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INTRODUCTION

Study of the current regime and water circulation in the Mediterranean Sea has been increasing significantly during the last years. Up to the present time, the relatively small amount of direct current observations in the open sea does not permit the Mediterranean investigators to set up a general pattern of circulation. Most of the known patterns of Mediterranean circulation have been obtained only through indirect methods and computations: by constructing T-S diagrams, and sections of horizontal and vertical distributions of some physical and chemical properties of sea water such as salinity, temperature, and oxygen (Nielsen, 1912; Lacombe and Tchernia, 1958, 1960; Miller, 1963; Moskalenko and Ovtchinnikov, 1965); by the so-called »core method« of Wüst (1960, 1961), by the »dynamical method« (Ovtchinnikov and Feodosyev, 1965; Ovtchinnikov, 1966); and by the method of the total water flux (Moskalenko, 1968).

Each of the above approaches has its relative advantages and shortcomings. A brief review of some of the methodologies cited above will be given. The basis for a model which will apply to the oceanographic conditions of the Mediterranean Sea and in particular to the eastern basin is the concern of this paper.

THE NEED FOR A NUMERICAL MODEL

The various indirect methods applied to obtain a general pattern of water circulation in the Mediterranean Sea cannot satisfactorily give a complete understanding of the whole complex of the circulation problem.

The information obtained from different distributions of the physical and chemical properties give only a general picture of the circulation system. One, for example, can identify the different water masses, their characteristics and movements, etc. Such distributions in the Mediterranean Sea could clearly indicate the existence of the two opposite superimposed currents: the upper or Atlantic current, moving toward the east and the lower, of Mediterranean origin, moving toward the west. It is difficult, however, to determine some dynamical characteristics of these two layers including the exact line of interface between them and their velocities, based on the distribution of hydrographic characteristics.

The »core method« of Wüst (1960, 1961) permits one to follow the spreading and mixing processes of the main water masses, which are characterized by intermediate maxima or minima of salinity, temperature and oxygen, along curved core layers. Thus the mean, steady deep circulation can be delinated in the whole expanse of the sea. Meanwhile, the application of the »core method« in the Mediterranean Sea has met some criticism, and Ovtchinnikov (1965) showed that the information based on the distribution of maximum and minimum salinities, the main indicators in the core method, were not confirmed by the deep direct current measurements made during the 6th Mediterranean Expedition of the Soviet R/V *AKADEMIK VAVILOV*. Thus the general pattern of circulation obtained by the core method should be taken with more caution. This consequently leads to a preference for the dynamical method.

The dynamical method, on the other hand, has a major limitation in the selection of the so-called »level of no motion«. The existence of such a level is itself still problematic and questioned. The first dynamic topography charts for the whole of the Mediterranean Sea were obtained for the surface and the 500 m level relative to the 1000-decibar surface for both summer and winter seansons by Ovtchinnikov and Feodosyev (1965). It is clear, however, that on evaluating the Mediterranean circulation according to these charts, it is necessary to keep in mind the fact that they reflect only the geostrophical currents, while the pure drift currents are not, of course, considered. Therefore, the dynamical computations of currents cannot give full information about the circulation regime and the water structure in the Mediterranean.

The numerical calculation of the stationary wind currents in the Central and Eastern Mediterranean basins was carried out by Moskalenko (1968) thus solving the problem of the total water flux function. This concept was originally used by Shtockman (1946). However, in studying the wind circulation based on the method of total water flux function, the vertical component of the current is ignored. This is due to the fact that all of the equations are integrated from the surface, where the vertical component of velocity is negligibly to the baroclinic depth and where the motion is presumably disappearing. In other words, the distribution of the vertical component of current velocity obviously does not effect the total water flux function used to estimate circulation.

Moreover, it is quite obvious that any attempt to solve the circulation problem analytically would naturally face some serious mathematical difficulties. This is because of the non-linearities involved in the system and the necessity for taking into consideration all the forces generating or dissipating the water movements, and the effect of horizontal and vertical exchange processes. In some areas, the effect of bottom topography must be considered as well. The theoreticians usually find themselves obliged to approximate the problem or to ignore the role of some factors in order to simplify analytical solutions. Hence their conclusions are idealized and far from natural.

