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Large-scale properties of the Eastern Mediterranean: a review

General circulation
Wind and thermohaline forcing
Water masses
Numerical modelling
Eastern Mediterranean

Circulation générale
Forçage du vent et thermohalin
Masses d'eau
Modélisation numérique
Méditerranée orientale

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ABSTRACT

A review is provided of the present state of knowledge of the Eastern Mediterranean, including both its phenomenology (general circulation, water masses, specific local processes) and the theoretical efforts devoted to modelling these properties. The general conclusion is that very little is known of the Eastern Mediterranean in comparison with other interesting regions of the world's ocean. The phenomenological evidence is still inconclusive and contradictory, and leaves unsolved the major questions concerning the basic physical mechanisms and driving forces of the circulation itself (wind versus thermohaline driven). The role of tracer distributions in determining circulation patterns is still poorly understood. Modelling efforts are scanty and often provide contradictory results. We address the major and critical questions which must be answered to obtain a basic understanding of the dynamics of the Eastern Mediterranean; we review the present knowledge of its phenomenology and of the modelling research carried out up to now, critically assessing what is still poorly known or ambiguous.

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RÉSUMÉ

La circulation générale de la Méditerranée orientale : synthèse de sa phénoménologie et modélisation

Nous présentons une synthèse de l'état actuel des connaissances relatives à la phénoménologie de la Méditerranée orientale (circulation générale, masses d'eau, phénomènes locaux spécifiques) et des efforts théoriques poursuivis pour modéliser ces propriétés. La conclusion générale est que la Méditerranée orientale est très mal connue, comparée aux autres régions intéressantes de l'océan mondial. La connaissance phénoménologique est encore contradictoire et peu concluante; les principales questions ne sont toujours pas résolues dans le domaine des mécanismes physiques fondamentaux et des forces qui déterminent la circulation elle-même (due au vent, thermohaline). Le rôle de la répartition des traceurs dans la détermination des modèles de circulation est encore mal compris. Les essais de modélisation sont rares, et conduisent souvent à des résultats contradictoires. Nous posons les questions fondamentales nécessaires à la compréhension de la dynamique de la Méditerranée orientale; nous faisons la synthèse des connaissances actuelles de sa phénoménologie et de la recherche effectuée jusqu'à présent pour la modéliser, et nous inventorions ce qui reste mal connu.

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INTRODUCTION

The Eastern Mediterranean Sea lies to the east of the Strait of Sicily and comprises the Ionian and Levantine basins and the Adriatic and Aegean Seas. Compared with other interesting regions of the world's ocean, so little is known about the Eastern Mediterranean as to leave still unsolved the major questions which may be formulated concerning the Mediterranean circulation. These questions address the basic physical mechanisms and driving forces of the circulation itself; the most fundamental amoung them are: 1) What is the dominant driving force of the Eastern Mediterranean circulation: a) the wind stress field; b) thermohaline fluxes; or c) source/sink distribution of flow? 2) Is there a quasi-steady, yearly component of the circulation or is the seasonal cycle the dominating pattern?

The phenomenological evidence is still ambiguous and fails to provide complete or satisfactory answers to these questions. The seasonal signal seems to be much stronger in the Mediterranean Sea than in other parts of the world ocean. This is reflected for instance in the climatology of the wind stress pattern, as discussed below. In so far as the thermohaline fluxes are concerned, it is well known that the Levantine basin is the region of formation of the Levantine salty water which spreads out from Gibraltar into the Atlantic Ocean and forms the Upper North Atlantic Deep Water. Dense water formation is a phenomenon typically occurring in wintertime through more or less intense episodes of deep convection in localized areas (*see* Sankey, 1973, for a review of the Medoc programme in the western Mediterranean). Thus, also the thermohaline fluxes should have a strong seasonal signal. On the other hand, both the distribution of tracers such as salinity and oxygen in the different vertical layers seem to point at a long-term, quasi-steady component of the circulation of equal importance as the seasonal cycle. Quasi-steady features of the circulation seem also to be major currents, such as the North African current which can apparently be traced from Gibraltar to the Levantine Basin all the year long.

Even the modelling effort carried out in the past literature for the entire Mediterranean Sea in general, and its eastern part in particular, is very reduced. These modelling results are so minor that they not only leave unsolved the major problems addressed above but also show critical contradictions between each other and even inconsistencies with the phenomenological evidence.

In this paper we review the present state of knowledge of the Eastern Mediterranean, critically assessing what is still unsolved, poorly understood, contradictory or inconsistent. The next section is devoted to a review of the phenomenology of hydrography and water masses and the third part to the review of modelling efforts carried out up to now. In conclusion, we stress the importance of carrying out a thorough series of field surveys capable of providing a definitive phenomenology of the Eastern Mediterranean as well as a systematic theoretical investigation aimed at elucidating and answering *inter alia* the major questions set out above. The existence of the ongoing international POEM (Physical Oceanography of the Eastern Mediterranean) cooperative programme (*see* UNESCO Reports 30, 35 and 44; POEM Newsletters 1 and 2) proves that these needs are timely and of paramount importance to the understanding of one of the oceanographically most interesting regions of the world ocean.

Three final comments are necessary. Firstly, even though the focus of the review is on the Eastern Mediterranean, short accounts are provided, where necessary, of the evolution of properties from Gibraltar, through the Western Mediterranean and into the Eastern basin. It is impossible, in fact, always to make a distinction in the discussion between the Eastern and Western basins, although we have endeavoured to do so wherever dynamically plausible and consistent.

Secondly, the present review addresses only the large-scale features of the circulation and of property distributions. There is no discussion of the phenomenology of the mesoscale eddy field, even though this can significantly drive the mean circulation through the eddy momentum fluxes. Investigations, both experimental and theoretical, of the mesoscale eddy field in the Eastern basin are completely lacking in the past literature. The study of the mesoscale eddy-field is in fact one of the three major scientific objectives of POEM.

Lastly, it is unfortunate that no unified, coherent picture of the general circulation of the Eastern Mediterranean can be offered to the reader as the result of a review of the existing literature. The best we can do is to assess critically the past results, pointing out inconsistencies and contradictions as well as what seems to be established beyond any doubt. It is to be hoped that a definitive phenomenology and consistent theoretical understanding of the large scale properties of the Eastern Mediterranean will be one of the major scientific achievements of POEM.

REVIEW OF THE HYDROGRAPHY AND WATER MASSES

The Eastern Mediterranean Sea is defined as the body of water situated east of the Sicilian straits. It is a partially enclosed sea whose hydrography and water masses are determined by the local meteorological climate as well as by the mutual exchanges of water with the adjacent seas: the Western Mediterranean, the Adriatic Sea, the Aegean Sea, the Sea of Marmara and the Black Sea (Fig. 1). The flow of water between the various basins is restricted and controlled by the straits connecting them—*i. e.* the straits of Sicily, Otranto, Antikythera, Kasos, Karpathos, Rhodes, Dardanelles and Bosphorus (Fig. 1). The geometry of these straits is a crucial factor in the circulation of the entire complex system (Assaf, Hecht, 1974). The Eastern Mediterranean Sea is also connected to the Gulf of Suez and the Red Sea through the Suez Canal, but the small size of the cross-section of the canal prevents any significant exchanges of water through it. A chain of Greek islands, of which Crete is the most important divides the Eastern Mediterranean Sea into the Ionian

