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NUMERICAL INVESTIGATION OF M2-TIDES IN THE MEDITERRANEAN AS A CLOSED BASIN.

By

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Key words: Tides, Mediterranean.

ABSTRACT

A Numerical model for calculating M2 - Independent Tide in the Mediterranean (as a closed basin) has been developed. The sea was considered, firstly, as composed of two communicated rectangular areas of constant depth of 500 m with a resolution of 1° X 1°, secondly, as bounded nearly with its natural coastal and bottom configurations and tested twice with resolutions of 1° X 1° and 15' X 15' respectively. The sea is assumed to be driven by the potential tidal forces.

The computed amplitudes and phases obtained from the proposed cases were compared with each other and also with observations. The deduced values obtained from rectangular basins type with constant depth of 500 m are relatively greater than that calculated by the real boundaries type. Meanwhile, the results of the model with finer grid resolution 15' X 15' are more significant than that with resolution of grid 1° X 1° and more confirmative with observations. The boundaries have minor influences while the dimensions of the basins have significant impacts on the tidal pattern.

INTRODUCTION

The Mediterranean is a deep, elongated, irregular depression stretched from 6° W to about 36° E and extended in width from 30° N to about 47° N. It is communicated with the Atlantic Ocean through the Strait of Gibraltar which is narrow of only 20 km wide and 320 m depth at the sill. The Mediterranean is mainly composed of two basins (Eastern and Western), which are connected through the Sicilian Channel with a sill of an average depth 350 m and the very narrow Strait of Messinia with an average depth of 300 m. The eastern basin is connected with the Adriatic Sea through the Strait of Otranto and with the Aegean Sea through two straits located to west and east of Creat Island (Fig.1).

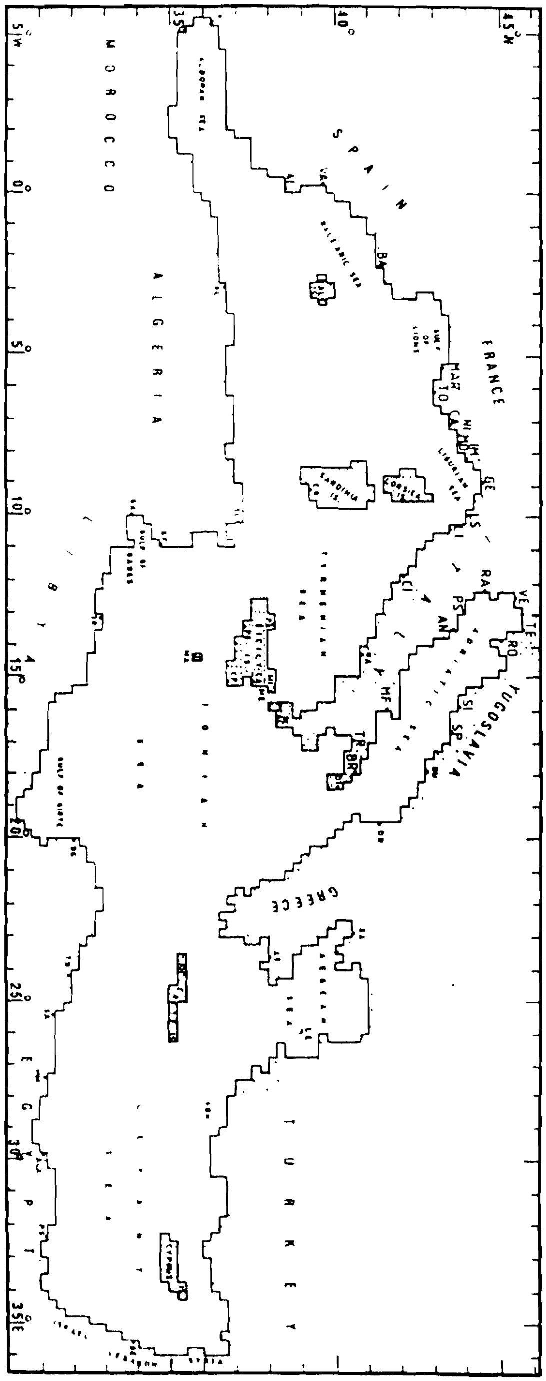

Figure 1: The Mediterranean Sea.

The Mediterranean as a closed system

The western basin is more deeper than the eastern basin. In addition, the shelf is relatively wide in the eastern basin, particularly to the east of Tunis and along the Egyptian coast, while it is nearly absent in the western basin.

Although the tidal range in the Mediterranean is small, not exceeding 1 m, few investigators (Sterneck, 1915; Defant, 1916 & 1960; Purga et al., 1979; Mosetti, 1987; Mosetti and Purga, 1985) have attempted to explain the tidal phenomena of the Mediterranean. Sterneck (1915) used the coastal observations of the water level in the Western and Eastern basins to investigate the tidal motion in the Mediterranean. He found that three nodal lines are existing along the basin, one in the middle of each basin, while the third one is located between the two basins in the Straits of Messinia and Tunis. He also added that the rotation of the earth causes strong transverse oscillations which transform these nodal lines into amphidromies with anticlockwise sense of rotation. Moreover, he applied the hydrodynamical equations to calculate the tidal components in the Mediterranean. He examined first the direct effect of the tide generating forces for each of the two basins, assuming that these basins are completely closed. He found that the co-oscillating tidal motion of the eastern basin with the other adjacent seas is nearly negligible compared with the independent tidal components. Moreover, the western basin has co-oscillating tides with both the Atlantic Ocean and the eastern basin.