It is obvious, therefore, that a numerical model, avoiding the shortcomings of other methods, is needed to treat the problem of the general Mediterranean circulation. Such a model should take into consideration all the physical and boundary conditions so that the results obtained through applying this model would more or less represent the natural situation confirmed by observations. It is now possible to construct such a model using modern electronic computers and computation technology.

THE SUGGESTED MODEL

The numerical treatment of Bryan and Cox (1967) and the method used by Sarkisian (1966, 1967) to obtain the general circulation using the observed density and wind (or atmospheric pressure) fields with an account for the so-called »joint effect of baroclinicity and bottom relief« of Sarkisian and Ivanov (1971) serve as the main basis of the approach taken here in treating this problem. The advantages of such an approach are:

1) The real bottom relief of the sea is taken as the lower boundary of the fluid. Thus the uncertainty in the choice of the level of no motion of the dynamical method is excluded.
2) The effect of coasts, islands and bottom relief is considered.
3) The method enables, when needed, calculation of not only the horizontal components of velocity, but also the vertical component.

THE PHYSICAL STATEMENT OF THE MODEL

The physical nature of the model is the following. Consider an oceanic basin of arbitrary form and arbitrary bottom relief. If part of the wall of the basin is an open boundary, assume that the normal mass flux is given there in the basin the density field is also given as an arbitrary function of the coordinates. At the surface of the basin the wind stress is given. It is required to calculate the current velocity and other hydrodynamical characteristics. The sphericity of the Earth is taken into account by the β — effect.

For solving this problem, the following system of equations is used:

Equations of motion:

$$\nu \frac{\delta^2 u}{\delta z^2} + fv = \frac{1}{\rho_o}\frac{\delta p}{\delta x} + u \frac{\delta u}{\delta x} + v \frac{\delta u}{\delta y} - A_e \cdot \triangle u,$$

$$\nu \frac{\delta^2 v}{\delta z^2} - fu = \frac{1}{\rho_o}\frac{\delta p}{\delta y} + u \frac{\delta v}{\delta x} + v \frac{\delta v}{\delta y} - A_e \cdot \triangle v.$$

Equation of continuity:

$$\frac{\delta u}{\delta x} + \frac{\delta v}{\delta y} + \frac{\delta w}{\delta z} = 0,$$

Hydrostatic equation:

$$P = \rho_o g \zeta + g \int_o^z \rho \, dz$$

where

ν = coefficient of vertical turbulent viscosity,
A_e = coefficient of horizontal turbulent viscosity,
u, v, w = current velocity components in the x, y, z directions taken toward the east, the north and vertically downward.
P = the pressure field,
ρ = the density field,
ρ_o = average density value,
f = 2 ω Sin φ is the Coriolis parameter
ω = the angular velocity of the Earth's rotation and
φ = is the geographical latitude.

The boundary conditions *at the free sea surface* are the following:

$$Z = -\zeta(x,y), \quad P = Pa \text{ (atmospheric pressure).}$$

$$\rho_o \nu \frac{\delta u}{\delta z} = -\tau x \ ; \ \rho_o \nu \frac{\delta v}{\delta z} = -\tau y \ ;$$

$$w = O$$

where τx and τy are the tangential components of wind stress. The boundary conditions at the bottom are: Z = H (x, y); H is the depth to bottom, the non-slippery condition is taken as

$$u = v = w = o$$

For open boundaries the quasigeostrophic method to estimate the water flux is used, specificatlly the function:

$$\zeta^{(0)} = -\frac{1}{\rho_o} \int_o^H \rho \, dz$$

Evaluation of the order of magnitude of the different terms involved in such a system showed that for large scale oceanic circulation, the non-linear terms and effect of the lateral exchange could be neglected for first approximation without much change in the results. Then, solving the above system of equations with the given boundary conditions, the following expression for the horizontal components of the current velocity (u, v) was obtained:

$$u + iv = \frac{1}{\rho_o f}\left(i\frac{\delta p}{\delta x} - \frac{\delta p}{\delta y}\right) + \frac{\tau x + i\,\tau y}{\alpha\,\rho_o\,\nu(1+i)}\, e^{-\alpha z(1+i)}$$

$$- \frac{1}{\rho_o f}\left(i\frac{\delta PH}{\delta x} - \frac{\delta PH}{\delta y}\right) e^{\alpha (z-H)(1+i)}$$

where $\alpha = \sqrt{\omega \,\mathrm{Sin}\, \varphi / v}$ and P_{II} = the pressure at the bottom.