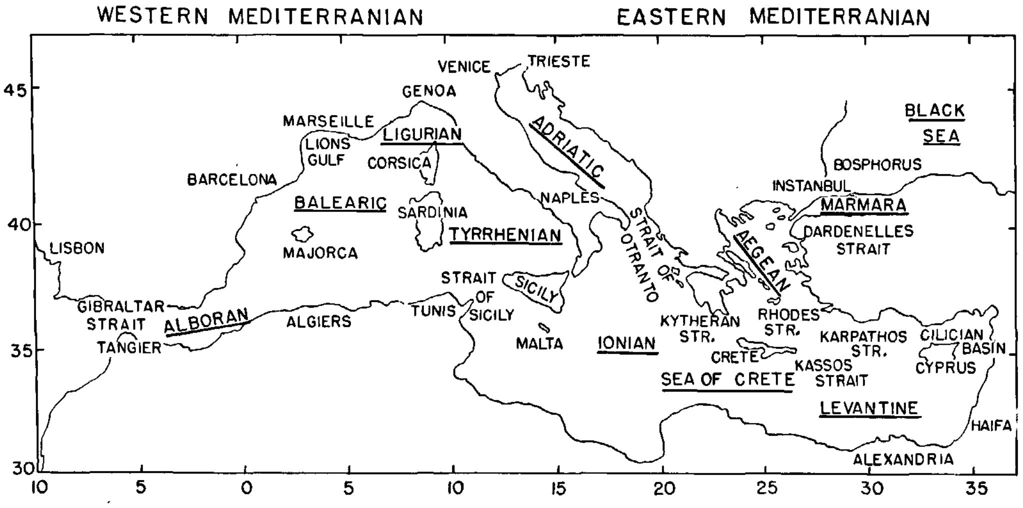

Figure 1

Morphology of the Mediterranean Sea.

and the Levantine basins; but due to the large size of the cross-section of the Cretan Straits (1 800 m deep and 300 km wide), the flow between the two basins does not seem to be impeded to any significant degree. Finally, one must mention the Strait of Gibraltar which, although geographically not belonging to the Eastern Mediterranean Sea, is the ultimate bottleneck controlling the exchange of water between the Mediterranean Sea and the Atlantic Ocean. Thus, even though the focus of the present review is on the Eastern Mediterranean, a short discussion will be given, where necessary, of the evolution of hydrographic properties from Gibraltar, throughout the Western Mediterranean and into the Eastern basin.

Since the Mediterranean Sea as a whole is a concentration basin, *i.e.* the total evaporation exceeds precipitation and runoff, the conservation of mass and salinity are maintained by the balance of the flow through the Strait of Gibraltar (for an evaluation of the budgets of the Mediterranean Sea *see* Carter, 1956; Bethoux, 1977; 1979; 1980). Here, one finds a two-layer flow regime, with the upper layer consisting of inflowing Atlantic waters and the lower layer consisting of outflowing Mediterranean waters, separated at a depth of about 150 m by a sharp discontinuity in the temperature and in the salinity profiles (for a review of the regime of the straits of Gibraltar, *see* Lacombe, Richez, 1982). Characteristically, the Atlantic water enters the Mediterranean Sea at Gibraltar with a salinity of about 36.15×10^{-3} (Lacombe, Richez, 1982) and a temperature of about 15°C. Upon leaving the strait, these water masses form an anticyclonic gyre in the Alboran Sea, after which they appear to hug the African coast. During their flow eastwards, they are depleted by branching off into the Balearic and Tyrrhenian Seas as well as by evaporation and mixing into the lower layers. During the summer, as soon as the Atlantic waters enter the Mediterranean, heat, evaporation and relatively weak winds induce the creation of an upper hot and saline layer, beneath which the Atlantic waters can maintain their low salinity and can thus be identified throughout the Mediterranean Sea (Fig. 2, from Lacombe, 1975). By the time these waters have reached the Strait of Sicily, their salinity is in the range 38.5×10^{-3} to 38.7×10^{-3} (Morel, 1971). They still maintain their identity through the straits of Crete (38.6×10^{-3}), and as far as the shores of Israel (38.7×10^{-3}, Oren, 1971) and the southeastern shores of Turkey (38.6×10^{-3}, Ozsoy *et al.*, 1981). Atlantic waters have also been identified in the Aegean Sea (38.7×10^{-3}) by Lacombe *et al.* (1958). The general circulation pattern in the Eastern Mediterranean according to Nielsen (1912) is shown in Figure 3 (from Lacombe, 1975). For a review of the Western Mediterranean phenomenology, *see* Hopkins (1983).

Lower average evaporation rates together with more intense mixing during the winter prevent the formation of the hot and saline upper layer "lid" and contribute to a faster depletion of the Atlantic waters entering the Mediterranean Sea. As a result the presence of these waters is not as obvious in the winter salinity profiles (Lacombe, 1975) as it was in the equivalent summer salinity profiles. Moreover, Carter (1956) shows that at the strait of Gibraltar the net flux varies seasonally, and that while there is a net influx in the summer, there is actually a net outflux in the winter. This assertion is supported qualitatively by Ovchinnikov (1974), who quotes direct current measurements to maintain that

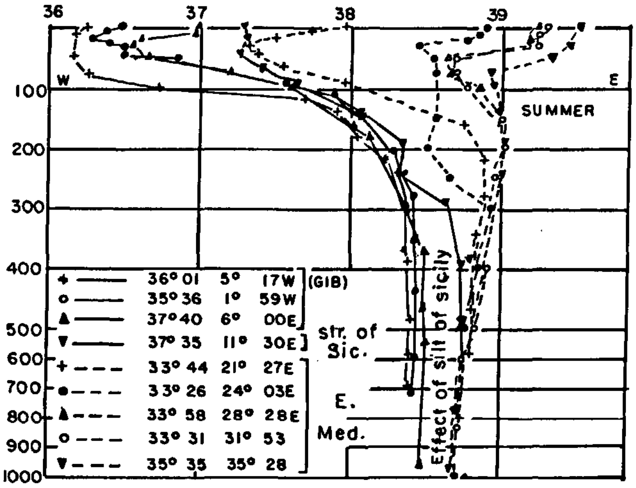

Figure 2

Summer salinity profiles along the Mediterranean Sea (from Lacombe, 1975).

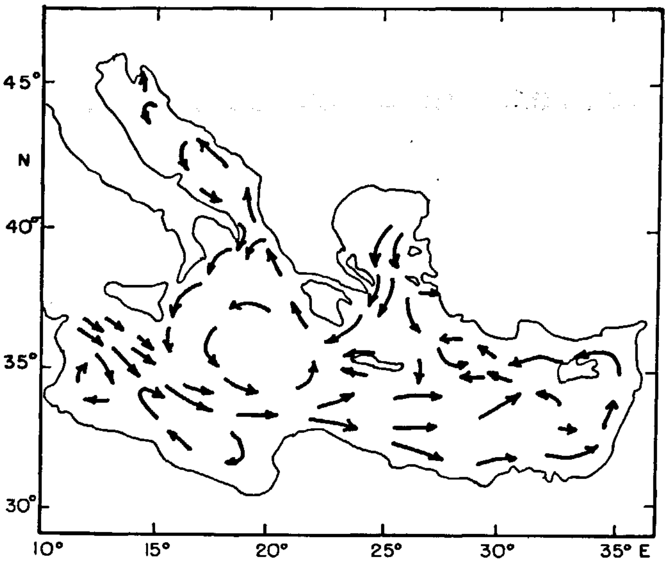

Figure 3

General circulation of the Mediterranean Sea according to Nielsen (1912; *from Lacombe,* 1975).

the two opposing fluxes are equal only during the spring and autumn (when Carter indicates zero net flux), while in summer the influx is twice the efflux and in winter the influx is about one third of the efflux (*see* also Ovchinnikov, 1978; Plakhin, Smirnov, 1982). Some investigators have concluded that in the winter the Atlantic waters may penetrate as far as the Ionian Sea, since there is some evidence of their presence at this time in the straits of Sicily (Frassetto, 1965). However, they almost certainly do not reach as far as the Levantine basin (Oren, 1971; Morcos, Hassan, 1976; Hopkins, 1978). A different opinion is expressed by Moskalenko and Ovchinnikov (1965), Ovchinnikov and Fedoseyev (1965) and Ovchinnikov (1966). On the basis of a geostrophic analysis of the Russian winter cruises in the Mediterranean, they maintain that Atlantic waters reach and spread into the Levantine basin in the winter. This is only one of the examples of contradictory phenomenological evidence.