Actually the previous results obtained by the theoretical calculations as well as that obtained from observations are not sufficient to interpolate the co-range and the co-tidal lines over the Mediterranean Sea particularly along the African coast and in the offshore water.

Later, numerical solutions of the hydrodynamical equations developed by many investigators to compute the tides and storm surges in the oceans and adjacent seas (Hansen, 1956 & 1962; Fischer, 1959 ; Bretschneider, 1968; Krauss, 1973; Flather and Heaps, 1975; Sharaf El Din & Morsy, 1977; Soliman, 1979; Parke, 1982 and Schwiderski, 1983). The pattern of the tide in the Mediterranean could be investigated more deeply by applying these numerical methods after some developing to compute the natural tides or the tides in closed areas.

The present study deals with the mathematical model and the difference scheme. The model was applied to investigate the semi-diurnal M2-independent tide in the Mediterranean, which was assumed to be formed by one of the following shapes:

1- Two rectangular basins of constant depth (500 m), which are connected together through an opening of 2° width, having a grid system of mesh size 1° * 1° (Fig. 2a).

2- The basin is nearly represented by its natural boundaries with the following resolutions:

a) 1° * 1° (Fig. 2b).
b) 15' * 15'(Fig. 2c).

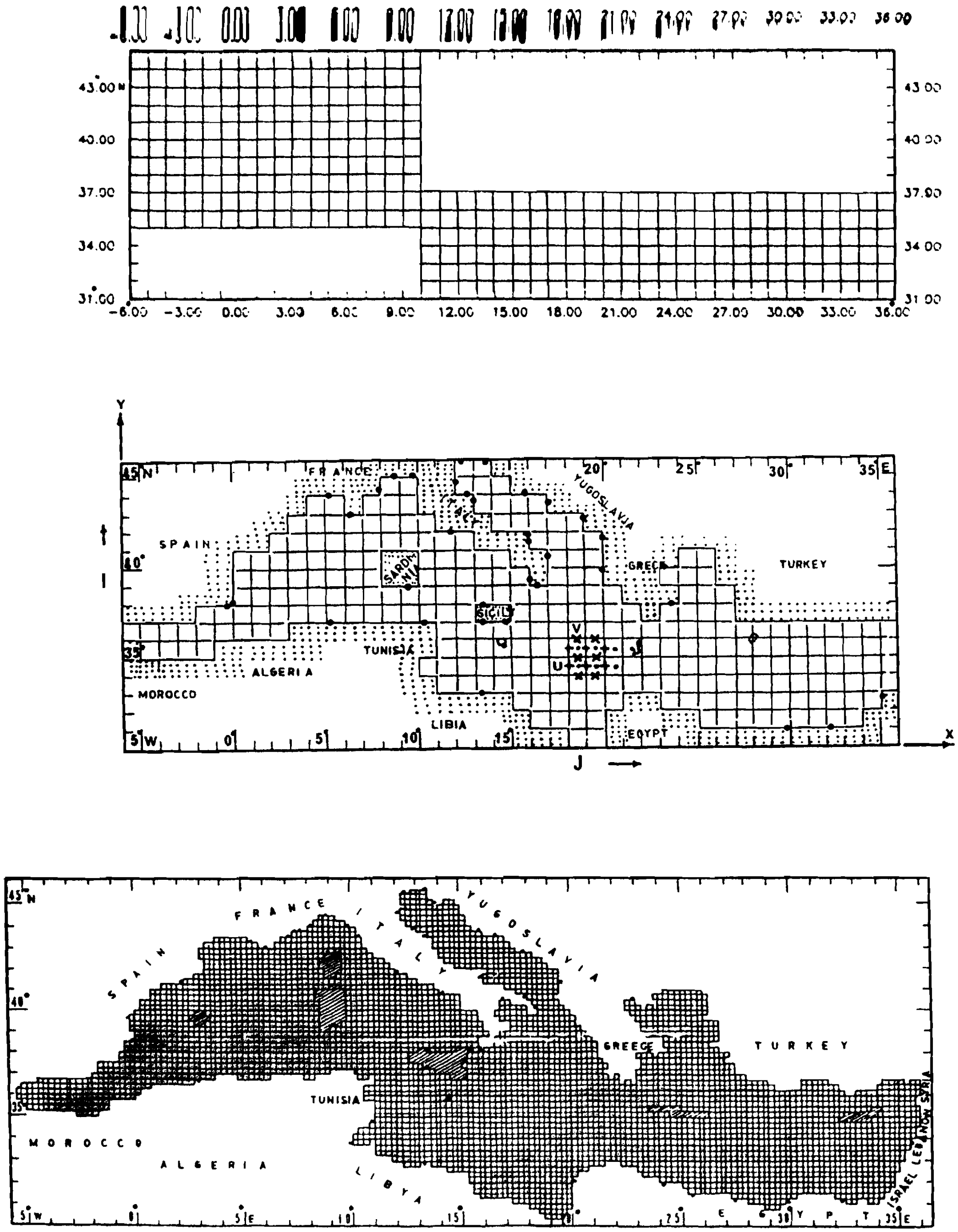

Figure 2: The sea with different shapes and different grid sizes.