The pure drift current could be obtained from the expression:

$$u_d = \frac{1}{\rho_o f}\sqrt{\frac{\nu'}{\nu}}\left(\frac{\delta Pa}{\delta x}\,\mathrm{Sin}\,\alpha z - \frac{\delta Pa}{\delta y}\,\mathrm{Cos}\,\alpha z\right) e^{-\alpha z}$$

$$v_d = \frac{1}{\rho_o f}\sqrt{\frac{\nu'}{\nu}}\left(\frac{\delta Pa}{\delta x}\,\mathrm{Cos}\,\alpha z - \frac{\delta Pa}{\delta y}\,\mathrm{Sin}\,\alpha z\right) e^{-\alpha z}$$

where ν' is the coefficient of vertical turbulent viscosity of the air. Other expressions could be obtained for the vertical component of current velocity w and for the sea level function ζ. But since w and ζ are not to be discussed in the present paper, their expressions are not given here.

In the computations, a network of points in the Eastern Mediterranean basin, from the eastern boundary of the Mediterranean Sea to the 20°E meridian was considered. These points were taken at distances of half a degree of latitude and longitude (about 40 km apart). At each of these points, the pure drift current and the gradient (density) current were computed at 12 standard levels, 0, 10, 20, 50, 75, 100, 150, 200, 250, 300, 400, 500 m. The water structure in the Mediterranean Sea shows a strong stratification in salinity and temperature from the surface to a depth of about 500 m (Gerges, 1972). In almost all of the Mediterranean basins, the density varies very little below 500 m and hence the vertical density gradients are insignificant and could be considered equal to zero. Thus water above the 500 m level is considered baroclinic while that below it are homogeneous. The 500 m depth is taken here as the baroclinic depth, i.e., the lower limit of the baroclinic layer of water in the Mediterranean. The computations for the model extended only to the baroclinic depth. The coefficients v and $v_{,}$ were given the values 10^2 and 10^4 cm^2/sec respectively.

MATERIAL

The computations for the model are of the winter season. Oceanographic data used were those from several Mediterranean expeditions, including R/V *AKADEMIK VAVILOV* (1960—61), R/V *ATLANTIS* (1961—62), R/V *AKADEMIK KOVALEVSKY* (1970), R/V *CHELEKEN* (1971) and R/V *MUSSON* (1971). The bottom relief data were taken from Mikhaelov (1965) and Emery, Heezen and Allan (1966). Information about the atmospheric pressure field was obtained from the Russian Atlas of Physical-Geographical Data of the Mediterranean Sea (1957) and the Dutch Atlas »Middellandse Zee« (1957).

The criteria for the selection of the data to be used in constructing the model included:

1) Coverage of entire Eastern Mediterranean basin suitable for density field interpolation.
2) Synoptic to semisynoptic observations so that the inhomogenity due to the time difference is minimized. Although almost all of the data used were collected in different years, they were collected during the main winter months of January and February.
3) Reliable data to minimize doubt of the accuracy of the observations. Any single observation showing remarkable anomalities was excluded to avoid anomalous effects in the density and hence in the obtained velocity fields.

RESULTS AND DISCUSSION

The complete surface circulation pattern was obtained by computing separately the pure drift current, i.e., the current component driven only by wind, then the gradient component of currents followed by summation to obtain the total surface current. Figures 1, 2 and 3 represent the drift, gradient and total currents at the surface.

