2 and the figures below. Since rotation was not included in the calculations, the nodal lines do not become amphidromic systems but simply separate regions whose phases differ by 180°.

a. *The first Adriatic mode—21.9 h* (Fig. 6). The calculation with the high resolution 0.1° M grid gives a period of 21.9 h for the fundamental oscillation of the Adriatic Sea. The amplitude of the oscillation increases monotonically from the mouth to the northern shore. This oscillation is well-known in the literature, with reported periods between 21 and 22 h.

b. *The second Adriatic mode—10.7 h* (Fig. 7). This mode exhibits an additional nodal line inside the Adriatic Sea. The oscillation in the northern quarter of the Sea is out of phase with the rest of the basin. Because the nodal line at the mouth of the adriatic sea extends further out into the Mediterranean than for the first and third modes, there is considerable (up to 30% of the maximum) amplitude even in the Straits of Otranto.

c. *The third Adriatic mode—6.7 h* (Fig. 8). The third mode of the Adriatic Sea has two nodal lines inside the Sea, separating it into three oscillating regions with the phase in the center region opposite to that in the other two. The greatest amplitude in the central region is 30% of the maximum amplitude, and the greatest amplitude in the southern region is only 20% of the maximum.

Table 2. *Computed and observed periods of the lowest gravitational modes of the Adriatic Sea*

	Computed period in hours		Observed period in hours	
Mode	Bajc (1972) channel model	Present two-dimensional model	Defant (1961)	Godin and Trotti (1975)
A1	21.0	21.9	22.0	21.5
A2	12.5	10.7	11.0	11.1–11.4
A3	8.7	6.7	8.5	—

Fig. 6. Calculated structure of the first mode of the Adriatic Sea with a period of 21.9 h on the high resolution grid with no rotation. Solid lines are co-range lines relative to a maximum of 100.

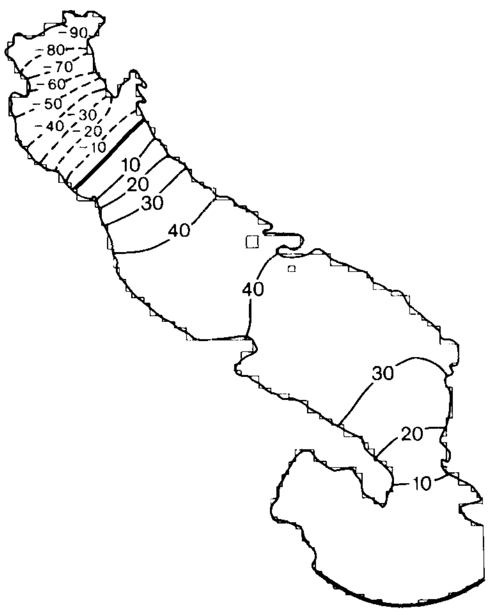

Fig. 7. As in Fig. 6, but for the second mode of the Adriatic Sea with a period of 10.7 h.

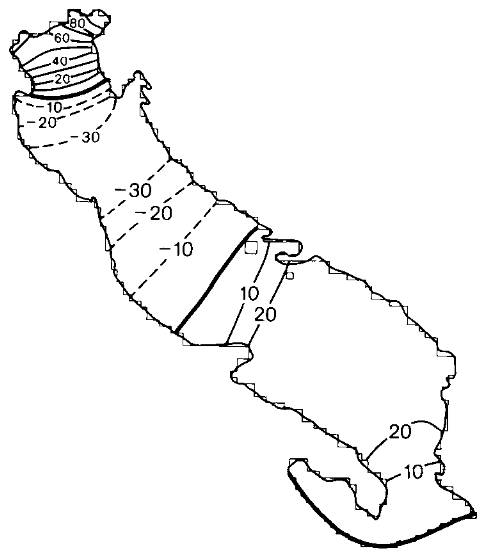

Fig. 8. As in Fig. 6, but for the third mode of the Adriatic Sea with a period of 6.7 h.