MATHEMATICAL CONSIDERATIONS:

The integrated hydrodynamical differential equations over the whole water column have been taken as follows:

$$\frac{\delta \zeta}{\delta t} + \frac{\delta (Hu)}{\delta x} + \frac{\delta (Hv)}{\delta y} = 0 \qquad \ldots\ldots (1)$$

$$\frac{\delta u}{\delta t} - fv + ku + g\frac{\delta \zeta}{\delta x} - X = 0 \qquad \ldots\ldots (2)$$

$$\frac{\delta v}{\delta t} + fu + kv + g\frac{\delta \zeta}{\delta y} - Y = 0 \qquad \ldots\ldots (3)$$

where:

- x,y :cartesian co-ordinates in the east and north direction respectively,
- t : time,
- ζ : water elevation of the sea surface,
- u,v :components of the depth mean current in x & y directions respectively,
- H : total water depth,
- f : Coriolis parameter,
- k : coefficient of bottom friction in the linear form,
- g : acceleration of the earth's gravity,
- X,Y : the components of the tide - producing force in east and north directions respectively.

To solve such equations, the initial and boundary conditions were introduced:

i) Initial conditions:

The tidal motion was suggested to start from rest;

$$u = v = 0 \quad \text{at} \quad t = 0 \qquad \ldots\ldots (4)$$

ii) Boundary conditions:

At the boundary, the normal component of the depth mean current has to vanish i.e. $u = 0$ along the longitudinal boundary and $v = 0$ along the lateral boundary, or generally,

$$V_n = 0 \quad \text{at } H = 0 \qquad \ldots\ldots (5)$$

iii) Bottom friction:

In order to damp growing of waves with time, bottom friction was taken into account which might be considered either as quadratic or linear form , i.e.:

$$r\,u\,(u2 + v2)^{1/2}\ /H \quad \text{or } ku \quad \text{in the } x\text{-direction,}$$
$$r\,v\,(u2 + v2)^{1/2}\ /H \quad \text{or } kv \quad \text{in the } y\text{-direction} \qquad ..(6)$$
$$\text{with} \quad r = 10^{3} \qquad \text{and} \quad k = 10^{-6}\ sec^{-1}$$

NUMERICAL SOLUTION:

To solve the hydrodynamical and continuity equations (1-3) numerically, a finite difference scheme with a grid system as given below was used:

i) Grid system:

The grid system was constructed such that each grid has a u- point on the y-directed sides and denoted by a (+) sign, a v- point on the x- directed sides and denoted by a (x) sign and a ζ - point at the middle of the grid. The water elevation as well as the components of the depth mean current u and v were then computed step by step at each of ζ -, u- and v- points respectively (Fig. 3).

ii) The difference scheme:

A relatively simple explicit finite difference scheme is employed to evaluate $\zeta(i,j)$, $u(i,j)$ and $v(i,j)$ at time $t+\Delta t$ from the known values already computed at time t with forward time differences and central differences for all space derivatives as indicated below:

$$\zeta(i,j,t+\Delta t) = \zeta(i,j,t) - 0.5 * \Delta t * [\ ((H(i,j)$$
$$+H(i,j+1)) * u(i,j,t) - (H(i,j) + H(i,j-1))$$
$$* u(i,j-1,t))/\Delta x + ((H(i,j) + H(i+1,j)) * v(i,j,t)$$
$$-(H(i,j) + H(i-1,j)) * v(i-1,j,t))/\Delta y\ ] \quad .....(7)$$

$$u(i,j,t+\Delta t) = u(i,j,t) + \Delta t * [0.25 * f(i) * (v(i,j+1,t)$$
$$+ v(i,j,t) + v(i-1,j+1,t) + v(i-1,j,t)) - g/\Delta x$$
$$* (\zeta(i,j+1,t+\Delta t) - \zeta(i,j,t+\Delta t)) - k$$
$$* u(i,j,t) + X(i,j)] \quad .....(8)$$