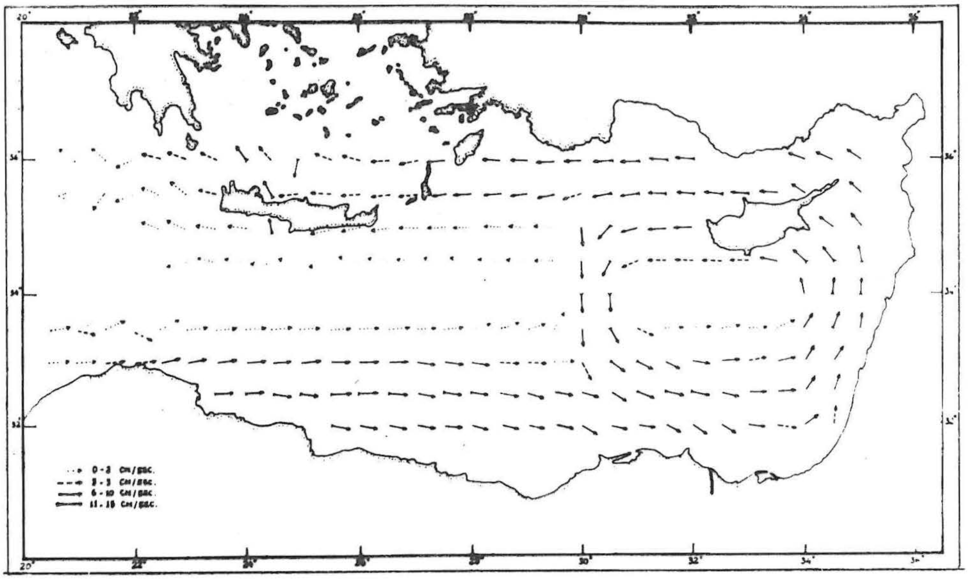

Fig. 1 — Drift current at the surface

As the drift current component weakens with depth, the total current was directly summed and given for the rest of the levels below the surface layer. Included here are only four levels, namely the 50, 100, 300 and 500 m levels and the circulation patterns are shown in Figures 4 through 7. The levels

