*Earth-Science Reviews*, 32 (1992) 285–309
Elsevier Science Publishers B.V., Amsterdam



# General circulation of the Eastern Mediterranean

The POEM group
(Physical Oceanography of the Eastern Mediterranean)

A.R. Robinson [a], P. Malanotte-Rizzoli [b], A. Hecht [c], A. Michelato [d], W. Roether [e], A. Theocharis [f], Ü. Ünlüata [g], N. Pinardi [h], A. Artegiani [i], A. Bergamasco [q], J. Bishop [c], S. Brenner [c], S. Christianidis [f], M. Gacic [j], D. Georgopoulos [f], M. Golnaraghi [a], M. Hausmann [k], H.-G. Junghaus [k], A. Lascaratos [l], M.A. Latif [g], W.G. Leslie [a], C.J. Lozano [a], T. Oğuz, E. Özsoy [g], E. Papageorgiou [f], E. Paschini [i], Z. Rozentroub [c], E. Sansone [m], P. Scarazzato [d], R. Schlitzer [c], G.-C. Spezie [m], E. Tziperman [r], G. Zodiatis [f], L. Athanassiadou [n], M. Gerges [o], M. Osman [p]

[a] *Harvard University, Division of Applied Sciences and Department of Earth and Planetary Physics, Cambridge, MA, U.S.A.*
[b] *Massachusetts Institute of Technology (MIT), Department of Earth, Atmospheric and Planetary Sciences, Cambridge, MA, U.S.A.*
[c] *Israel Oceanographic and Limnological Research Ltd. (IOLR), Tel Shikmona, Haifa, Israel*
[d] *Osservatorio Geofisico Sperimentale (OGS), Trieste, Italy*
[e] *University of Bremen, Bremen, Germany*
[f] *National Centre for Marine Research (NCMR), Athens, Greece*
[g] *Institute of Marine Sciences, Middle East Technical University (IMS-METU), Erdemli, Içel, Turkey*
[h] *Istituto per lo Studio dello Metodologie Geofisiche Ambientali (IMGA-CNR), Modena, Italy*
[i] *Istituto di Ricerche sulla Pesca Marittima (IRPEM-CNR), Ancona, Italy*
[j] *Institute of Oceanography and Fisheries, Split, Croatia*
[k] *Heidelberg University, Institut für Umweltphysik, Heidelberg, Germany*
[l] *University of Athens, Department of Applied Physics, Athens, Greece*
[m] *Istituto di Meteorologia e Oceanografia, IUN, Napoli, Italy*
[n] *Ministry of Agriculture and Natural Resources, Fisheries Department, Nicosia, Cyprus*
[o] *UNESCO, Nairobi, Kenya*
[p] *University of Alexandria, Alexandria, Egypt*
[q] *Istituto Studio Dinamica Grandi Masse (ISDGM-CNR), Venice, Italy*
[r] *The Weizman Institute of Science, Rehovot, Israel*

(Revised manuscript accepted February 15, 1992)

ABSTRACT

The POEM group, 1992. General circulation of the Eastern Mediterranean Sea. *Earth-Sci. Rev.*, 32: 285–308.

A novel description of the phenomenology of the Eastern Mediterranean is presented based upon a comprehensive pooled hydrographic data base collected during 1985–1987 and analyzed by cooperating scientists from several institutions and nations (the POEM project). Related dynamical process and modeling studies are also overviewed. The circulation and its variabilities consist of three predominant and interacting scales: basin scale, subbasin scale, and mesoscale. Highly resolved and unbiased maps of the basin wide circulation in the thermocline layer are presented which provide a new depiction of the main thermocline general circulation, composed of subbasin scale gyres interconnected by intense jets and meandering currents. Semipermanent features exist but important subbasin scale variabilities also occur on many time scales. Mesoscale variabilities modulate the subbasin scale and small mesoscale eddies populate the open sea, especially the south-eastern Levantine basin. Clear evidence indicates Levantine Intermediate Water (LIW) to be present over most of the

*Correspondence to:* A.R. Robinson, Harvard University, Division of Applied Sciences, Cambridge, Ma 02138, USA.

0012-8252/92/$15.00 © 1992 – Elsevier Science Publishers B.V. All rights reserved

Levantine Basin, implying that formation of LIW is not localized but rather is ubiquitous. The Ionian and Levantine basins are confirmed to form one deep thermohaline cell with deep water of Adriatic origin and to have a turnover time of one and a quarter centuries. Prognostic, inverse, box and data assimilative modeling results are presented based on both climatological and POEM data. The subbasin scale elements of the general circulation are stable and robust to the dynamical adjustment process. These findings bear importantly on a broad range of problems in ocean science and marine technology that depend upon knowledge of the general circulation and water mass structure, including biogeochemical fluxes, regional climate, coastal interactions, pollution and environmental management. Of global ocean scientific significance are the fundamental processes of water mass formations, transformations and dispersion which occur in the basin.