5. Discussion

5.1. *Mediterranean modes*

The period of the first Mediterranean mode (38.5 h) puts it beyond the main tidal periods, so that sea level oscillations due to this mode should be apparent in detided sea level records. Lamy et al. (1981) analyzed sea level and bottom pressure records from the Gulf of Lions on the French Mediterranean coast during summer. Although their spectra do not show a peak in this frequency range, time series plots of adjusted sea level and bottom pressure with the tidal signals removed occasionally show a small amplitude oscillation with about this period, although it is generally overwhelmed by oscillations in the 4–7-day period range. We are not aware of any other analyses of detided sea level records in the Mediterranean that might confirm this calculation.

It is interesting to note that rotation reduced the period of the fundamental mode in contrast to classical results for ideal rectangular and circular basins. Previously, Platzman (1972) has found that the period of the fundamental oscillation of the Gulf of Mexico decreased with rotation, consistent with the theoretical results of van Dautzig and Lauwerier (1960) for rotating rectangular bays. More recently, the results of Wübber and Krauss (1979) for the normal modes of the Baltic Sea show a remarkable decrease in the period of the fundamental oscillation (from 40.55 to 31.03 h) with the inclusion of rotation. In their calculations, the Baltic Sea is treated as an enclosed basin. The lowest mode is a co-oscillation of the Western Baltic and the Gulf of Bothnia, which are connected by a relatively narrow strait. From these results and from our results for the lowest mode of the Mediterranean Sea, we conclude that when the fundamental mode of the system has the character of a co-oscillation between two basins, the period decreases with rotation as it would for the Helmholtz mode in a bay.

The period of the second mode (11.4 h), on the other hand, is very close to the semi-diurnal tidal period (12.4 h), and a close examination of the structure reveals many features of the observed semi-diurnal tide (Fig. 9 redrawn from Defant, 1961, and originally Sterneck, 1915). The locations of the amphidromic systems are very close in the tide and the second Mediterranean mode, but the tidal charts show an additional nodal line near the Straits of Gibraltar owing to the fact that the tide just inside the Straits is still in phase with the tide outside. The nodal line marks the transition to the eastern oscillating sector, which is in opposite phase to the tide outside the Straits of Gibraltar. The maximum tidal amplitude occurs in the northern Adriatic Sea, and the tide has the same phase in the eastern and western Mediterranean sectors. Apparently the proximity of the tidal period to the period of the second Mediterranean mode gives the tide a very similar structure to the normal mode.

Spectra of the detided sea surface fluctuations presented by Lamy et al. (1981) show a conspicuous peak at approximately 8 h. This period is about 1/3 the diurnal period and this energy may represent non-sinusoidal behaviour of the diurnal tide. On the other hand, it is also close to the calculated periods of the third and fourth Mediterranean modes (8.4 h and 7.4 h).

5.2. *Adriatic Sea modes*

As mentioned previously, the free oscillations of the Adriatic Sea were well known. Defant (1961) summarizes the results of von Kesslitz (1910) and Vercelli (1941) for periodic components observed in detided sea level records from the Adriatic Sea. He reports periods of 22, 11, and 8.5 h for the lowest three longitudinal modes and a period of

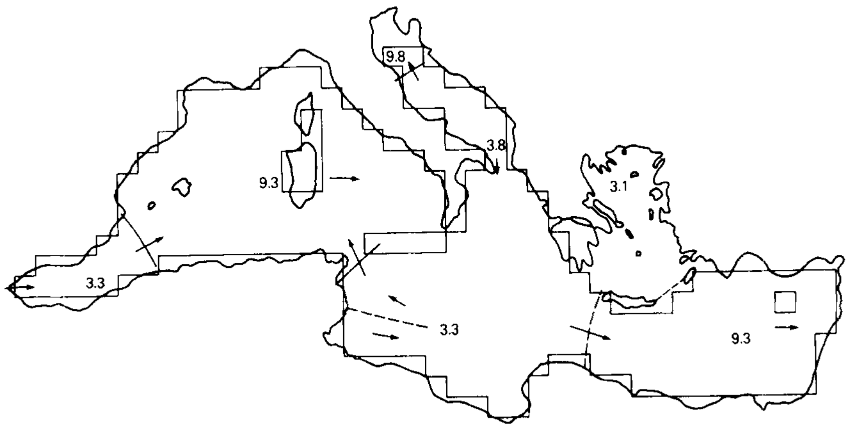

Fig. 9. Oscillating areas of the Mediterranean for the semi-diurnal tide (numbers indicate average establishments in central European time. Redrawn from Defant, 1961 and originally Sterneck, 1915).