As mentioned before, the influx of Atlantic waters through the strait of Gibraltar is balanced by an efflux of Mediterranean waters which carry out the excess water mass and salts. This efflux is assumed to be composed of two types of water: Western Mediterranean Deep Water and Levantine Intermediate Waters (LIW; Bryden, Stommel, 1982). The LIW, as their name implies, originate in the Levantine basin, where they can be identified by a conspicuous salinity maximum (39.1×10^{-3}) at a depth of about 250 m and a temperature of about 15°C (Fig. 4, from Wüst, 1961). This salinity maximum can be observed practically anywhere in the Levantine basin throughout the year (Hecht, 1986).

From their region of formation, the LIW flow westwards (Fig. 4, from Wüst, 1961), spread out into the other basins and mix with waters from the layers above and beneath them. Their salinity diminishes but, nevertheless, remains distinct enough to make the LIW core conspicuous throughout the Ionian basin, in the Adriatic Sea, as well as in parts of the Western Mediterranean Sea (Lacombe, Tchernia, 1960; Wüst, 1961; Moskalenko, Ovchinnikov, 1965; Katz, 1972; Hopkins, Goneg, 1977; Lavenia *et al.*, 1983). At the straits of Crete, the core salinity is approximately 38.9×10^{-3}; at the straits of Sicily of 38.7×10^{-3}. To complete the picture, the Mediterranean waters that penetrate into the Atlantic are known to sink to about 1200 m and spread out in a layer which can be identified as far as the American continent (Lacombe, Tchernia, 1960; Katz, 1970; Emery, Dewar, 1982; Plakhin, Smirnov, 1982; 1984).

Nielsen (1912) points to the central and northern regions of the Levantine basin as the source of the LIW, since it is there that during the winter one finds the appropriate combination of high surface salinities and low temperatures favorable to limited thermohaline convection. Appropriate conditions for LIW formation were also observed by Lacombe and Tchernia (1960) in the region between Rhodes and Cyprus; by Wüst (1961) both north and south of Rhodes; by Morcos (1972) in the southern Levantine basin; by Moskalenko and Ovchinnikov (1965), by Ozturgut (1976) and by Ozsoy *et al.* (1981) in the northeastern Levantine basin.

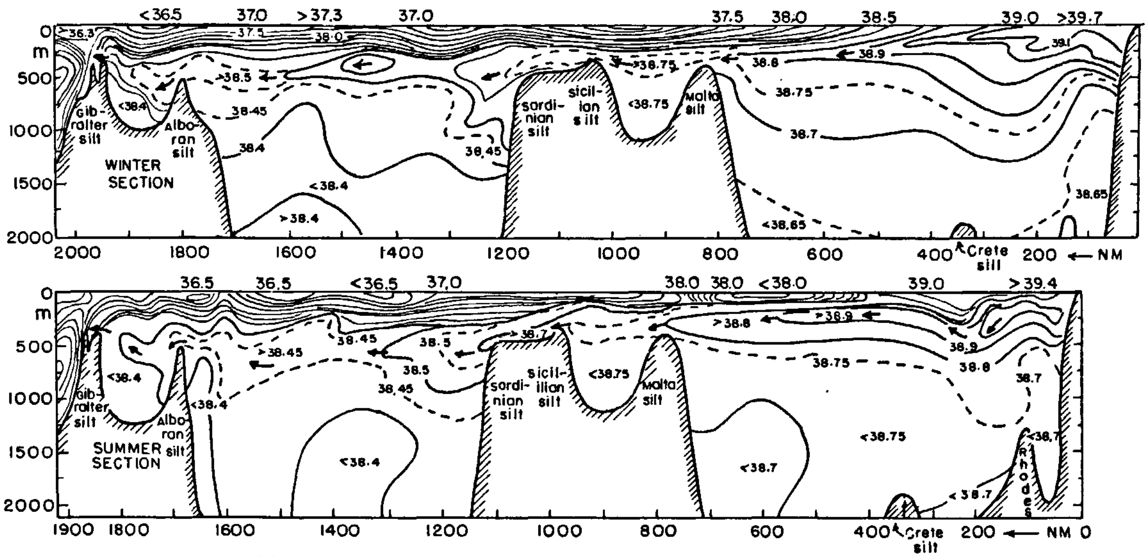

Figure 4

Core of the Levantine Intermediate Waters (LIW) along the Mediterranean Sea (from Wüst, 1961).

Miller (1963) even points to the surface waters of the Aegean Sea as a possible contributor to LIW. The above leads us to believe that LIW formation may not necessarily be restricted to a unique region but may form simultaneously in more than one place. So far, however, there seems to be no experimental evidence of LIW patchiness.

The most propitious season for LIW formation is the winter, when dry, cold, continental air masses cross the Eastern Mediterranean Sea (Ozsoy, 1981), evaporation and mixing are enhanced by strong winds, the seasonal thermocline has been eradicated, and the Atlantic waters are well mixed and do not impede convection. Thus, at the strait of Sicily one would expect the flow of LIW to be significantly stronger in the winter than in the summer, and indeed, Wüst (1961) describes the summer flow as "perceptibly weaker" than the winter flow. However, other investigators (Katz, 1972), do not recognize any significant seasonal variations in the flow of LIW through the straits of Sicily. A continuous flow of LIW through the strait of Sicily would imply that these waters either form continuously throughout the year or that they form solely during the winter but are "stored" and released slowly throughout the year. There does not seem to be any published investigation that indicates LIW formation in the summer.

Two Russian cruises in the Mediterranean Sea in the winter (Ovchinnikov, 1984) devoted some time to the investigation of the region between Rhodes and Cyprus. Ovchinnikov's (1984) analysis of the resulting measurements points out that the meteorological and oceanographic conditions in the region in the winter are particularly propitious for the formation of LIW. Ovchinnikov (1984) and Ovchinnikov and Plakhin (1984) show that the LIW form by convective mixing in the Rhodes cyclonic gyre and that the process has a time and a space scale respectively of the order of a few days and a few tens of miles. According to those investigations, LIW sink down to a depth of 300-400 m where they spread throughout the Mediterranean Sea at an extremely slow rate. Ovchinnikov (1984) also mentions that given the appropriate conditions, other cyclonic gyres in the Levantine basin may contribute to the LIW "pool". Thus the formation of LIW in the winter seems to be established, and the description of the flow through the straits of Sicily needs to be reconciled with it.