## 1. INTRODUCTION

The physical oceanography of the Eastern Mediterranean Sea is currently of interest because rapid progress is occurring in the description of the scales, features and variabilities of the circulation and water masses. This is providing the basis for novel and realistic dynamical research and model development. Additionally, the capability now exists of providing the realistic transport fields necessary for interdisciplinary ocean scientific research, e.g., productivity and recruitment studies in biological and chemical oceanography. This in turn provides the basis for the application models of the deep Eastern Mediterranean essential for resource management and pollution control, including the simulation and prediction of the exchanges of materials across the shelf areas which rim the basin. Air-sea interaction studies, related to regional weather and climate effects are also implicated. Most importantly, because of unique circumstances, the Eastern Mediterranean constitutes a laboratory basin for global ocean climate processes.

The Mediterranean Sea, although relatively small, is of sufficient size for its circulation to be governed by large-scale ocean dynamics. It is among the most interesting of our planet's semi-enclosed seas because of the great range of processes and interactions which occur within it (Malanotte-Rizzoli and Robinson, 1988). Most physical processes which characterize the global general ocean circulation, many of which are not well known or understood, occur directly or analogously in the Mediterranean. All major forcing mechanisms, surface wind and buoyancy fluxes and lateral mass exchange, are present. Air–sea interaction is vigorous and both deep water masses and intermediate water masses are formed. Increased density due to saltiness caused by intense surface evaporation is important for water mass formations and for the main thermohaline cell analogously to the global ocean process.

The Mediterranean, connected to the Atlantic by the shallow Straits of Gibraltar, is composed of two similar size basins separated by the shallow and narrow Straits of Sicily. The Eastern Mediterranean is thus itself an isolated basin with multiple forcings and water mass formations driving the processes and interactions of global interest. Logistically the basin is convenient for operations. Resource-wise, it is both observationally and computationally feasible to conduct basin-wide research in the Eastern Mediterranean with grids of fine enough resolution to define the physical processes of interest. These factors provide a unique opportunity for oceanographic research of general interest as well as of critical regional importance.

Intensive research has been underway now for several years, coordinated by the international POEM (Physical Oceanography of the Eastern Mediterranean) program (Malanotte-Rizzoli and Robinson, 1988). Research has included: multiple-ship surveys, the sharing of pooled and intercalibrated data sets, and cooperative analyses, syntheses and modeling. This has resulted in the recent rapid progress in knowledge and understanding. Although certain aspects of the circulation have been known generally or speculatively for some time (Lacombe and Tchernia, 1972; Malanotte-Rizzoli and Hecht, 1988),

The POEM Group

POEM (Physical Oceanography of the Eastern Mediterranean) is an international cooperative research program. It was established to determine the circulation of that sea, to research associated fundamental processes, and to construct realistic models for physical, biological and chemical studies and applications. POEM was initiated by scientists interested in both the regional oceanography and the potential of the Eastern Mediterranean to provide a laboratory basin for global processes. The idea for the program was introduced to the community at a round table discussion in 1982 in Cannes, France during a Congress of the International Commission for the Scientific Exploration of the mediterranean, and the plan was developed at a workshop held at Lerici, Italy in 1983.

Scientists constitute the Steering Committee for POEM, which has the endorsement and the support for collective activities, of both the Intergovernmental Oceanographic Commission and UNESCO. Scientific activities included field work (1985–1987), data analysis and modeling. Scientific workshops for communication, planning, intercalibration and syntheses were held in Erdemli (Turkey), Trieste (Italy), Cambridge (Massachusetts) and Venice (Italy). Scientists from Cyprus, Croatia, Egypt, England, France, Germany, Greece, Israel, Italy, Turkey, the United Kingdom and the United States of America have participated.

Phase one of POEM concluded at the end of 1990, and the scientific contributions to the physical oceanography of the Eastern Medirranean which were achieved are overviewed and summarized here. The POEM Group consists of the scientists who substantially contributed to the research reviewed. The second, interdisciplinary phase of POEM-BC, including Biology and Chemistry, is now underway.

locations, rates and dynamics of water mass formations and transformations are beginning to emerge. Furthermore, a new picture of the scales, structures and dynamics of the horizontal general circulation and its variabilities is becoming apparent (Robinson and Golnaraghi, 1991, hereafter RG91). Thus the basis now exists for research in understanding climate related dynamical processes of global relevance, in detail and in a basin-wide context.

Modeling, of course, plays a significant role in modern ocean scientific research. Multiple and interacting scales and processes require a multi-faceted modeling approach. Dynamics in the model studies overviewed here range from geostrophy to full primitive equation and include quasigeostrophy and linearized primitive equations with active thermodynamics. Methods range from geochemical modeling with no dynamics to prognostic studies with multiple forcing functions and include inverse modeling. Domains range from regional to the full eastern basin to the entire Mediterranean Sea and both climatological and POEM data sets are utilized. Furthermore, the assimilation of data into models, the construction of melded estimates from models and observations and data-based simulations now provide efficient mechanisms for exploiting observations. Data assimilative models are not only useful research tools. They also provide the best mechanism for estimating the four-dimensional fields required for transport estimates for heat, chemicals, particles, etc. necessary for climate related research and other interdisciplinary marine science and technology. A realistic set of high resolution multiscale basin-wide management models can be based upon the research models developed for general circulation and climate change research.

The following sections will discuss processes, describe the multiscale circulation, review recent modeling studies and illustrate data assimilation for the Eastern Mediterranean Sea. A preliminary and less comprehensive version of this review appears in the Proceedings of the Symposium on "Oceans, Climate and Man" (Robinson, 1992).