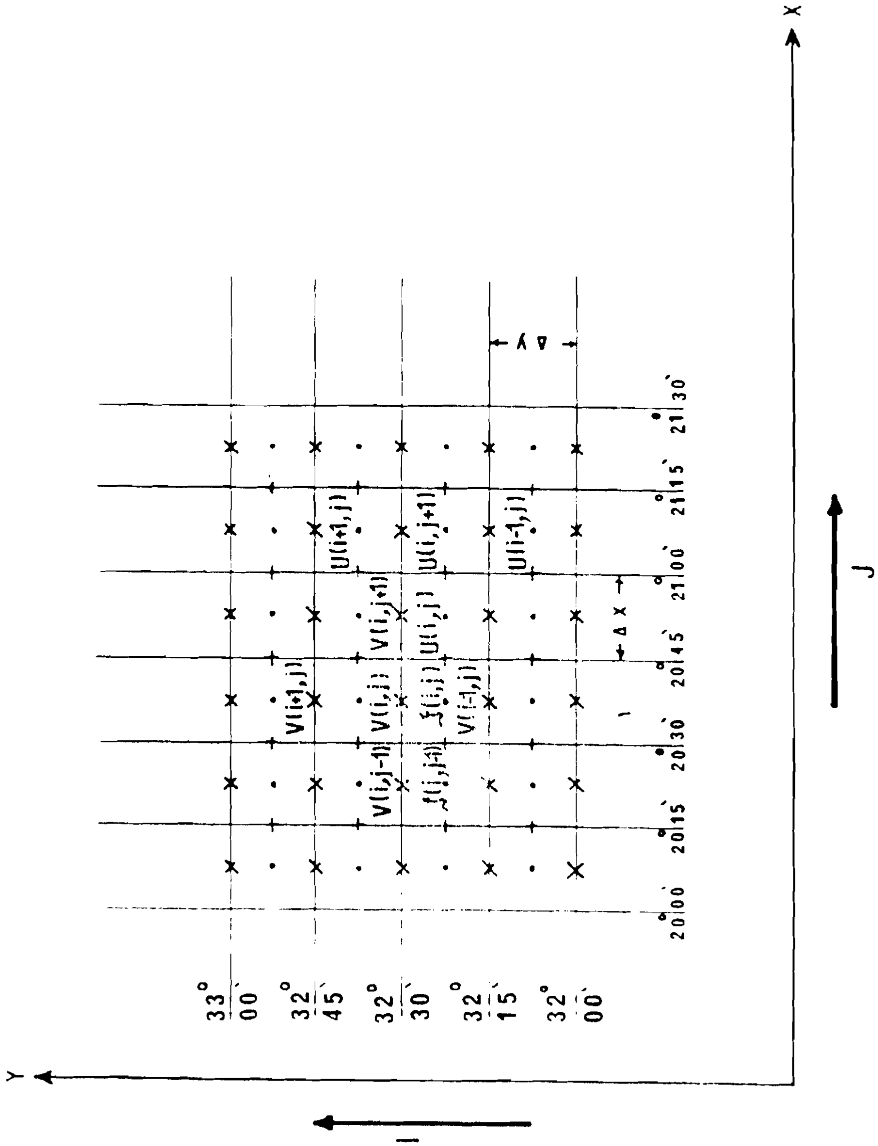

Figure 3: The grid system.

$$v(i,j,t+\Delta t) = v(i,j,t) + \Delta t[-0.25 * f(i) * (u(i+1,j,t)$$

$$+ u(i+1,j-1,t) + u(i,j,t) + u(i,j-1,t))$$

$$g/\Delta y\ (\zeta(i+1,j,t+\Delta t) - \zeta(i,j,t+\Delta t)$$

$$- k * v(i,j,t) + Y(i,j)] \quad \ldots\ldots(9)$$

The initial and boundary conditions were also expressed as follows:

$$\zeta(i,j,t) = u(i,j,t) = v(i,j,t) = 0 \quad \text{at } t = 0 \quad ..(10)$$

and

$u(i,j,t) = 0$ at each u-point on a y-directed boundary ,

$v(i,j,t) = 0$ at each v-point on a x-directed boundary ..... (11)

iii) Stability conditions:

The Friedriches-Lewy Criterion for the stability of a simple wave is given by:

$$\Delta t < \Delta x / (2gH_{max})^{1/2} \quad \text{for } k = f = 0 \quad (12)$$

$$\text{and } \Delta t < k / f^2 \quad \text{for } f \neq 0 \quad (13)$$

These relations were applied to estimate the time interval for each case considered during the present study:

1- The first case, with grid system of mesh size 1° * 1° ,
Δx = 90.6 km ,

H = 500 m and

Δt < 900 sec ,

accordingly Δt was taken as 621 sec = 10' in lunar time

2- The second case, with grid system of mesh size:

a) 1° * 1° :

Δx = 90.6 km ,

H max $\simeq$ 4200 m and

$t < 320$ sec ,

accordingly t was taken as 207 sec = 10/3' in lunar time.

b) 15` * 15` :

$x = 22.65$ km.,

H max $\simeq$ 4200 m and
$t < 80$ sec ,

accordingly,t was taken as 62.12 sec = 1' in lunar time. The time incrementt was taken in fraction of a lunar hour to make the period as integer number of time steps.

The model reached the stability condition after running the program five complete tidal cycles.

RESULTS AND DISCUSSION

The Mediterranean is a complicated sea in its irregular boundaries and bottom configuration. Accordingly, their corresponding impact on the tidal motion and generally on the water circulation in the Mediterranean is assumed to be so strong.

The present developed model, which is mainly driven by the potential tidal forces was primarily examined to calculate the M2-independent tide in two rectangular basins (of mesh size 1° X 1°) connected to each other through a narrow strait. Such type of structure is nearly similar in configuration to the Mediterranean. The model was then used to calculate the M2-independent tide in the sea with nearly its real boundaries and depths using grid systems of mesh sizes: 1° X 1° and 15' X 15' respectively. The bottom friction was assumed as 10^{-6} sec^{-1}.

i) Two rectangular basins:

The water depths in the two basins were assumed to be constant (500 m) and the opening between the two basins as 2° width. Figure (4) shows the co-tidal lines of equal amplitudes in centimeters and the co-range lines in hours as the Moon transits the equator at Greenwich.

The patterns indicate the presence of three nodal lines, one of which is transformed by the rotation of the earth into a contra solem amphidromy (anticlockwise-direction) which occupies the western basin. The co-ranges are nearly ellipses around the amphidromic point which is nearly located at the center of the basin. The oscillations in the western basin appear as a standing wave oscillating in the longitudinal direction with establishments of 3h and 9h.