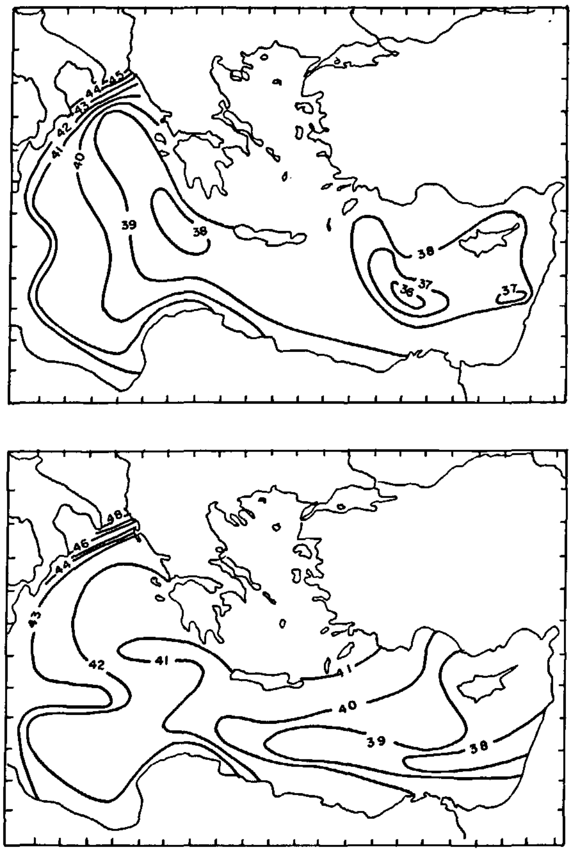

Figure 5

Minima and maxima of oxygen distribution in the Mediterranean Sea (from Pollak, 1951).

The waters below LIW—that is, below approximately 600 m—can be divided into three layers: 600-1 500 m, 1 500-3 000 m, and 3 000 m to bottom (Wüst, 1961). This is perhaps an unnecessarily fine distinction, and Moskalenko and Ovchinnikov (1965) prefer to consider this entire body of water as one single layer. These waters are characterized by a temperature of 13.6°C and a salinity of $< 38.7 \times 10^{-3}$. Their oxygen content of 3.5 ml/l (slightly lower in the Levantine than in the Ionian basin) would indicate that these waters are certainly not stagnant. Pollak (1951), who refers to the waters below 1 600 m as deep waters, rejects the hypothesis that these deep waters are formed in the Aegean Sea. He shows that they are formed in the North and Central Adriatic where, during the winter in particular, appropriate conditions of dilution, heat loss and ventilation are encountered. Pollak traces the maxima and the minima of the oxygen content of the deep waters and thus follows their flow through the core method over the Otranto sill at about 800 m, well below the Sicilian sill to about 1 600 m, through the Ionian basin and along the African coast into the Levantine basin, where insufficient data prevent him from continuing his detailed description (Fig. 5). Wüst (1961) disagrees with some of the details of Pollak's (1951) description, such as the actual path of these waters in the Ionian Sea and the contribution of the Aegean Sea which Wüst finds minor but not negligible. Lacombe *et al.* (1958) and Miller (1963) also found evidence that characteristic deep Eastern Mediterranean waters (13.6°C, 38.7×10^{-3} and 5×10^{-6} O_2) form in the Aegean, at least sporadically, and flow into the Levantine basin through the Kasos and Karpathos straits.

A far more sophisticated core method is presented by Roether *et al* (1983), who use tritium and ^{3}He to trace the origins and the flow of the subsurface waters. The extent of their measurements in the Eastern Mediterranean Sea is somewhat limited, but in general they confirm that the bottom waters of the Eastern Mediterranean form in the Adriatic Sea, from where they flow to the bottom of the Ionian basin and then eastwards into the Levantine basin. In the Ionian basin, these authors could not identify any waters that could be ascribed to Aegean Sea origins. Tracer methods also provide us with some quantitative information on the time scale of the renewal rates, which for Eastern

Mediterranean bottom waters turn out to be approximately 150 years.

Deep water formation is not necessarily limited to marginal seas and shallow regions such as continental shelves. Mid-ocean deep water formation through baroclinic instability has been demonstrated in the Western Mediterranean by Stommel (1972) and by Gascard (1978). This type of convective circulation is induced by the invasion of dry polar or Arctic continental air over relatively warm and saline waters. The path followed by such air masses is determined by the continental mountain ranges and the passes through them. In the Eastern Mediterranean region, during the winter (February, March, April), orographic constraints force the dry and cold continental air to flow southwards over the Adriatic Sea or southwestwards over the Sea of Marmara and the Aegean Sea (Ozsoy, 1981).

Thus, Ovchinnikov and Plakhin (1965) mention the central Ionian basin as a region where such convective overturn may occur and therefore a region of potential deep water formation. In two later papers, Plakhin (1971; 1972) computes the heat loss necessary to induce convective circulation that reaches the bottom of the sea, replenishes there the oxygen of the bottom waters and produces waters which can be recognized as characteristic bottom waters. He determines that the characteristic properties of the bottom waters of the Western Mediterranean are sufficiently different from those of the Eastern Mediterranean to warrant the assumption that each of those basins has local independent bottom water sources and that there is no interchange of bottom waters between the two basins. For the Eastern Mediterranean Sea, Plakhin identifies the following potential bottom water producing regions: the Northern and Central Adriatic Sea; almost the entire Aegean; the northeastern part of the Levantine coast; and the region southeast of Crete. The fact that the Southern Adriatic Sea is indeed a region of wintertime deep water formation has been demonstrated through an extensive hydrographic analysis reviewed in Buljan and Zore-Armanda (1976).

Anati (1985) reviews the processes of deep water formation and shows that a cold dome structure which he finds southeast of Rhodes (Anati, 1984) is a potential region of deep water formation. The "dome" described by Anati (1984; 1985) appears to be precisely the same structure described by Ovchinnikov (1984) and shown to be the one that leads to LIW formation, another example of contradictory interpretations of phenomenological evidence. The most recent analysis of water masses and circulation patterns in the deep layers has been carried out by El-Gindy and El-Din (1986), to which the reader is referred for a review.

The core method has given us a qualitative description of the Mediterranean horizontal circulation and, by implication, has hinted at the vertical circulation. Schematically these results have been summarized by Anati's (1977) figure (Fig. 6). However, direct current measurements (Ovchinnikov, 1965) indicated a marked discrepancy between the progression of the "cores" and the direction of the currents. In fact, the "cores" are not necessarily a true representation of the advection, since they are the result of advection as well as of turbulent diffusion. Currents are, moreover, basically determined by the density structure of the field. According to Ovchinnikov (1965), in the Mediterranean the main factor which determines the density structure of the field is temperature distribution, while salinity, which is the main tracer followed by the core method, is only a secondary factor. Obviously this argument becomes even more important if one considers other chemical, biological or radioactive tracers.

Thus the core method has exhausted its potential without providing the answers to a number of crucial questions. For instance, this method could not determine the penetration scale of the Atlantic waters in the winter into the Eastern basin, or the rate and the kind of depletion acting upon the Atlantic waters on their journey eastwards. Similarly, the core method could not point to the region(s) where the LIW were formed, and much less to any time frame for this occurrence, the rate at which it occurred, or the LIW path westwards and the depletion processes they encountered. The list of questions is rather long; it has been dealt with previously and in great detail and depth by Miller and Charnock (1972).

A different approach that could contribute significantly to our understanding of the physical processes occurring in the Mediterranean Sea is the geostrophic dynamics approach. Its first results appeared in 1912 when Nielsen, with very scant information, produced the map of the surface currents shown in Figure 3. Since Nielsen's work, the scarcity of data in this region has plagued us continuously. Anati (1977), who made a very thorough compilation of the data for the Eastern Mediterranean, found that a 65-year period (1908 to 1973) produced only 5 559 hydrographic stations, about half of these obtained by Israeli oceanographers and most of them in shallow waters. In his attempt to compute the dynamic topography, he found that he could rely upon only 1 092 stations which were deep enough to be useful. Anati used these data to compute two dynamic topography maps: one for the winter, which he defined as February, March and April; and one for the summer, which he defined as July, August, September and October. His maps (Fig. 7) were com-

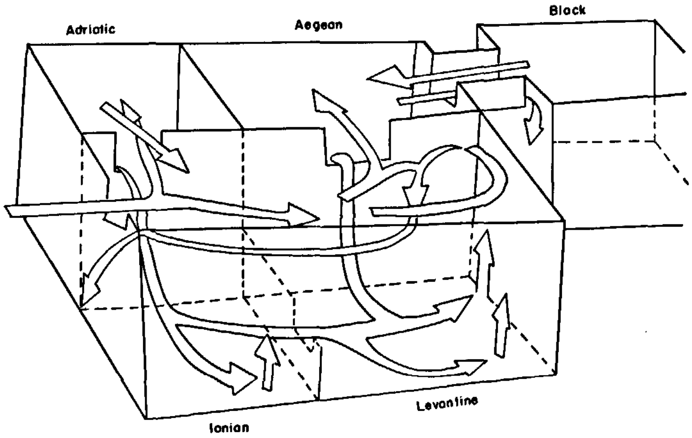

Figure 6

Schematic flow of water masses in the eastern Mediterranean basin (from Anati, 1977).