## 2. PROCESSES

Processes of global relevance for ocean climate dynamics include aspects of the thermohaline circulations, water mass formations

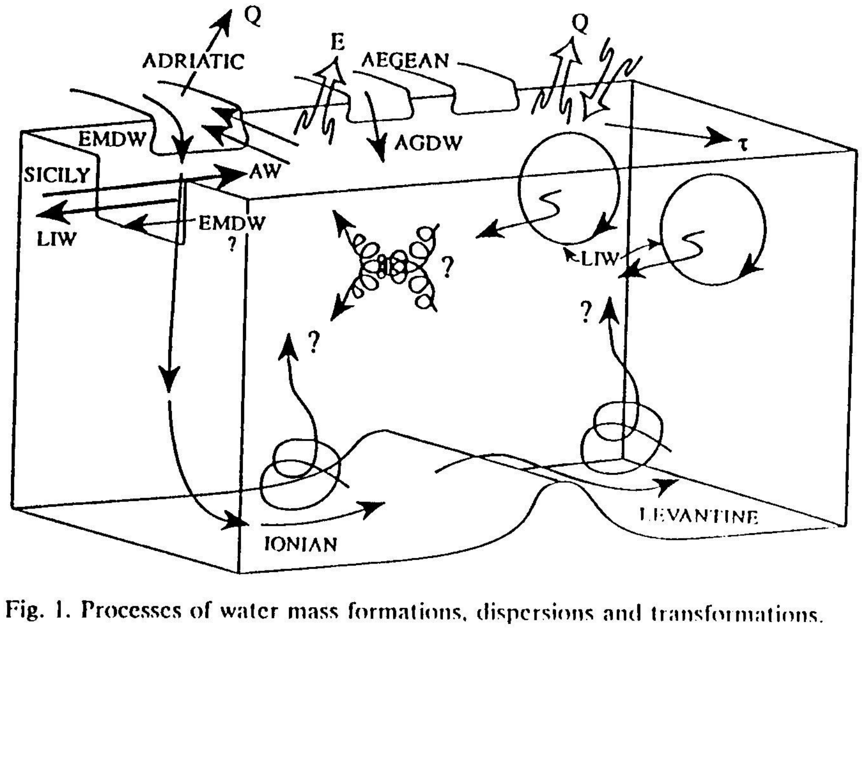


Fig. 1. Processes of water mass formations, dispersions and transformations.

and transformations, dispersion and mixing. Processes are sketched schematically on Fig. 1. Fresh water of Atlantic origin (*AW*) enters through the Straits of Sicily. As it circulates, driven by the wind ($\tau$) and other forces, evaporation ($E$) greatly exceeds precipitation at the surface and the water becomes more saline and dense. Net heating ($Q$) occurs in summer and cooling in winter. In the Levantine basin, predominantly in March, Levantine Intermediate Water (*LIW*) is formed during storm events. The newly formed water mass circulates and disperses at depths down to a few hundred meters. Some LIW recirculates within the basin and some exits beneath the AW through the Sicily Straits. The ratio of recirculation to eflux is not well known but the net inflow and outflow transports through the Sicily Straits are estimated between 1–1.5 Sverdrup ($10^6$ $m^3/s$). LIW is the predominant source of the Mediterranean water masses in the Atlantic.

Deep water formation occurs primarily in the Adriatic Sea, which produces bottom water, the Eastern Mediterranean Deep Water (*EMDW*). However, Aegean Deep Water (*AGDW*) also forms, sinking to depths somewhere in the middle of the water column. The site of EMDW formation in winter is the southern Adriatic which is several hundred meters deep. Very cold and dry air storms apparently cause deep convection throughout the water column. The detailed formation process is not well known but it involves surface water admixed with LIW which has entered from the Mediterranean. The newly formed EMDW then exits the Adriatic through the Straits of Otranto, plunges to the bottom, and moves off along the deep western boundary of the Ionian basin. A single vertical thermohaline cell exists for the whole Eastern Mediterranean, although the partitioning of the rising motion between the Ionian and Levantine basins is not known. Other essential unknowns are the locations and rates of mixing between waters of LIW and EMDW origins. This is symbolized by the crossed corkscrew arrows on Fig. 1. There is also no observationally based quantitative estimate at present of the amount of (mixed) EMDW which exists at the base of the LIW flow through the Straits of Sicily.

The thermohaline circulations, which are included on Fig. 1 are redrawn for clarity in Fig. 2. For simplicity, the schematic mixing of EMDW and LIW has been omitted. There is an internal cell, a single vertical cell encompassing both the Ionian and Levantine basins, and an external cell. The external thermoha-