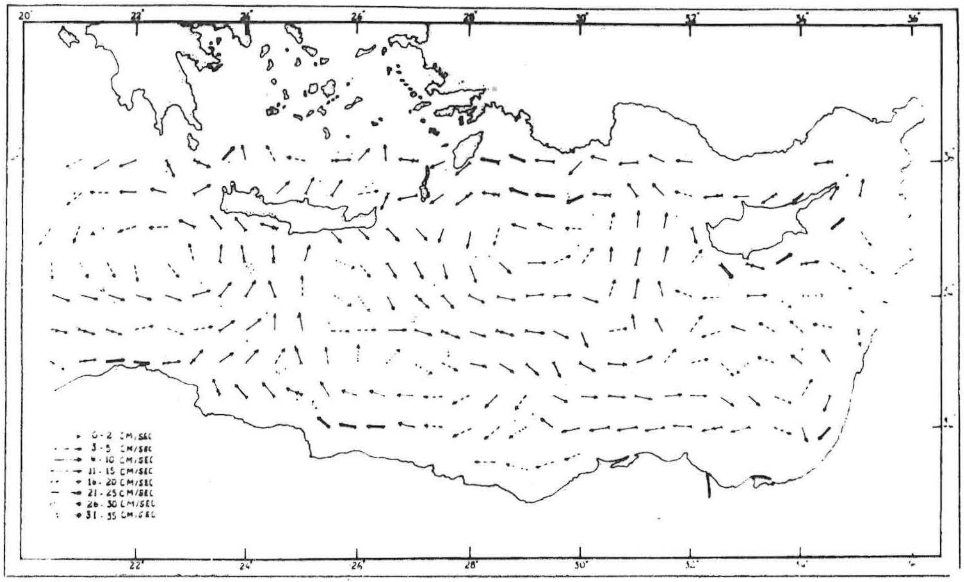

Fig. 2 — Gradient current at the surface

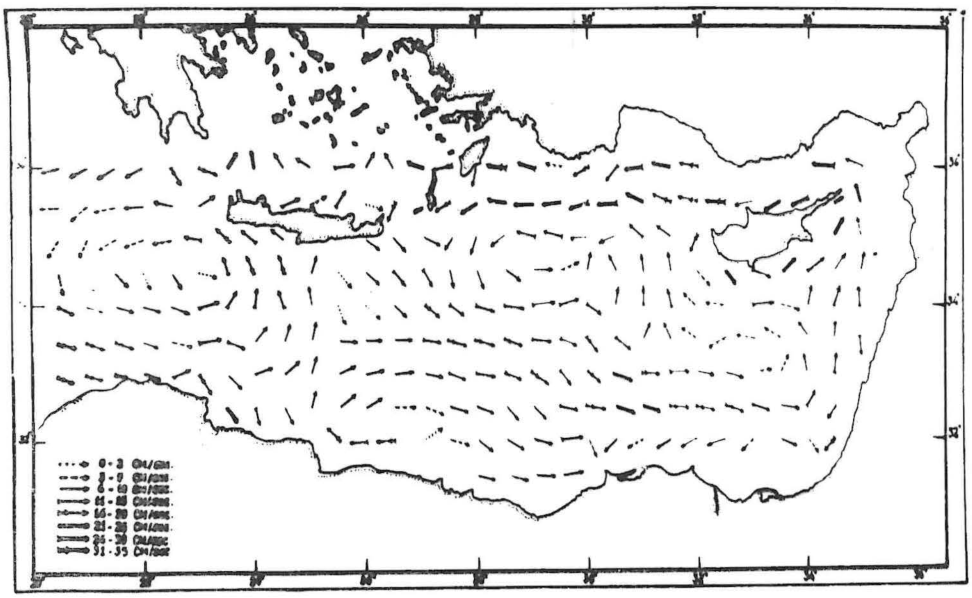

Fig. 3 — Total surface current.

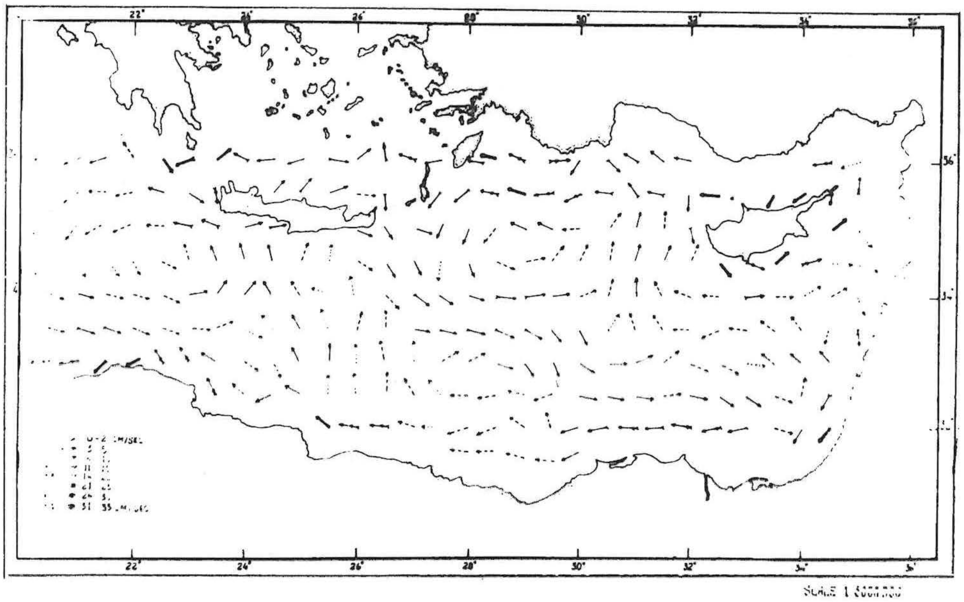

Fig. 4 — Total current at 50 m.