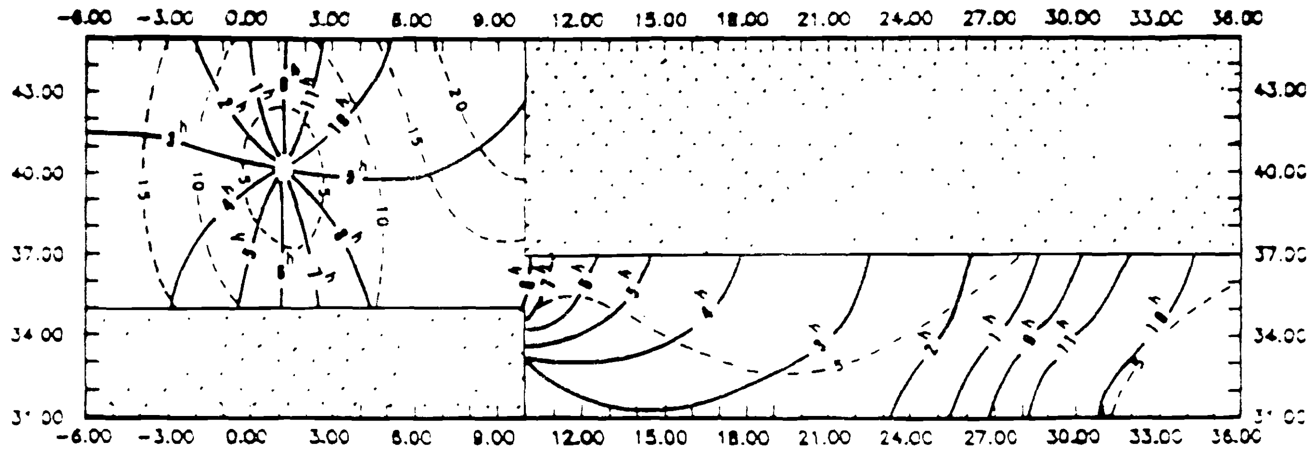

Figure 4: M2- Independent Tide in the Mediterranean Sea as consisting of two connected rectangular basins with constant depth of 500 m and grid size 1° X 1°. The co-ranges are in cm, and the co-tidal lines correspond to lunar hours of high tide after lunar-transit at Greenwhich.

In the eastern basin two nodal lines were produced which described a longitudinal motion propagating along the basin. The co-ranges in the western basin are relatively greater than that in the eastern basin.

ii- a- Real boundaries and mesh size 1° X 1° :

In this case, the depths were averaged over each grid and allocated at its center. It is clear from Fig. 5 that the Mediterranean is consisting of more than one basin. Each basin has its own length, width and depth which may influence separately its tidal characteristics.

The tidal motion in the Alboran Sea is very weak. The water rises and falls slowly with a maximum amplitude of about 4.0 cm. More than three nodal lines are generally observed in the Mediterranean, one amphidromy contra solem in the Tyrrhenian Sea, a degenerated cum sole amphidromy on the Tunisian coast and a nodal line in the Alboran Sea. The tidal motion in the eastern basin is nearly similar to that observed in the preceding case.

Great range values are observed in the Gulf of Gabes (more than 25.0 cm) and along the eastern boundary of the Mediterranean (more than 10.0 cm). Such pattern does not appear in the case of rectangular basins with constant depth of 500 m. The tidal ranges in the western basin are relatively lower than that observed in the above mentioned case. Across the Adriatic, a nodal line also exists and the water level changes gradually northwards. There is a phase difference of about 9 hours between the occurrence of high tides at the mouth of the Adriatic Sea and its northern end. The tidal ranges on the eastern side are generally higher than that on the western side. A phase difference of about 6 hours was found between the occurrence of high water in each of the two consequent seas: Levantine and Ionian; Levantine and Aegean; Levantine and southern part of the Adriatic. This indicates that while the water falls in the Levantine, northern part of the Adriatic and western basin of the Mediterranean, it rises in the Ionian, Aegean, southern part of the Adriatic, and the Gulf of Gabes. Generally, the results obtained in this case is much better than that obtained with constant depth and they are more or less in agreement with observations.

ii- b- Real boundaries and mesh size 15'X 15' :

In order to get more confirmative results comparable with observations, a grid system with high resolution mesh size of 15'X 15' was used. The basic array comprises 10816 elements with a dimension of I= 64 and J= 169. The time step of iteration processes was taken as 62.1 seconds to fulfil the stability criteria.

By using the new grid system more precise results were obtained everywhere. Relatively high ranges were observed in the eastern basin, relative to that in the western, particularly in the Gulf of Gabes (Libia) with a maximum range of