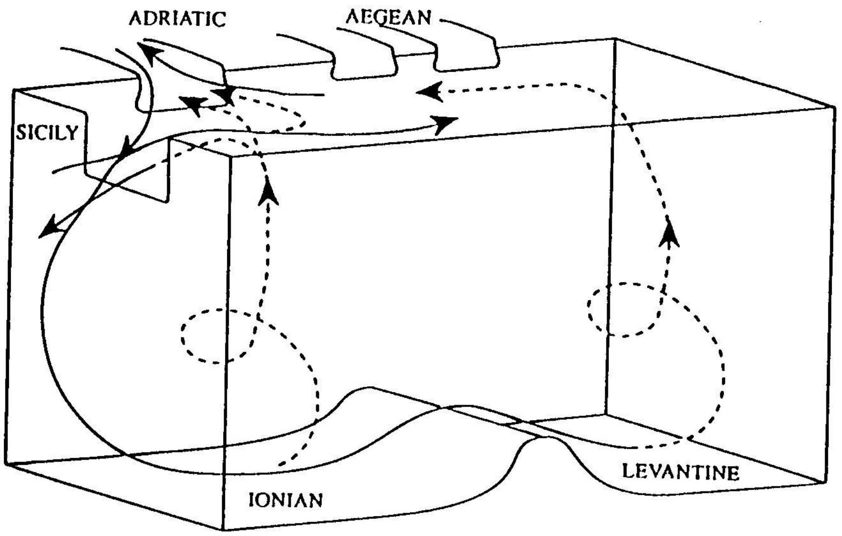


Fig. 2. The thermohaline cells.

line cell involves an exchange of water through the Straits of Sicily. The remote excursions of EMDW and the return paths in the Western Mediterranean and Atlantic Ocean are not known.

There is special interest attached to the internal cell in that it is a closed thermohaline cell in which the deep water formation involves a preconditioning process of density increase due to saltiness. Thus, it is to some extent an analog of the global scale "conveyor belt" thermohaline cell whose deep water forms in the North Atlantic (Gordon, 1986; Broecker, 1987). A detailed understanding of the Eastern Mediterranean cell should be achievable in the near future which should be expected to contribute insights into globally relevant processes.

## 3. THE MULTISCALED CIRCULATION

It is now known that the general circulation and its variabilities consist of three predominant spatial scales which must be understood together with their nonlinear interactions. This concept is depicted schematically in Fig. 3. The slow (vertical) thermohaline cell is *basin* scale. The basin scale general circulation of the main thermocline of the upper ocean is composed of *subbasin* scale gyres linked by subbasin scale jets. There are a variety of subbasin scale variabilities which will be described below. The energetic *mesoscale* which is present is illustrated in Fig. 3 on one of the subbasin scale gyres by a field of internal eddies and a meandering of the outer swirl flow, and as the meandering of a jet segment.

The POEM program conducted five quasi-synoptic nominally basin-wide hydrographic surveys from 1985 through 1987 (Robinson et al., 1991). The sampling patterns were grids with nominal spacings of one half degrees of latitude and longitude, which provides fine general circulation (subbasin) scale and coarse mesoscale resolutions (Robinson et al., 1987). The best coverage, achieved with six ships during August–September 1987, is shown in Fig. 4. A basin-wide multiscale experiment was conducted simultaneously from the F/S *Meteor*, whose track is superimposed over the survey grid on Fig. 4. Transient tracer measurements were made to investigate the deep thermohaline circulation and XBT's were taken uniformly every ten kilometers along the ship track to explore the characteristics of mesoscale phenomena throughout the basin. CTD stations were also carried out.

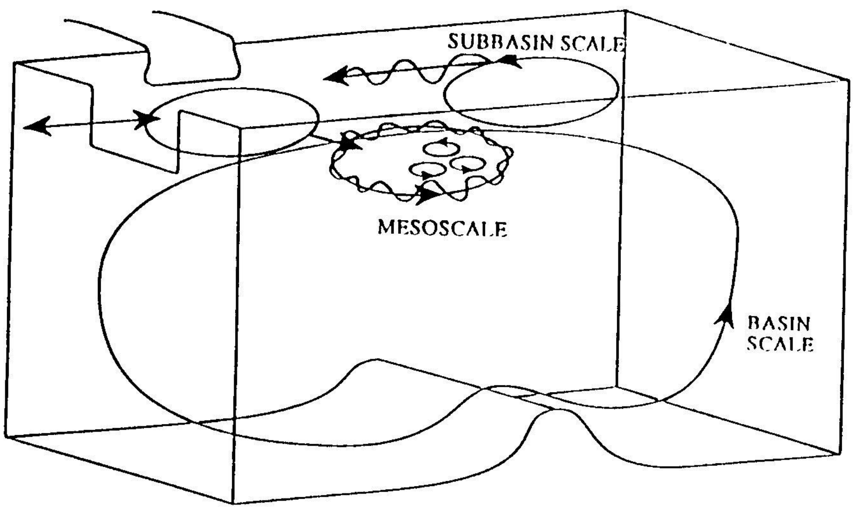


Fig. 3. Scales of circulation variabilities and interactions.

### 3.1. The basin scale thermohaline cell

The transient tracer experiment consisted of 62 stations where chlorofluoromethane (CFM) and tritium were measured (Schlitzer et al., 1991). The CFM Freon 12 distribution along the sections *AB* (east–west) and *FG* (north–south), shown in Fig. 4 are presented in Fig. 5. The source of Freon 12 is the atmosphere, and there is, of course, a large concentration in the upper ocean. But, there is also a maximum in the Freon distribution in the deepest water in the western basin (off the Malta escarpment) which is clear evidence for the presence of recently formed deep water of Adriatic origin. Note also the minimum concentration at mid-depths in the eastern Ionian basin.