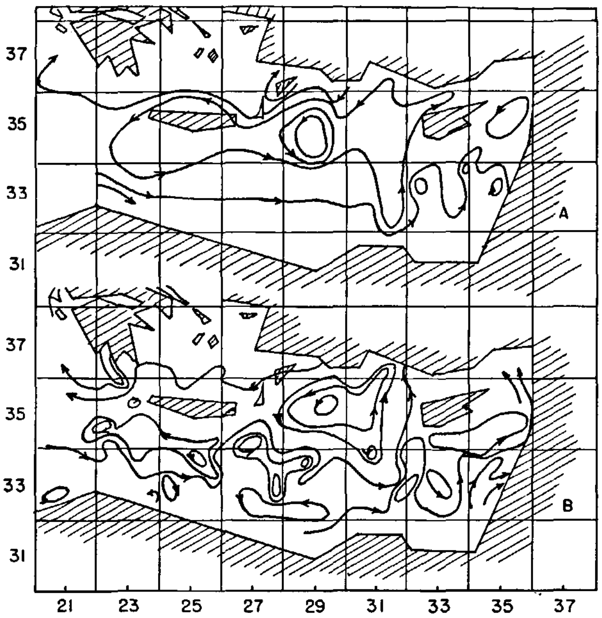

Figure 7

Geopotential anomaly topography of the surface referred to 1 000 *m. A. winter: February, March, April. B. summer: July, August, September, October (from Anati, 1977).*

puted from 0.5° square averages and are related to the 1 000 m level. The results appear to be a very complex pattern of cyclonic and anticyclonic gyres that defy simple description and much less comparison with other similar maps or additional information.

So far, the most detailed dynamical investigation of the Mediterranean Sea is due to Ovchinnikov and Fedoseyev (1965), who used solely Russian data from the *Academician-S.-Vavilov* cruises. This investigation was complemented by Ovchinnikov (1966), who incorporated in his analysis selected measurements from other, non-Russian cruises and supported his depiction of the circulation with some current meter measurements. Their results will be also discussed in the next section from the modelling perspective.

Summarizing, the Ovchinnikov and Fedoseyev (1965) winter upper circulation map (Fig. 8 *a*) shows the Atlantic waters entering the Eastern Mediterranean Sea through the straits of Sicily, and forming a well-developed cyclonic gyre in the Ionian Sea. The Atlantic waters flow further eastwards through the southern part of the straits of Crete and appear to reach as far as the coast of Israel where they turn northwards, east of Cyprus, and flow westwards. Some other features depicted in this map are the cyclonic Rhodes gyre, a large anticyclonic gyre along the coast of Egypt, two eddy-like features south and southwest of Cyprus, and the westward flow in the northern part of the straits of Crete. The Ovchinnikov (1966) map shows the same pattern. Ovchinnikov and Fedoseyev (1965) as well as Ovchinnikov (1966) depicted the circulation pattern of LIW through an analysis of the maps of the geopotential anomaly at 500 dbars relative to the 1 000 dbar level, and claim that during the winter, as well as during the summer, the general features of the circulation at 500 dbars resemble those of the respective surface layer. Some additional dynamic topography investigations, such as those of Mosetti *et al.* (1972), Morcos and Hassan (1976), Sharaf El-Din and Karam (1976) and Lavenia *et al.* (1983), are of a much more local nature and do not add significantly to the patterns described above.

An additional line of research which has been barely explored in the Eastern Mediterranean Sea is the measurement of the spatial and temporal distribution of currents in general and currents in straits in particular. Only recently, a major experimental effort has been carried out in the straits of Gibraltar through an international cooperative program (Kinder, Bryden, 1987). We shall next review the field work carried out in the straits of the Eastern Mediterranean.

The flow through the straits of Sicily was investigated by Frassetto (1965), who described an upper layer extending from the surface to about 60 m and flowing south or southeastwards at speeds varying between 10 and 90 cm s^{-1}, and a lower layer between 60 and 400 m flowing northwards at speeds varying between 2.5 and 12 cm s^{-1}. Frassetto (1965) identified the upper layer as Atlantic waters with their core of minimum salinity and maximum oxygen at about 20 m, and the lower layer as LIW with their core of maximum salinity at about 300 m. The current velocity in both layers oscillated between extreme values, but an attempt to

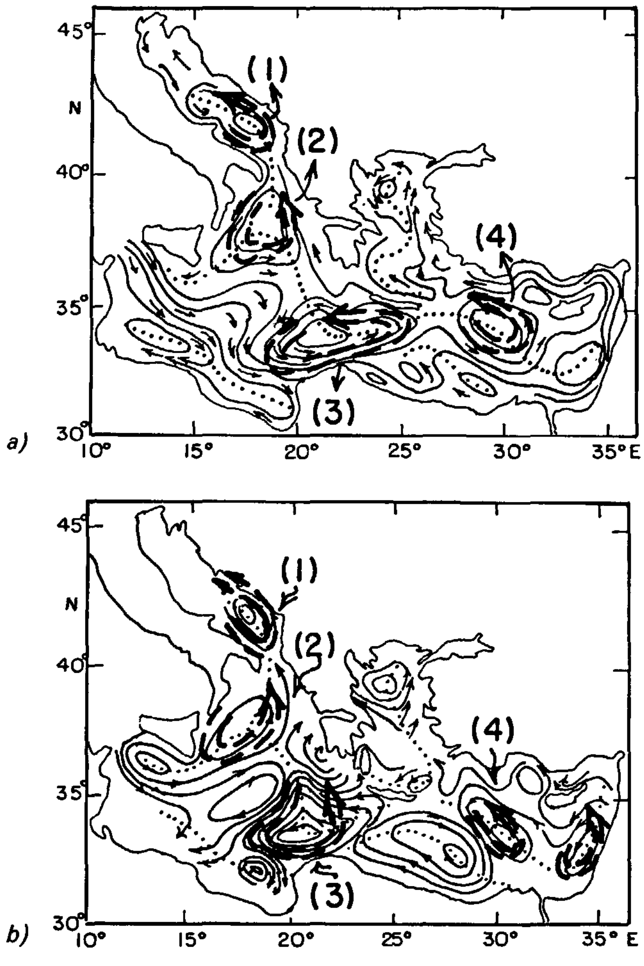

Figure 8

Circulation patterns in the Eastern Mediterranean:

a) Geostrophic components of Mediterranean currents in winter at the surface (from Ovchinnikov, 1966).

b) Winter distribution of the Mediterranean transport integrated over the layer 0-1,000 *m. Contour interval:* 100 m^3/s *(from Ovchinnikov,* 1966).

correlate these oscillations with local tides or with air pressure changes was not successful. On the other hand, the fluctuation of the surface currents appeared to be correlated with the local winds. More recently, the current structure in the straits of Sicily has been investigated by Grancini and Michelato (1987) and JANUS Group (1987). The latter effort was part of the field plan of POEM and the results are still preliminary. However, these two most recent analyses of the flow through the straits of Sicily confirm the results obtained by Frassetto (1965).