2.5–3 h for the first transverse mode. More recently, Godin and Trotti (1975) analyzed detided sea levels from Trieste and reported periodicities of 21.5, 11.1–11.4, and 5.4 h. They attribute the first two periods to the two lowest longitudinal modes of the Adriatic Sea and the third to the fourth longitudinal mode or a transverse mode. These observations are compared to periods computed here and to periods computed with a channel model by Bajc (1972) in Table 2. The present results are closer to observed periods for both the first and second longitudinal modes, but further from Defant's reported period for the third mode. In Bajc's calculations the first and third modes were computed by treating the Adriatic as a conventional bay with a nodal line at the mouth. The period of the second mode was obtained by considering the Adriatic as an enclosed basin by closing off the Straits of Otranto. Earlier Defant (1961) had speculated that the observed period of 11 h in the Adriatic could only be explained by considering it as a closed basin. The present calculations show that this period can be obtained without closing the mouth of the Adriatic if the position of the nodal line at the mouth is proper for this mode.

It was previously reported by Rao et al. (1976) that the nodal line for the second mode of Green Bay extended further into Lake Michigan than either the first or third mode. An area for further investigation is the question of why the second mode and (as supplementary calculations have shown) other even numbered modes of a bay have their nodal line farther out into the connecting basin than the first, third, and other odd numbered modes. The first and third modes tend to position their nodal line close to the natural mouth of the bay, while the second mode tends to establish an antinode there, moving its nodal line further out into the main basin.

Some of the power spectra of detided sea level records at Trieste from periods when non-tidal oscillations were apparent are redrawn from Godin and Trotti (1975) in Fig. 10, along with vertical lines at the periods of the Mediterranean and Adriatic modes calculated here. The agreement for the lowest longitudinal mode is apparent. There is also reasonable agreement between the computed period of the second Adriatic mode and the observed peaks in the spectra. The rest of the spectral peaks are considerably lower than these two, but during some events (particularly B, H, J, L) there is an indication of subsidiary peaks not only at A3 (6.7 h) but also at M3 (8.4 h) and M4 (7.4 h), indicating that the higher Mediterranean modes may also be active in the Adriatic.

6. Summary

Normal modes of the combined Mediterranean–Adriatic system were calculated with uniform depth and no rotation, with variable depth and no rotation, and with variable depth and rotation. The results showed that the effect of topography was