In order to obtain quantitative information about the deep water renewal rate from this data set, Roether and Schlitzer (1991) have constructed a 22 box model with compartments for the Ionian and Levantine deep water below 1000 m depths. More details are presented in the modeling Section 4 below. They find that the water formed in the Adriatic is a mixture of surface water (AW) and intermediate water (LIW) from the Mediterranean which, therefore, has also previously been subject to surface fluxes. Their results indicate unambiguously that the thermohaline circulation consists of a single vertical cell throughout the entire Eastern Mediterranean, flowing coherently throughout both the Ionian and Levantine basins. The turnover time for the deep water is 126 years.

The rate of deep water supply is $0.29 \pm 0.09$ Sverdrups ($10^6$ $m^3/s$). This is about one third of the inflow or outflow rate of all waters through the Sicily Straits. There is some qualitative evidence observationally, from transient tracer measurements (Roether and Schlitzer, 1991) that some EMDW does exit through the Straits of Sicily. The only

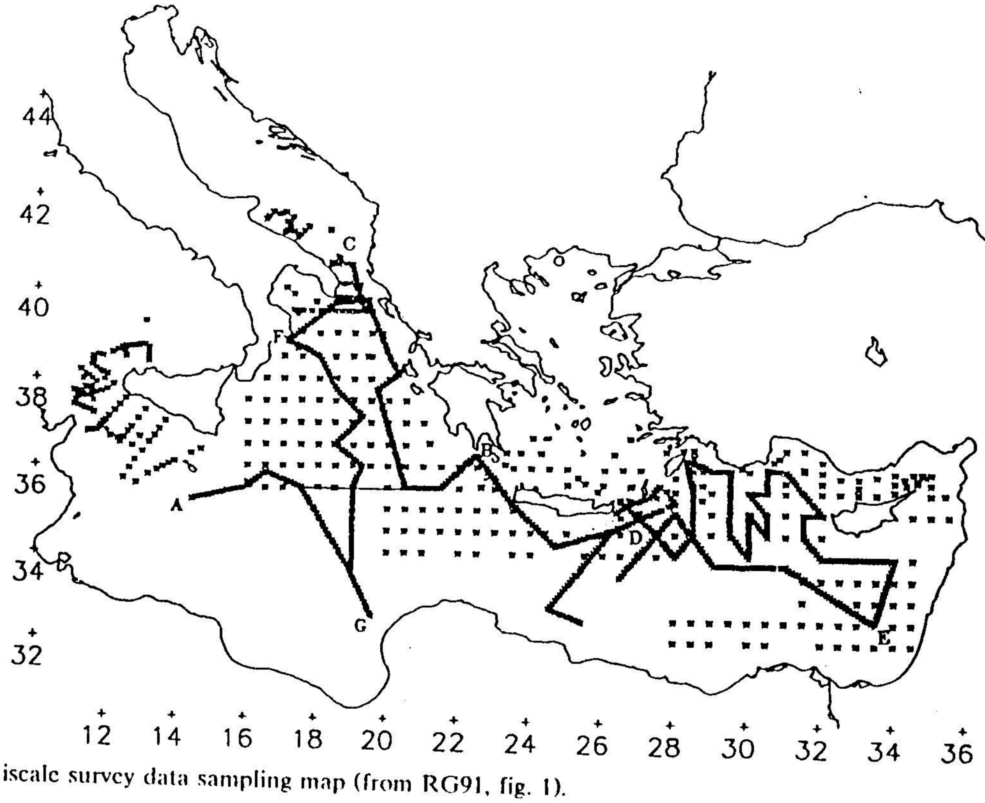


Fig. 4. Multiscale survey data sampling map (from RG91, fig. 1).

quantitative information comes from a numerical general circulation model for the Eastern Mediterranean which has active thermodynamics (Malanotte-Rizzoli and Bergamasco, 1991) although the stratification is imposed and the deep convective process is not modeled. The model is discussed in Section 4; in the model about one third of