In the straits of Otranto, most of the measurements appear to be concentrated in the bottom layer, *i. e.* the layer that is assumed to feed the deep waters of the Eastern Mediterranean Sea. Ovchinnikov and Fedoseyev (1965) mentioned "two anchor buoy stations" which revealed currents of the order of 30 cm s^{-1} flowing southwards at a depth of 600 and 700 m. There are no details on when and for how long these measurements were carried out. Ovchinnikov and Plakhin (1965) also mention Otranto bottom layer currents of the same magnitude, possibly referring to the same set of measurements. Buljan and Zore-Armanda (1976), in their review of the oceanography of the Adriatic Sea, quoted various measurements in the straits of Otranto, and also showed the seasonal fluctuations of the currents and respective water transports in the three dominant layers: surface, intermediate and bottom (*see* also Ovchinnikov, 1978); however, this reference is ambiguous since it is not clear whether measured or computed currents are discussed. The thickness of each of those layers is not mentioned. The surface layer flows with an average velocity of about 40 cm s^{-1}, sometimes reaching peak velocities of 88 cm s^{-1}. The direction of the flow in this layer changes from southeastwards in the summer to northwestwards in the winter (but *see* also Frassetto and Tomasin, 1979, who describe a particular set of measurements in which the flow of the surface layer in the winter is predominantly southwards). The intermediate layer flows northwestwards throughout the year, thus bringing LIW into the Adriatic Sea. The bottom layer appears to flow permanently southwestwards with an average velocity of 2 to 4 cm s^{-1}, but sometimes the velocity in this layer reaches peak values of 10 to 20 cm s^{-1} (Rad *et al.*, 1970, as quoted in Buljan and Zore-Armanda, 1976).

Current measurements in the straits between the Aegean and the Mediterranean Seas (Ovchinnikov, Plakhin, 1965) show "weak (2 cm s^{-1}) but stable transport of water at 750 m" from the Aegean Sea into the Ionian basin through the Antikythera straits, as well as a flow of water of unspecified velocity from the Levantine basin into the Aegean Sea through the Kasos straits at 700 and 800 m. Surface currents measured by Accerboni and Grancini (1972) show intense flow averaging at 40 cm s^{-1} from the Aegean Sea towards the Levantine basin through the three straits: Kasos, Karpathos and Rhodes. Current measurements in the straits of Crete were also presented by Ovchinnikov (1965) and by Ovchinnikov and Plakhin (1965). These were measurements carried out at seven diurnal anchor stations, but the description of the results is somewhat ambiguous with regard to the direction of the current. This sometimes has to be inferred from the dynamic computations which are also presented in the same paper. In the upper layer, 0 to 250 m, the currents were described as steady with a velocity of 50 cm s^{-1}, but no direction is given. Since Ovchinnikov (1965) stated that the currents agree well with his dynamic computations, and those indicate a predominantly eastern component in the 0 to 500 m layer, one must assume that the direction of the currents was also predominantly eastward.

Accerboni and Grancini (1972) also measured the currents in the surface layer of the straits of Crete roughly during the same season as the Russian measurements (end of summer). They compared their results with geostrophic currents computed from hydrographic data obtained at the same time as the current measurements. The reference level for the geostrophic computations was assumed to be 500 m. The results of the geostrophic computations show that in the central and in the southern sections of the straits the surface layer moves eastwards with speeds of up to 20 cm s^{-1}. In the northern section of the straits, the flow is westwards with speeds of the order of 10 cm s^{-1}. These computations appear to confirm the previous Russian geostrophic computations. However, the Accerboni and Grancini measurements show that the flow across the entire surface layer of the straits is eastwards, thus contradicting their own computations in the northern section of the straits.

At 500 m and at 1 000 m, Ovchinnikov (1965) described a current rotating clockwise with periods of 15-18 and 20-25 hours and "an almost zero mean velocity". It is not clear whether the zero velocity is due to the periodic variation in direction, in current or in both. At the bottom, at 1 500 m and at 2 500 m, the currents were described as steadier in direction but most of the time with velocities below instrumental accuracy, which is quoted as 3-5 cm s^{-1} (one wonders what is the directional sensitivity of the instrument at such speeds). A vertical section across the straits from 500 m to the bottom and a horizontal section at 1 500 m (Ovchinnikov, Plakhin, 1965) indicate that the flow through the straits is of the order of 1 cm s^{-1} and eastwards only through the middle of the straits, while in the southern and the northern sections of the straits the flow is westwards.

In summary, current measurements in the straits tend in general to confirm the flow pattern described by both the core method and the dynamic computations. These measurements also reveal a few small but significant differences, such as the westward flow at the bottom of the straits of Crete, the westward flow of the surface layer in the northern section of the straits of Crete, and the contribution of the Aegean to the bottom waters of the Mediterranean Sea. However, there are still not enough measurements for definitive assessments and proper quantitative estimates of water budgets.

There appear to be no current measurements at any depth in the open Eastern Mediterranean Sea except the Dutch Atlas (Konnklijk Nederlands Meteorologisch Instituut, 1957) which is based upon a compilation of computations from vessel surface drift. Dynamic computations as well as modelling attempts (*see* next section) provide some information on the horizontal and vertical distribution of the currents in the open sea, but the confirmation of those computations and their refinement require measurements and crucial experimentation.

A final comment concerns the phenomenology of mesoscale processes of the Eastern Mediterranean. It is well known, in fact, that the mesoscale eddy field profoundly affects the distribution of properties and the general circulation, which can be significantly driven by eddy momentum fluxes. Mesoscale features have been observed, for instance in satellite imagery, and well studied in the Western Mediterranean (*see*, for instance, Gascard, 1978). Such investigations both experimental and theoretical are, however, lacking in the past literature for the Eastern Mediterranean. They constitute one of the main scientific objectives and one of the major experimental and theoretical efforts of POEM, and results are forthcoming. Thus, in the present review, we focus only on the large scale properties of the Eastern Mediterranean.

REVIEW OF MODELLING EFFORTS

The first modelling study carried out to infer the seasonal circulation of the Mediterranean are the detailed dynamical computations by Ovchinnikov and Fedoseyev (1965), implemented by Ovchinnikov (1966) to include further data from non-Russian cruises. These investigations are also quoted in the previous section and they "bridge" the purely phenomenological studies and the more complex numerical modelling results to be discussed below. We shall take the above papers as the starting attempts in modelling the Mediterranean circulation through geostrophy and the thermal wind equations which are the modelling assumptions of the dynamic method. The vast majority of these studies were devoted to the entire basin. However, we show figures and discuss results only for the Eastern part. To our knowledge, the following studies are the only modelling results existing in the published literature for the Eastern Mediterranean.

Ovchinnikov (1966) constructs the charts of geostrophic currents for winter and summer, at 100, 200, 500 m levels relative to the 1,000 db surface taken as the level-of-no-motion. The justification for the choice of this reference level lies in the observed slight spatial variations of the hydrographic properties at 1,000 m depth and below. Ovchinnikov also gives the total transport in the layer 0-1,000 m. Figure 8 *a* shows the geostrophic currents in winter in the surface layer (at 100 m). Various important and semi-permanent features can be recognized. The first is a well developed North African current carrying the Atlantic waters from Gibraltar to the extreme Levantine basin. Second, various closed gyres can be unambiguously identified. Some of them have been proved to be (semi)-permanent features of the circulation through successive experimental and theoretical efforts. For the Western basin *see* Gascard and Richez (1985), Sankey (1973), Lacombe and Tchernia (1972), Crepon *et al.* (1982). In the Eastern basin, the only feature clearly shown to be permanent is the Adriatic cyclonic gyre (1) (Buljan, Zore-Armanda, 1976; Hendershott, Malanotte-Rizzoli, 1976; Franco *et al.*, 1982; Malanotte-Rizzoli, Bergamasco, 1983). The existence of the remainder of the gyres in the Eastern basin has not yet been proven unambiguously as a steady (yearly) feature of the circulation, even though they emerge quite developed in some (seasonal) hydrographic surveys. They are: the Ionian (2); the Cirenaican (3); and the Levantine (4) gyres.