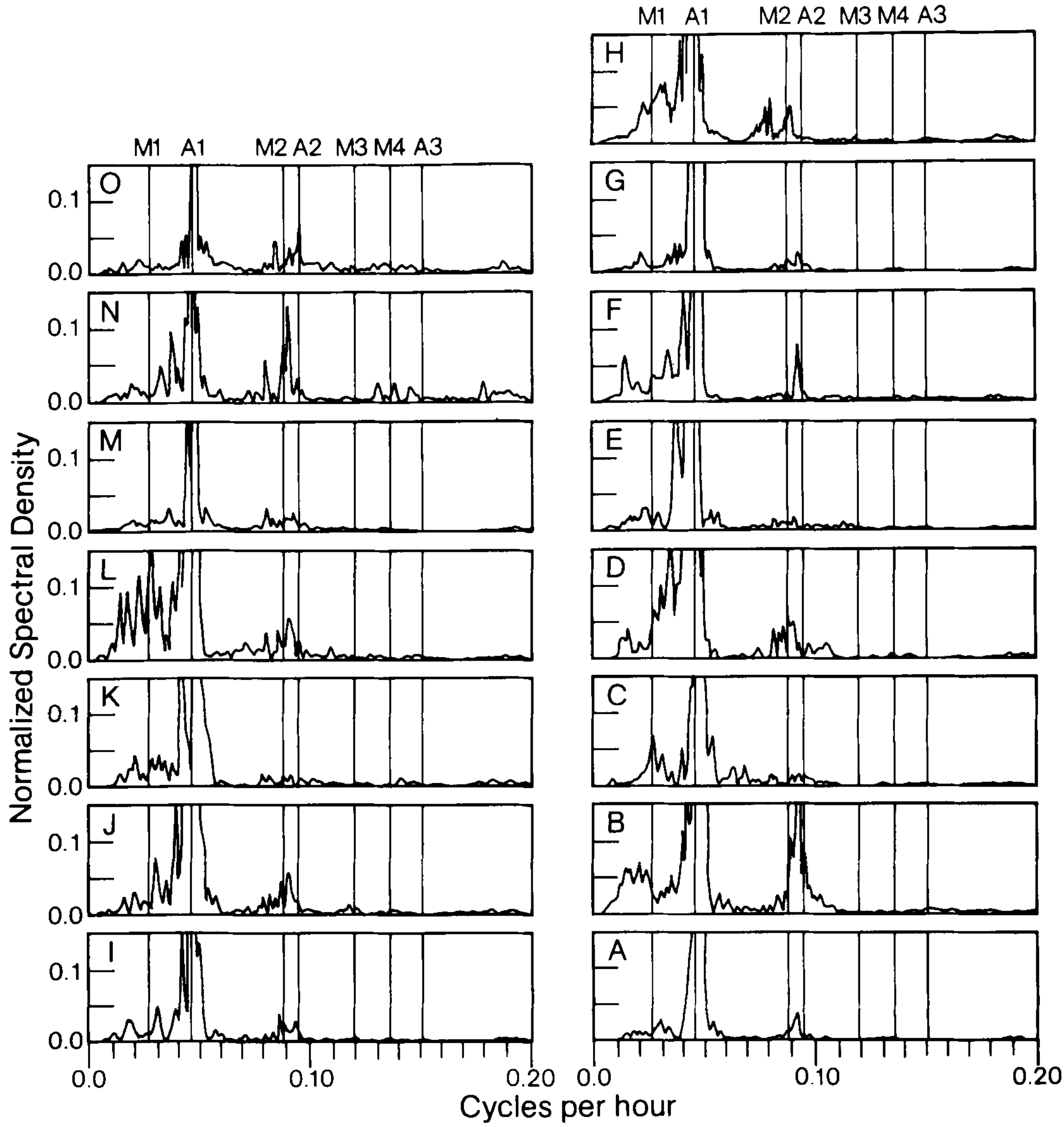

Fig. 10. Power spectra of detided water levels at Trieste for 15 cases during which seiche action was evident (redrawn from Godin and Trotti, 1975). Labelled vertical lines indicate calculated periods for the lowest modes of the Mediterranean and Adriatic Seas (see Tables 1 and 2).

much greater than that of rotation on the periods of the normal modes. The lowest mode of the Mediterranean Sea, with a period of 38.5 h, resembles a co-oscillation of the eastern and western basins with a nodal line across the Sicily Strait. Rotation transforms the nodal line into a positive (counterclockwise) amphidromic system. The calculated periods of the next three Mediterranean modes were 11.4, 8.4, and 7.4 h.

There is only scant evidence for verification of the period of the lowest mode. We await further studies of detided sea level records from stations on the eastern and western ends of the Mediterranean. The structure of the second mode bears a strong resemblance to the observed structure of the semidiurnal tide. This is thought to be due to the proximity of the calculated periods to the tidal period.

The lowest three normal modes of the Adriatic Sea were calculated on a high resolution grid without rotation. The position of the nodal line at the mouth of the Adriatic was determined from the combined Mediterranean–Adriatic calculation. It was close to the Straits of Otranto for the first and third modes, but extended much further into the Ionian Sea for the second mode. The calculated periods for the lowest two modes (21.9 and 10.7 h) agree very well with observations of periodicities in detided sea level records from the Adriatic.

7. Acknowledgements

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