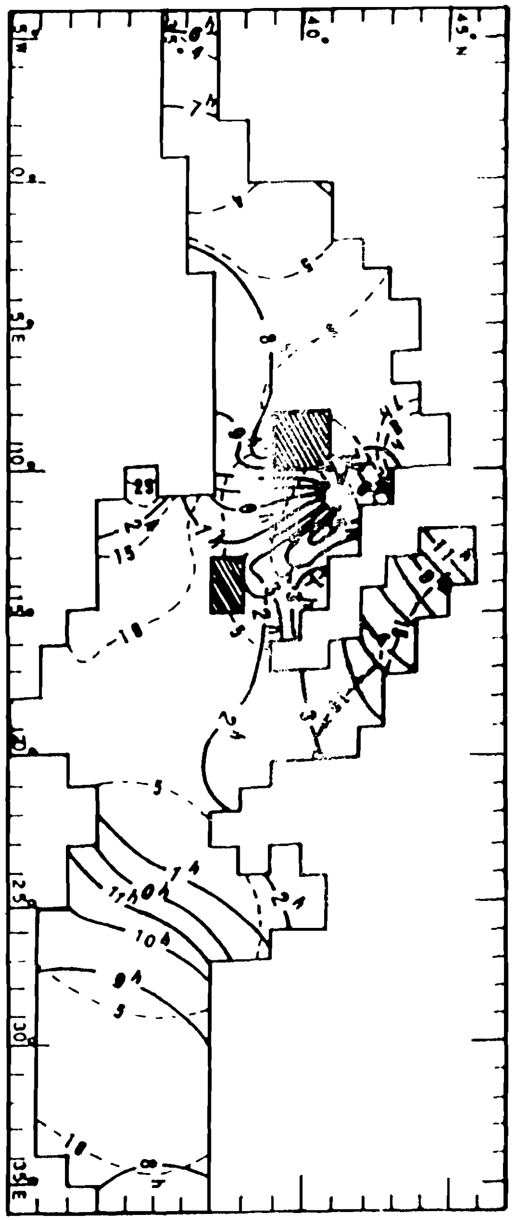

Figure 5: M2- Independent Tide in the Mediterranean Sea with its real boundaries and depths and grid size 1° X 1°. The co-ranges are in cm, and the co-tidal lines correspond to lunar hours of high tide after lunar-transit at Greenwich.

about 150.0 cm, in the Levantine of about 20.0 cm, in the Aegean Sea of about 30.0 cm and in the Adriatic of about 50.0 cm (Figs 6&7). The western basin was occupied by a degenerated amphidromy rotating in a clockwise direction.

A nodal line was located in the Strait of Messinia. The co tidal lines there were very close to each other indicating a sudden change in the water level between the Tyrrhenian and the Ionian Seas. In Sicily Strait there was an amphidromy contra solem which might result either from the rotation of the earth or from the superposition of the incident waves and the reflected ones either on the Libian Coast or on the eastern side of the Levantine.

A nodal line was also located between Egypt and Turkey characterizing the Levantine and Ionian Seas with establishments of nearly 3^h & 9^h respectively. The Aegean Sea has nearly same phases with an establishment of about 3^h. Finally, a contra solem amphidromy appeared in the northern part of the Adriatic indicating that there is a limit for the number of the grids which permits the formation of the amphidromy. The co-ranges appear like ellipses around the amphidromic point with values on the eastern side which is higher than that on the western. Generally speaking, the results obtained in the last case are more confirmable with observations (Table 1). More studies are essentially required to get more informations about the influence of boundaries, depth, friction and the rotation of the earth on the significance of the results.

SUMMARY AND CONCLUSIONS

The Mediterranean was assumed to be separated from the Atlantic Ocean by closing it at Gibraltar. Its water was only driven by the potential tidal forces. A numerical model with a finite difference scheme was established and then examined to calculate the M2- Independent tide in the sea, which was considered as composed of two rectangular basins with a constant depth of 500 m and then with its real boundaries and depths. Co-ranges and co-tidal lines of the different cases have been presented in charts.

The model with rectangular basins gave a descriptive idea about the type of tidal motions in closed basins. Actually more information are required to be estimated to discuss the reasons of the abrupt changes in the tidal ranges from one basin to another. Meanwhile, the model with real depths showed better results particularly with grid size 15'X15'. Generally, it is concluded the following:

1- The water depth distributions (bottom topography) has a great influence on the tidal motion as revealed from the constant depth patterns in comparison with the real depth patterns.

2 The coastal boundaries have minor influences while the dimensions of the basins have a great influence on the tidal motion.