Figure 8 *b* shows the total transport over the layer 0-1 000 m in winter. All the gyres identified in the surface layer circulation are present also in the vertically integrated transport. This robustness of the above cyclonic configurations, as well as of the North African current, seems to be indicative of features characterized by a strong steady signal and with a strong barotropic component, *i. e.* reaching down to the intermediate and deep layers of the Mediterranean circulation.

Ovchinnikov (1966) draws the following conclusions for the Eastern Mediterranean: a) in the eastern and central Mediterranean the winter circulation in the intermediate and deep layers coincides with the circulation in the surface one: the currents have the same direction at all levels, becoming only more attenuated with depth; b) the summer circulation (which he does not show) of both the surface and intermediate layers retains the basic features of the winter circulation, that is the seasonal variations are negligible.

Conclusion (b) by Ovchinnikov (1966) seems to be in contradiction with the dynamic calculations presented by Ovchinnikov and Fedoseyev (1965). In fact, the Ovchinnikov and Fedoseyev (1965) upper layer circulation map for summer (not shown) indicates two major changes from the winter one: first and foremost is the reversal of the Ionian Sea gyre and, second, the consequent result of the reversal of the upper layer current in the straits of Crete.

If, however, the negligible variability between summer and winter claimed by Ovchinnikov (1966) is true, this would point to a surface forcing function whose seasonal variability is also negligible. Most of the time this occurs for the wind stress pattern which usually has a long-term, yearly quasi-steady component. This yearly character of the wind-stress field is however very doubtful, as discussed in the following. Surface thermal and evaporation fluxes usually exhibit a major variation between winter and summer. In a geographic location like the Eastern Mediterranean, cooling and surface evaporation may become quite more intense in winter due to the prevalence of cold, dry air patterns blowing from the interior mainland onto the Mediterranean. This meteorological configuration, characterized by a high pressure zone over central Russia, is the one responsible for the outbreaks of (cold and dry) Mistral wind over the Provencal-Ligurian Sea; Bora over the Adriatic and an analogous wind pattern over the Levantine basin (Lacombe, Tchernia, 1960; Hendershott, Rizzoli, 1976). No systematic study, however, has been carried out of the climatology of the wind stress field as well as of the thermal and evaporative fluxes over the Mediterranean, nor of the relative intensity of their seasonal-yearly-multiannual components.

Moskalensko (1974) studied the steady wind-driven circulation in the Eastern Mediterranean. His model capitalizes upon Stommel's model (1948) for the transport streamfunction, with bottom friction on the β-plane, but extended to include a variable topography. A further extension from Stommel's homogeneous ocean is the inclusion of the water mass stratification through a function M which is the integral of the assumed interior density profile over the water column down to a depth-of-no-motion $D(x,y)$. The procedure is the same as in the classical paper by Sverdrup (1947); thus Moskalenko's study can be regarded as the application of Sverdrup's vertically integrated approach to Stommel's equation including a variable topography. The solution is found for the summer season as the used wind-stress fields is for the months June through September.

Figure 9 shows the transport streamfunction (9 *a*) and the velocity distribution of the currents at the surface (9 *b*). Figures 9 *a*, *b* show the summer reversal of the Ionian gyre. It is however impossible to separate the purely wind-driven component in Moskalenko's study due to the hybrid approach in which the (horizontally and vertically) varying density field is included to evaluate the total mass of the water column.

Gerges (1976; 1977) used Sarkisian's (1967) diagnostic model to study the Mediterranean circulation for the winter season. He used the model on the β-plane, with the observed winter density distribution and wind field.

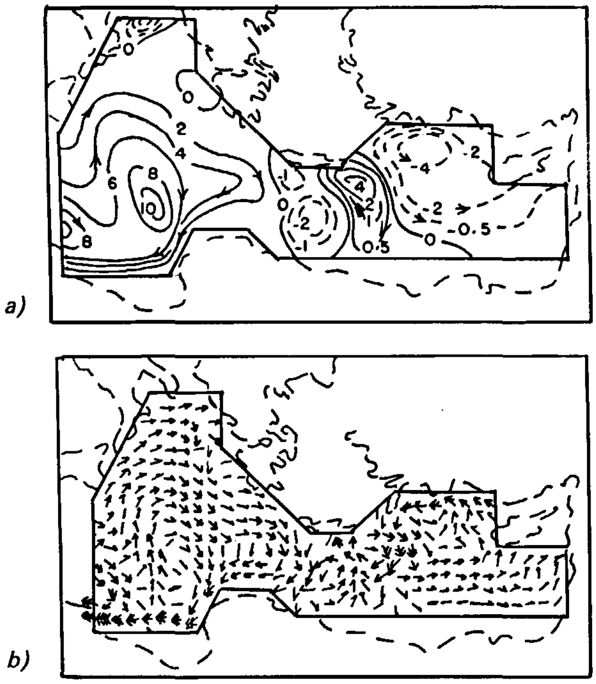

Figure 9

a) Transport stream function of the steady state wind-driven current in the Eastern Mediterranean. Units in 10^{+12} *cm*^{3} *s*$^{-1}$.

b) Velocity distribution of geostrophic currents at the surface in cm s^{-1} *(from Moskalenko,* 1974).

The real bottom relief is used as the lower boundary in the computations and the effects of coasts and islands are included. Gerges first studied the Eastern Mediterranean (1976) and then applied the model to the entire Mediterranean (1977). The winter pattern found by Gerges is very consistent with Ovchinnikov's winter pattern of Figures 8 *a*, *b*.

Gerge's conclusions for the eastern Mediterranean and for the winter circulation support, in part, the previously discussed studies. These conclusions are as follows: 1) In the Levantine basin the currents do not reverse direction with depth; the North-African current is directed eastward throughout the water column; from a succession of adjacent cyclonic gyres in the surface layer, the progression is towards one main cyclonic gyre at the deeper levels; 2) The North-African current reverses direction at about 150 m depth in the central basin (and western one); thus one observes an inflow of Atlantic waters in the surface layer about 100 m thick; at the 150 m level, there is the return flow of deep Mediterranean water towards Gibraltar; 3) As the same cyclonic pattern is observed throughout the depth in the Eastern basin, Gerges concludes that the thermohaline effects are dominating there.

To be complete, we mention the paper by Dzhioyev and Drozdov (1977). Their contribution is in fact simply a literal copy of the Gerges study in the Eastern Mediterranean (1976).