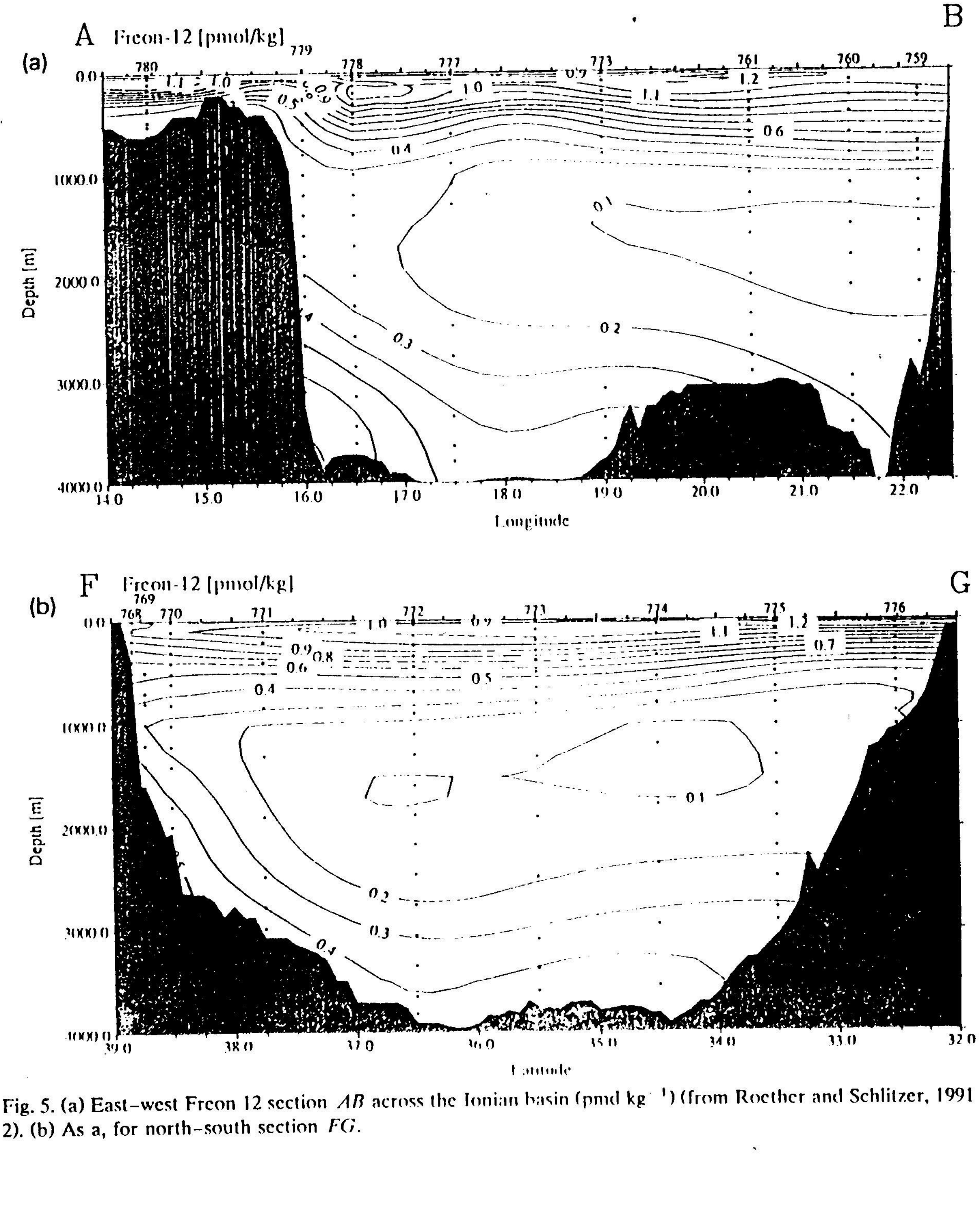


Fig. 5. (a) East–west Freon 12 section *AB* across the Ionian basin (pmol kg$^{-1}$) (from Roether and Schlitzer, 1991 fig. 2). (b) As a, for north–south section *FG*.

the water effluxing through the Straits of Sicily is deep water which has upwelled in the southern Ionian basin. At this time it would seem reasonable to assume that internal and external thermohaline cells are of comparable magnitude.