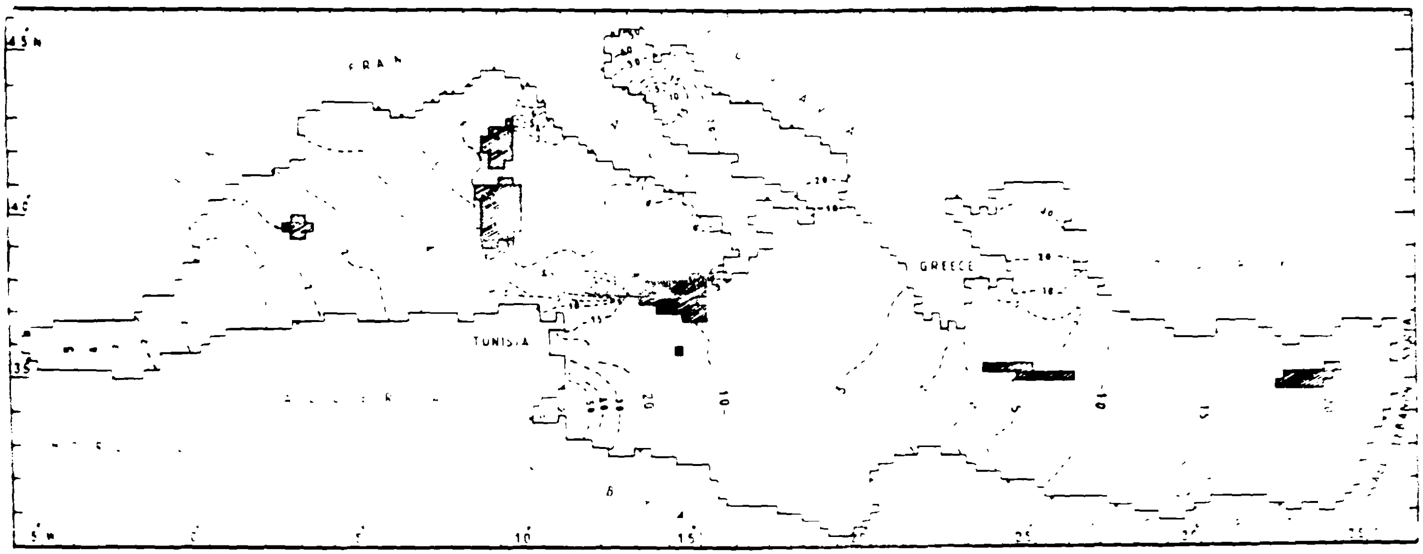

Figure 6-a: M2- Independent Tide in the Mediterranean Sea with its real boundaries and depths and grid size 15' X 15'. The co-ranges are in cm, and the co-tidal lines correspond to lunar hours of high tide after lunar-transit at Greenwich.

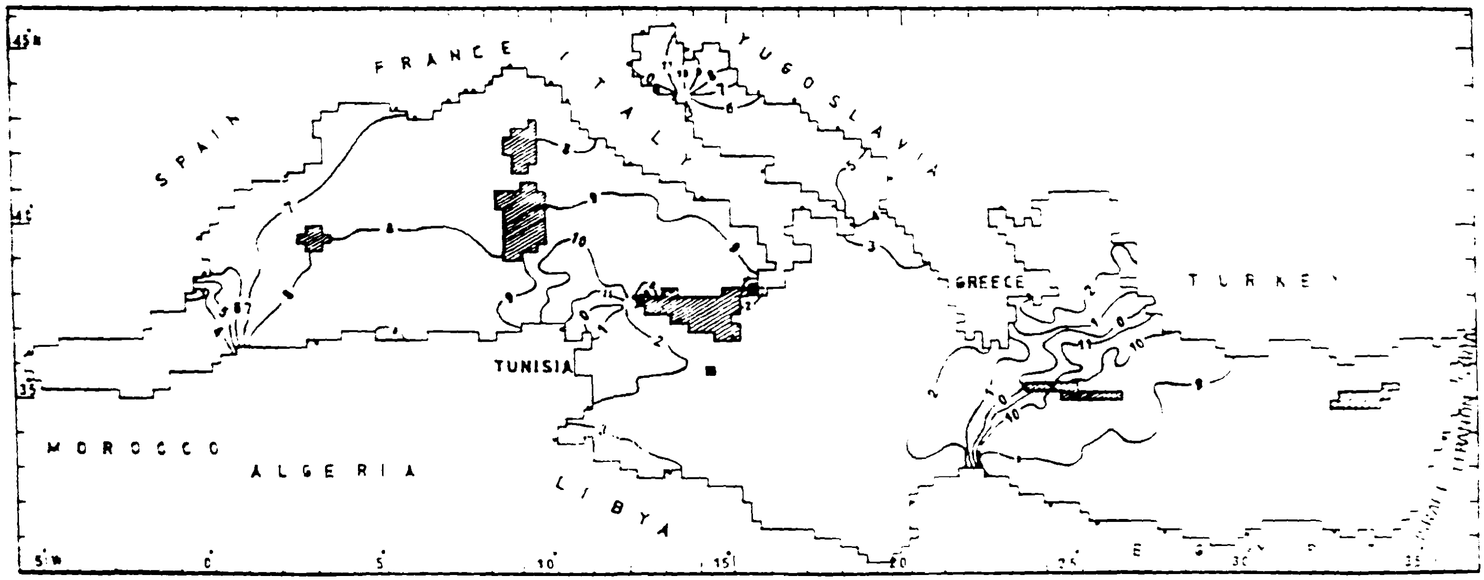

Figure 6-b: M2- Independent Tide in the Mediterranean Sea with its real boundaries and depths and grid size 15' X 15'. The co-ranges are in cm, and the co-tidal lines correspond to lunar hours of high tide after lunar-transit at Greenwich.

Table (1): Amplitudes (cm) and phases (in degrees, of high tide after lunar transit at Greenwich) of computed M2-Independent Tides in the Mediterranean Sea as consisting of two connected rectangular basins as well as with its real boundaries and grid sizes of 1° x 1° and 15' x 15'.