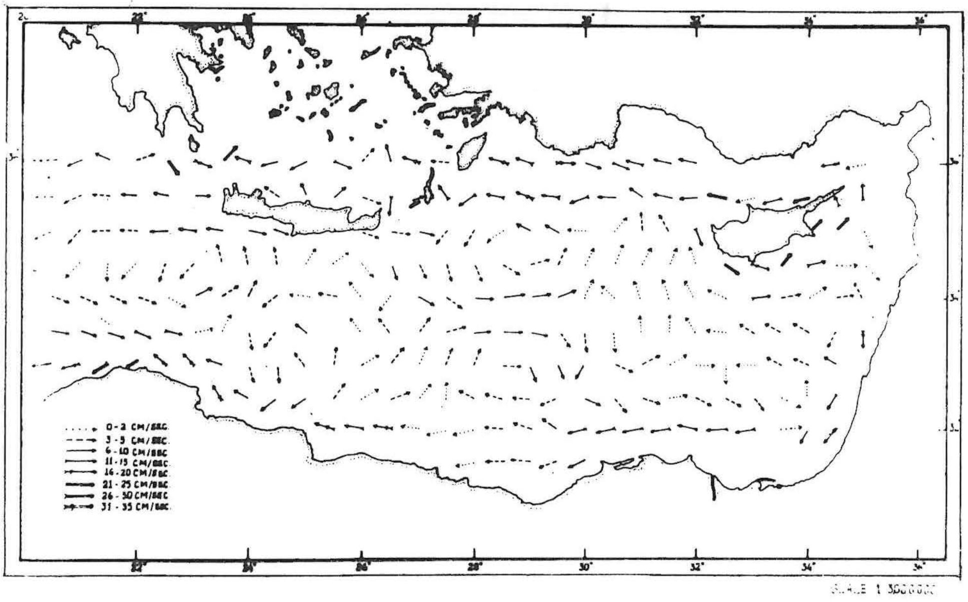

Fig. 5 — Current pattern at 100 m.

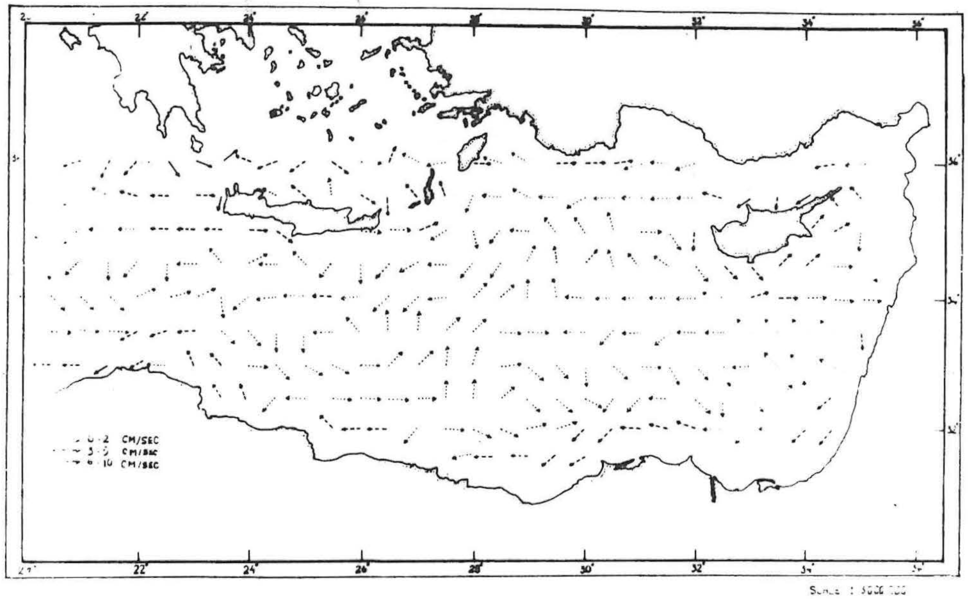

Fig. 6 — Current pattern at 300 m.