The last paper to be discussed in this review of modelling efforts of the Eastern Mediterranean circulation is by Menzin and Moskalenko (1982). They use the same approach used by Moskalenko (1974), only here they neglect any interior density stratification. Thus their ocean is homogeneous, on the β-plane and with variable depth. This model, which includes bottom friction, is now really the extension of Stommel's model to the variable depth case. They study the purely wind-driven circulation and compare the winter and summer patterns. Figures 10 *a*, *b* show the transport stream function in winter (10 *a*) and summer (10 *b*). The conclusions which can be drawn from the examination of Figures 10 *a*, *b* are: a) The purely wind-driven component of the barotropic circulation undergoes drastic changes from winter to summer in the Eastern Mediterranean; almost every gyre reverses; in particular, in winter a general cyclonic circulation connects together the Levantine basin and the interior of the Ionian sea, while a separate anticyclonic gyre characterizes the Libyan Gulf; in summer (10 *b*) the entire Ionian sea and Libyan Gulf are connected in a broad anticyclonic circulation pattern and the Levantine basin shows a succession of cyclonic vs. anticyclonic local gyres; b) Comparison with the dynamic calculations of Figure 8 *a*, *b* for the winter season, even though showing the same general cyclonic tendency, nevertheless have also considerable differences; this is indicative of the importance of the thermohaline component of the circulation.

This reversal of the barotropic, wind-driven component of the circulation is the only important result emerging from the above studies which can be substantiated dynamically. It can in fact be related to the marked

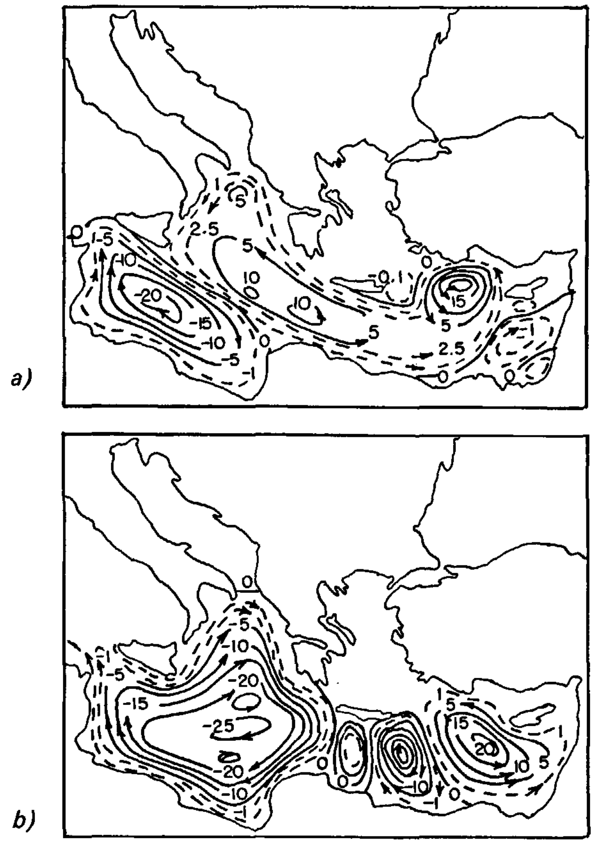

Figure 10

Transport stream function in 10^9 *cm*^{3} *s*$^{-1}$*: a) winter; b) summer (from Menzin, Moskalenko, 1982).*

difference between winter and summer in the wind-stress field which becomes clear when examining the climatological wind field. Figures 11 *a*, *b* show the average wind stress for the month of January (11 *a*) and August (11 *b*), taken to be representative of the winter and summer situation (from May, 1982). In the evolution of the wind stress from month to month in the climatological year, in fact, two quite distinct patterns emerge, that is those shown in Figures 11 *a*, *b*, with a smooth transition between the two.

The winter situation shows a mostly zonal wind field, aligned with the main (east-west) elongation of the Mediterranean Sea. Apart from the Ligurian-Provencal sea, in which the wind has also an important meridional component, the Eastern Mediterranean can be thought of as a zonal channel, with the wind blowing along it from Sicily towards the Levantine basin. The summer situation instead shows a wind stress field mostly meridional, blowing from Europe towards Africa throughout the Mediterranean, and with a westward-directed component (towards Gibraltar) in the Western basin. Thus it is not surprising that the resulting circulation actually reverses direction in the Eastern basin. The result of Moskalenko (1974) is confirmed in an extensive series of numerical experiments on the barotropic wind-driven circulation recently carried out by Malanotte-Rizzoli and Bergamasco (1988), and it is due to the reversal of the wind-stress curl from winter to summer over the Ionian basin. This discussion reinforces the assumption of strong seasonal character of the Mediterranean circulation. Caution must be exerted however in accepting the above results as definitive, as nothing is known about the seasonal or yearly character of the thermal-evaporative forcing functions and resulting thermohaline component of the circulation.

The above review of modelling efforts is meant to be exhaustive only as far as the Eastern Mediterranean is concerned. Modelling studies have been carried out also for the Western Mediterranean. We may add to the studies already mentioned those by McDonald *et al.* (1983), Loth and Crepon (1984), Heburn (1985), Pinardi *et al.* (1985), Crepon (1986), Preller (1986), to which the reader is referred for details.

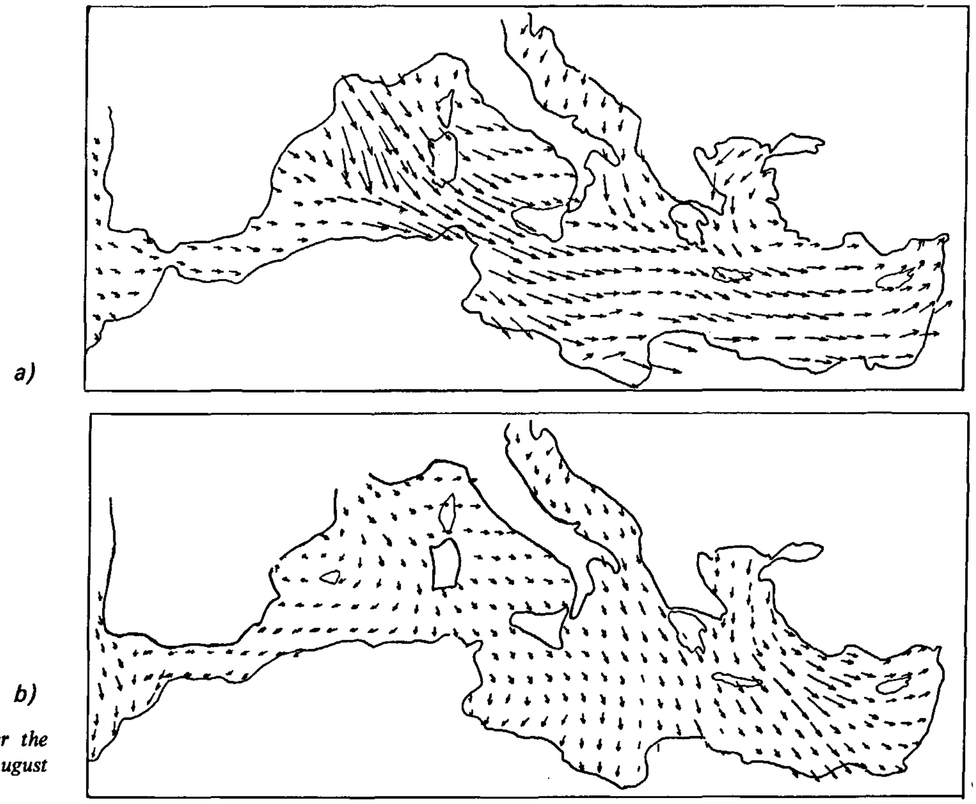

Figure 11

Climatological wind stress pattern over the Mediterranean: a) January mean; b) August mean (from May, 1982).

It is unfortunate that no unified, coherent picture of the general circulation, both wind-driven and thermohaline, of the Eastern Mediterranean can be offered to the reader, due to the very limited, often contradictory modelling results (as well as phenomenological evidence). The thorough theoretical investigation of the nature of the general circulation in the Eastern Mediterranean is one of the major scientific objectives of POEM and, in this context, results and definitive answers to the basic questions posed in the Introduction may be expected shortly.

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