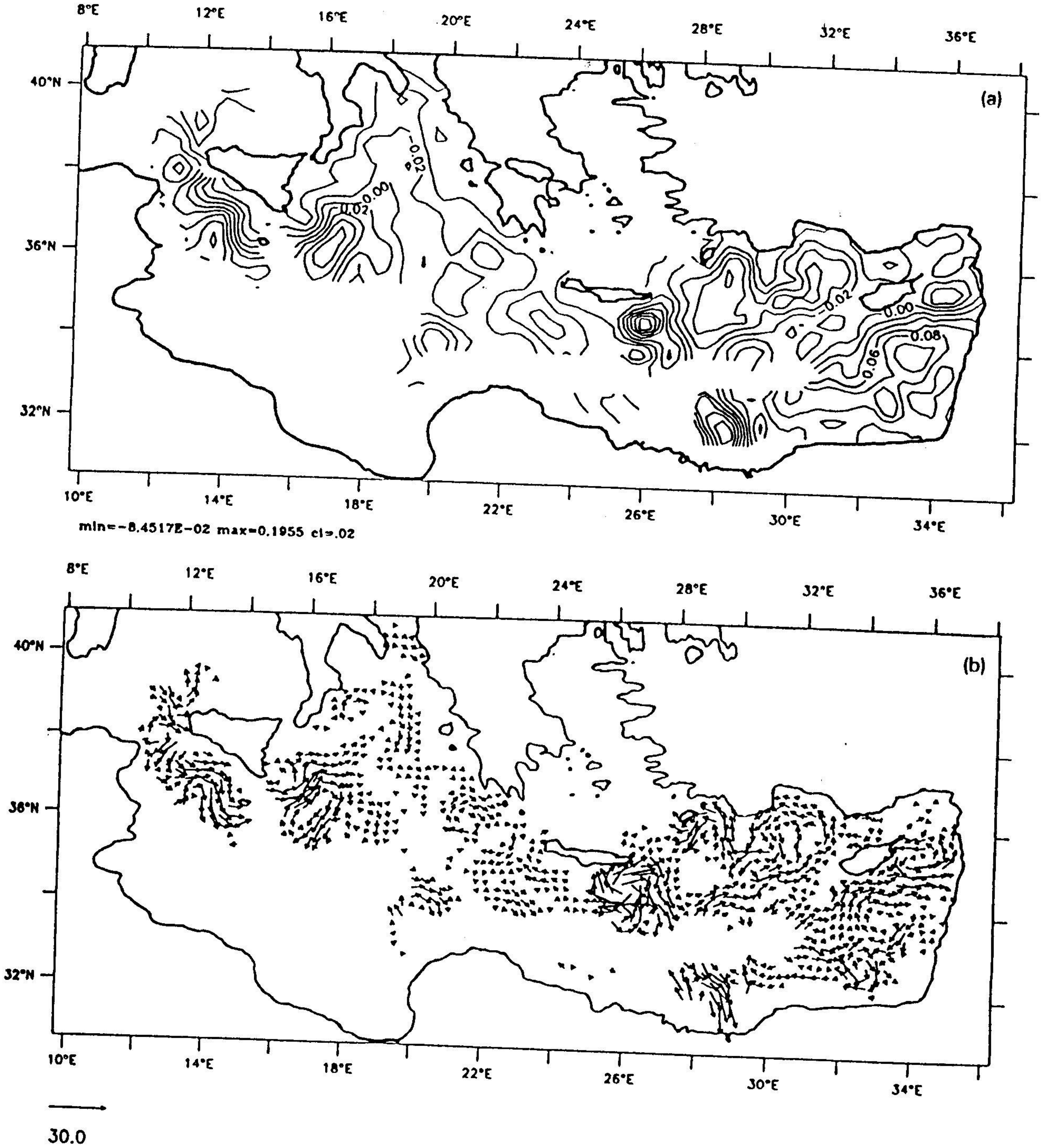


Fig. 6. (a) Dynamic height anomaly in the upper thermocline, 30 m relative to 450 m (dynamic meters) August–September 1987. (b) Associated horizontal geostrophic flow vectors (scale vector cm $s^{-1}$). (c) As a, but for October–November, 1985. (d) as b, for October–November, 1985 (from Robinson et al., 1991, figs. 7, 8).

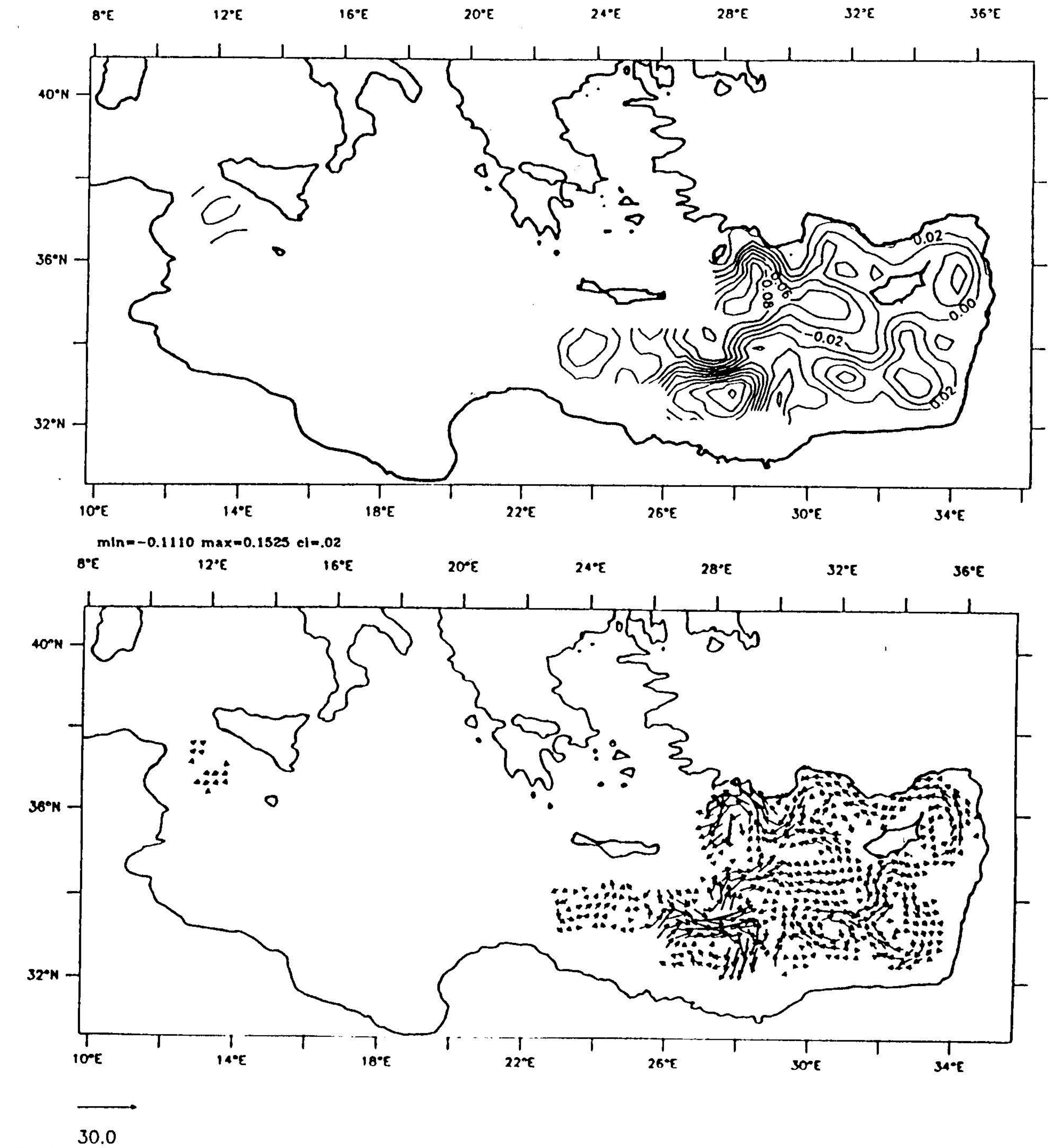


Fig. 6 (continued).