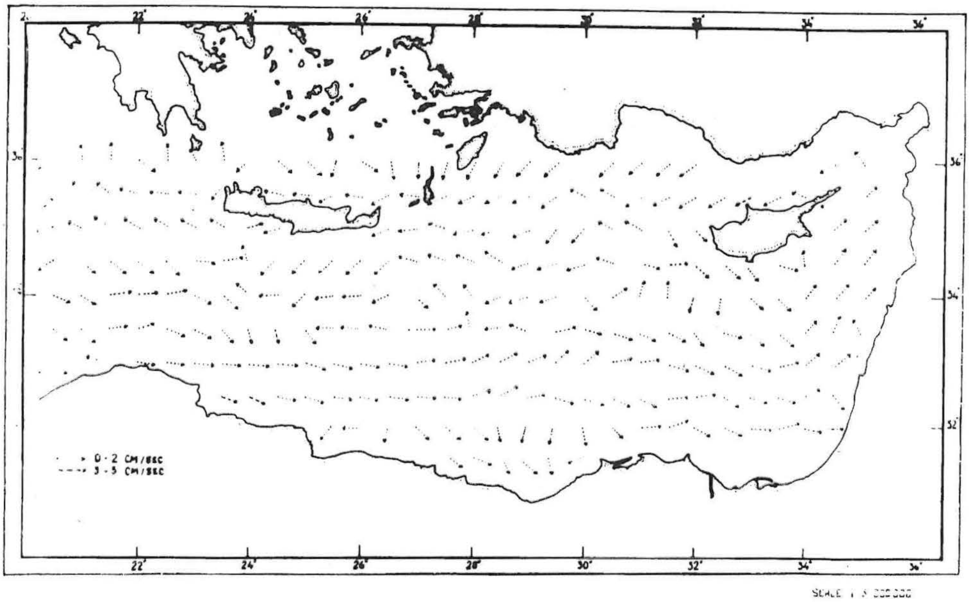

Fig. 7 — Deep circulation pattern at 500 m.

selected for representation here are assumed to represent the surface, the intermediate and the deep circulation patterns in the Eastern Mediterranean.

It is interesting to note that under given conditions, the gradient current is dominating the surface circulation and not the drift current, as might be expected. This leads to the conclusion that even at the surface, the water circulation in the Eastern Mediterranean is not mainly controlled by wind as previously thought. The computed velocity values of the total surface current range from 15 to 30 cm/sec, sometimes reaching 25 cm/sec near the coasts. The surface circulation has a general cyclonic direction. Three separate cyclonic gyres were obtained and clearly indicated: one to the southwest of Crete; the second in the central part of the basin covering the area between Crete and Cyprus to the south off the Turkish coast; and the third is located in the southeastern part of the basin. The existence of a unique anticyclonic gyre is also indicated and is found in the southern region of the central part close to the African coast.

One of the striking features is the intensification of current near the coasts and around the islands, where the current velocity always exceeds 20 cm/sec.

Below the surface level, the above mentioned features of circulation remain almost the same to the 100 m level. The velocity values, however, decrease noticeably with depth. This is to be expected due to the remarkable decrease of the pure drift component of current with depth.

Below the 100 m level, the distinct gyres generally weaken and some completely disappear including the anticyclonic gyre as shown in Figures 6 and 7. At the baroclinic depth (500 m) the circulation pattern becomes one big gyre, covering the whole basin and having a general cyclonic trend. The current velocities are much weaker, ranging from 2 to 5 cm/sec. This is clearly due to the very small density gradients observed at that level. This proves that in the eastern Mediterranean basin, the general circulation from the surface to the baroclinic depth has the same general cyclonic direction. Below the baroclinic depth, there are no pronounced density gradients and, hence, no remarkable change in the circulation pattern. Therefore, the circulation at that depth is assumed to be representative of the deep circulation in the Eastern basin. This leads to an additional conclusion that there is no reversed current in the deeper layers and that the general circulation in the Eastern Meditterranean from surface to bottom is unidirectional and has a general cyclonic character. Furter investigations of this type, using different conditions are planned for the future.

SUMMARY

A thermohaline circulation model in a baroclinic ocean is used to determine circulation at the surface, 50 m, 100 m, 300 m and 500 m. These levels are intended to represent the surface, intermediate and deep circulation patterns in the Eastern Mediterranean Sea. It is concluded that the general circulation from the surface to the baroclinic depth has the same cyclonic direction, is one-directional and that there is no reversed current in the deeper layers.

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REFERENCES

Anonymous, 1957. Atlas of physical geographical data of the Mediterranean Sea. Leningrad.

Bryan, K., and M. D. Cox, 1967. A numerical investigation of the oceanic general circulation. Tellus, *19* (1), pp. 54—80.

Emery, K. O., B. C. Heezen and T. D. Allan. 1966. Bathymetry of the Eastern Mediterranean. Deep Sea Res., *13* (2), pp. 173—192.

Gerges, M. A. 1972. Analogy in the oceanographic processes of the Mediterranean Sea and estuaries. Proc. Internat. Symp. Formation Deep Waters, Paris, Oct. 1972.