STATION	ABB.	Lat. N	Long.	TWO-BASINS H=500 m		REAL DEPTHS 1° x 1° r=10-		REAL DEPTHS 15'x15'	
				A(cm)	∅	A(cm)	∅	A(cm)	∅
		° '	° '		°		°		°
GIBRALTAR	GI	36 15	05 20 W	18.6	112	04.3	177	05.3	108
ALGER	AG	37 00	03 00 E	08.4	234	05.2	246	01.7	256
TUNIS	TU	37 00	10 10 E	05.7	229	10.1	028	09.1	--
SFAX	SF	34 35	10 45 E	01.2	210	25.6	083	84.0	--
GABES	GB	33 50	10 05 E	01.5	119	23.8	066	164.9	102
TRIPOLI	TL	33 00	13 15 E	02.9	086	15.0	054	21.8	088
BANGHAZI	BG	32 10	20 20 E	04.3	079	07.5	046	04.9	066
TUBRUQ	TQ	32 10	24 00 E	02.8	046	02.1	316	07.0	268
SALOM	SA	31 35	25 10 E	02.4	029	03.4	291	09.9	271
ERSA MATROH	MM	31 20	27 20 E	02.4	341	04.7	268	13.0	264
EL-HAMRA	HA	30 55	28 45 E	--	--	--	--	--	--
ALEXANDRIA	AX	31 10	29 50 E	03.6	309	06.1	256	15.0	258
PORT-SAID	PD	31 15	32 20 E	05.9	289	09.5	246	22.8	262
BEIROT	BE	33 50	35 30 E	06.7	278	10.4	243	20.8	256
SALONIKA	SL	40 35	22 55 E	--	--	08.8	067	35.4	076
ATHENS	AH	38 00	23 40 E	08.0	083	04.8	047	04.3	060
RHODES	RH	36 22	28 05 E	05.3	057	02.8	307	12.9	280
DURRES	DR	41 17	19 25 E	--	--	10.9	106	20.9	146
DUBROVNIK	DU	42 37	17 55 E	--	--	11.8	120	23.5	152
SPLIT	SP	43 30	16 25 E	--	--	16.0	184	25.6	172
SIBENIK	SI	43 40	15 55 E	--	--	16.3	198	23.4	181
ROVINJ	RO	45 05	13 40 E	--	--	09.2	333	38.5	329
TRIESTE	TS	45 40	13 45 E	--	--	09.2	333	49.3	338
VENEZIA	VE	05 25	12 20 E	--	--	09.2	359	50.9	351
RAVENNA	RA	44 30	12 18 E	--	--	09.2	359	34.6	357
PESARO	PS	43 55	12 50 E	--	--	07.8	336	26.7	360
ANCONA	AN	43 37	13 30 E	--	--	13.7	247	02.3	040
MANFRE DONIA	MF	41 35	15 55 E	--	--	08.6	115	23.9	153
BRINDISI	BR	40 37	17 55 E	--	-	--	--	19.1	151
OTRANTO	OT	40 10	18 30 E	--	--	--	--	08.0	124

Table (1) cont.

STATION	ABB.	Lat. N	Long.	TWO-BASINS H=500 m A(cm)	TWO-BASINS H=500 m ø	REAL DEPTHS 1o x 1o r=10- A(cm)	REAL DEPTHS 1o x 1o r=10- ø	REAL DEPTHS 15'x15' A(cm)	REAL DEPTHS 15'x15' ø
TARANTO	TR	40 25	17 15 E	--	--	07.5	082	06.5	079
GALLICO	GL	37 55	15 45 E	--	--	07.8	056	07.3	073
REGGIO CALABRIA	RC	38 05	15 40 E	--	--	02.4	093	07.3	073
PUNTAFARO	PF	38 15	15 40 E	--	--	02.4	093	03.2	044
NAPOLI	NA	40 50	14 15 E	--	--	01.4	077	04.3	262
CIVITA VECCHIA	CI	42 00	11 50 E	--	--	03.1	144	01.9	229
LIVORNO	LI	43 30	10 20 E	--	--	--	--	06.6	220
LA-SPEZIA	LS	44 05	09 50 E	24.4	281	08.9	218	07.0	217
GENOVA	GE	44 20	08 55 E	24.4	281	08.7	218	06.6	214
IMPERIA	IM	43 55	08 00 E	23.4	283	08.6	218	06.0	221
MONACO	MO	43 45	07 25 E	21.6	287	06.5	233	05.8	223
NIECE	NI	43 40	07 15 E	21.6	287	06.5	233	05.5	223
CANNES	CN	43 35	07 05 E	21.6	287	06.5	233	05.7	225
TOULON	TO	43 05	06 05 E	19.5	291	06.8	221	04.8	220
MARSEILLE	MS	43 15	05 20 E	17.1	297	06.9	216	05.1	209
BARCELONA	BA	41 20	02 10 E	09.9	332	05.4	217	03.1	194
VALENCIA	VA	39 30	00 20 W	--	--	04.3	220	01.0	168
ALICANTA	AL	38 20	00 30 W	--	--	03.7	219	01.1	134
CAGLIARI	CG	39 10	09 10 E	--	--	04.8	238	06.0	284
PORTO EMPEDOCLE	PE	37 15	13 30 E	--	--	10.3	047	14.9	066
CAPO PASSERO	CP	36 37	15 10 E	--	--	--	--	08.2	082
CATANIA	CA	37 30	15 05 E	--	--	09.7	053	09.3	056
TAORMINA	TA	38 00	15 25 E	--	--	--	--	03.2	044
GANZIRRI	GA	38 13	15 38 E	--	--	07.1	057	03.2	044
MESSINIA	ME	38 10	15 35 E	--	--	07.1	057	03.2	044
MILLAZZO	MI	38 17	15 15 E	--	--	02.3	056	03.1	300
PALERMO	PA	38 07	13 20 E	--	--	01.2	092	02.6	282
MALTA	MA	35 55	14 35 E	18.6	145	11.6	049	15.0	064

3- Instead of getting a nodal line in each basin, the nodal line is sometimes transformed into an amphidromic system which may be related either to the earth's rotation and wave reflection or to the depth distributions. The occurrence of an opening between two basins has also a certain impact on the wave motion and hence on the tidal pattern.

4- The tides in the Adriatic and Aegean Seas are mainly of co-oscillating type.

5- The higher resolution of the grid system increases the precession of the results obtained from the model.

6- The Mediterranean has generally low amplitudes accept at some localities.

7- The model has succeeded to estimate the independent M2 - tide in the Mediterranean although more information are required to understand the impact of the boundaries, friction and depth configurations on the tidal motion.

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