Lacombe, H. and P. Tchernia. 1958. Temperatures et salinités profondes en Mediterranée en periode d'ete. Étude préliminaire. Bull. Comm. Océanogr., Études Côtes, *10* (4), pp. 209—214.

Lacombe, H. and P. Tchernia. 1960. Quelques traits généraux de l'hydrologie Meditérranéenne. Cah. Océanogr., *12* (8), p. 527.

Middellandsee Zee, 1957. Oceanographische en Meteorologische gegevens. S'Gravenhage.

Mikhaelov, O. V. 1965. Bottom topography of Mediterranean Sea. In the monograph »Osnovnie tcherti geologitcheskogo stroenija gidrologitcheskogo rejima i biologii Sredizemnogo moria« Moscow, Izdat. Nauka, 224 p. (1968 translation by Inst. Modern Languages, Washington D. C.).

Miller, A. R. 1963. Physical oceanography of the Mediterranean Sea: a discourse. Rapp. Comm. int. Mer Médit., *17* (3), pp. 857—871.

Moskalenko, L. V. 1968. Study of stationary wind currents in the central and eastern parts of the Mediterranean Sea. Candidate Thesis, Inst. Oceanology, Moscow. (in Russian).

Moskalenko, L. V. and I. M. Ovtchinnikov. 1965. Water masses of the Mediterranean Sea (in Russian). Izdat. Nauka, Moscow.

Nielsen, J. N. 1912. Hydrography of the Mediterranean Sea and adjacent waters. Rap. Dan. Oceanog. Exped., 1908—1910, *1*, pp. 77—191.

Ovtchinnikov, I. M. 1965. The 6th Mediterranean Expedition on board »Akademik S. Vavilov«. Okeanologija, *5* (2). (in Russian).

Ovtchinnikov, I. M. 1966. Circulation in the surface and intermediate layers of the Mediterranean. Okeanologija, *6* (1), pp. 62—75. (Translation, Amer. Geophys. Union, *6* (1), pp. 48—59.)

Ovtchinnikov, I. M. and A. F. Feodoseyev. 1965. On the horizontal circulation of the Mediterranean Sea during summer and winter seasons (in Russian). Izdat. Nauka, Moscow.

Sarkisian, A. S. 1966. Fundamentals of the theory and calculation of oceanic currents. Leningrad, (in Russian).

Sarkisian, A. S. 1967. »Dynamics of non-periodical sea currents« (in Russian). Izvestia Akad. Nauk. SSSR., *3* (9),

Sarkisian, A. S. and V. F. Ivanov. 1971. The joint effect of baroclinicity and the bottom relief as an important factor in the sea current dynamics. Izv. AN USSR, Atmosphere Ocean Physics, *7* (2). (in Russian).

Shtockman, V. B. 1946. Equation of the field of total water flux excited by wind in an unfromogenous Sea. Doklady Akad. Nauk SSSR, *54* (5), (in Russian).

Wüst, G. 1960. Die Tietenzirkulation des Mittelandischen Meeres in den Kernschichten des Zwuischen und des Tiefenwassers. Deutsch. hydrogr. Zeitschr., *13* (3).

Wüst, G. 1961. On the vertical circulation of the Mediterranean Sea. J. Geophys. Res., *10*, p. 3261.

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KRATAK SADRŽAJ

Za istočni Mediteran je postavljen numerički model cirkulacije uz uvažavanje poznatog polja gustoće, stupnja baroklinosti morske vode, trenja vjetra i β-efekta.

Dobivena je sezonska cirkulacija za zimu na 12 nivoa od površine do 500 m. Preliminarna analiza pokazuje da je površinska cirkulacija pod većim utjecajem gradijentskih struja nego struja vjetra. Strujanje je općenito ciklonalno. Prisutno je nekoliko odijeljenih vrtloga na raznim nivoima. Na površini su svi ciklonalni, a na nekim dubinama se u sredini bazena formira anticiklonalni vrtlog. On slabi s većom dubinom i konačno nestaje na 500 m, gdje je ponovno prisutno ciklonalno strujanje. Brzine struja su ispod 200 m dubine općenito slabije (rijetko preko 5 cm/sek) u usporedbi s gornjim slojevima gdje katkada dostignu 30—35 cm/sek.