### *3.2. The subbasin scale components of the general circulation*

A synthetical study has been carried out for the five independent quasisynoptic realizations contained in the pooled data set of POEM (Robinson et al., 1991). Özsoy et al. (1991) review the Levantine basin POEM data together with some additional northern basin data extending to 1988. The currents

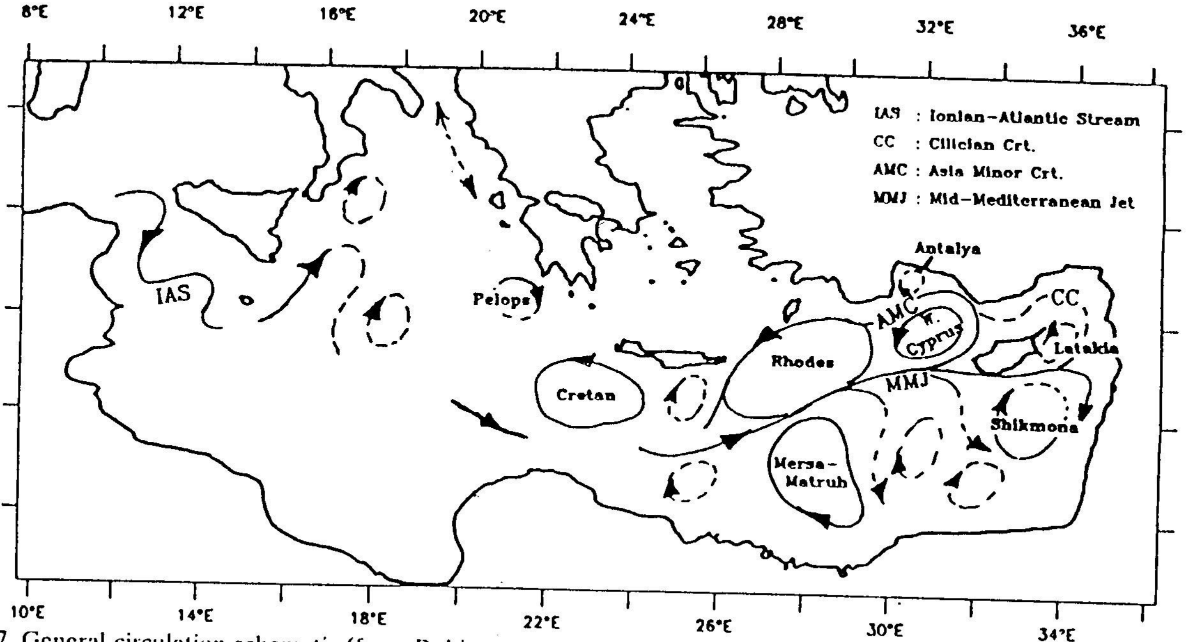


Fig. 7. General circulation schematic (from Robinson et al., 1991, fig. 2).

and circulation of the upper ocean thermocline for the summer of 1987 and the fall of 1985 are shown on the objectively analyzed dynamic height (30 m relative to 450 m) and current vector maps of Fig. 6. In the objective analysis the correlation function is time independent with a zero crossing at 100 km and an e-folding scale of 67 km, and a constraint of no flow into the coast is imposed. The complex patterns of cyclonic and anticy-

TABLE 1

Upper thermocline features (from Robinson et al., 1991, table 1)

| Features | Type | ON 85 | MA 86 | MA 87 | AS 87 |
|---|---|---|---|---|---|
| Ionian Atlantic Stream | P | – | – | Y | Y |
| Mid Med. Current | P | Y | Y | – | Y |
| Asia Minor Current | P | Y | N | Y | N |
| Cilician Current | R | Y | Y | – | Y |
| Southeast Levantine Jets | T | Y | Y | – | Y |
| Rhodes C | P | Y | Y | – | Y |
| West Cyprus C | P | Y | Y | – | Y |
| Mersa Matruh AC | P | Y | Y | – | Y |
| Cretan Sea C | P | Y | ? | – | Y |
| Shikmona AC | R | Y | Y | – | Y |
| Latakia C | R | Y | N | N | Y |
| Antalya AC | R | ? | Y | – | N |
| Pelops AC | ? | – | Y | ? | Y |
| Ionian eddies AC | T | – | – | – | Y |
| SE Levantine eddies AC | T | Y | Y | – | Y |
| Eddies in the Strait of Crete | T | Y | Y | – | Y |

Definitions: P = Permanent, R = Recurrent, T = Transient, ? = Not enough information to classify, C = Cyclone, AC = Anticyclone.

clonic gyres linked by jets and current segments is real; no contours are plotted where the expected error of the objective analysis is greater than 75%.

The two realizations shown in Fig. 6 illustrate the general features of the circulation and its variabilities. The jet of Atlantic water entering through the Sicily Straits and mean-

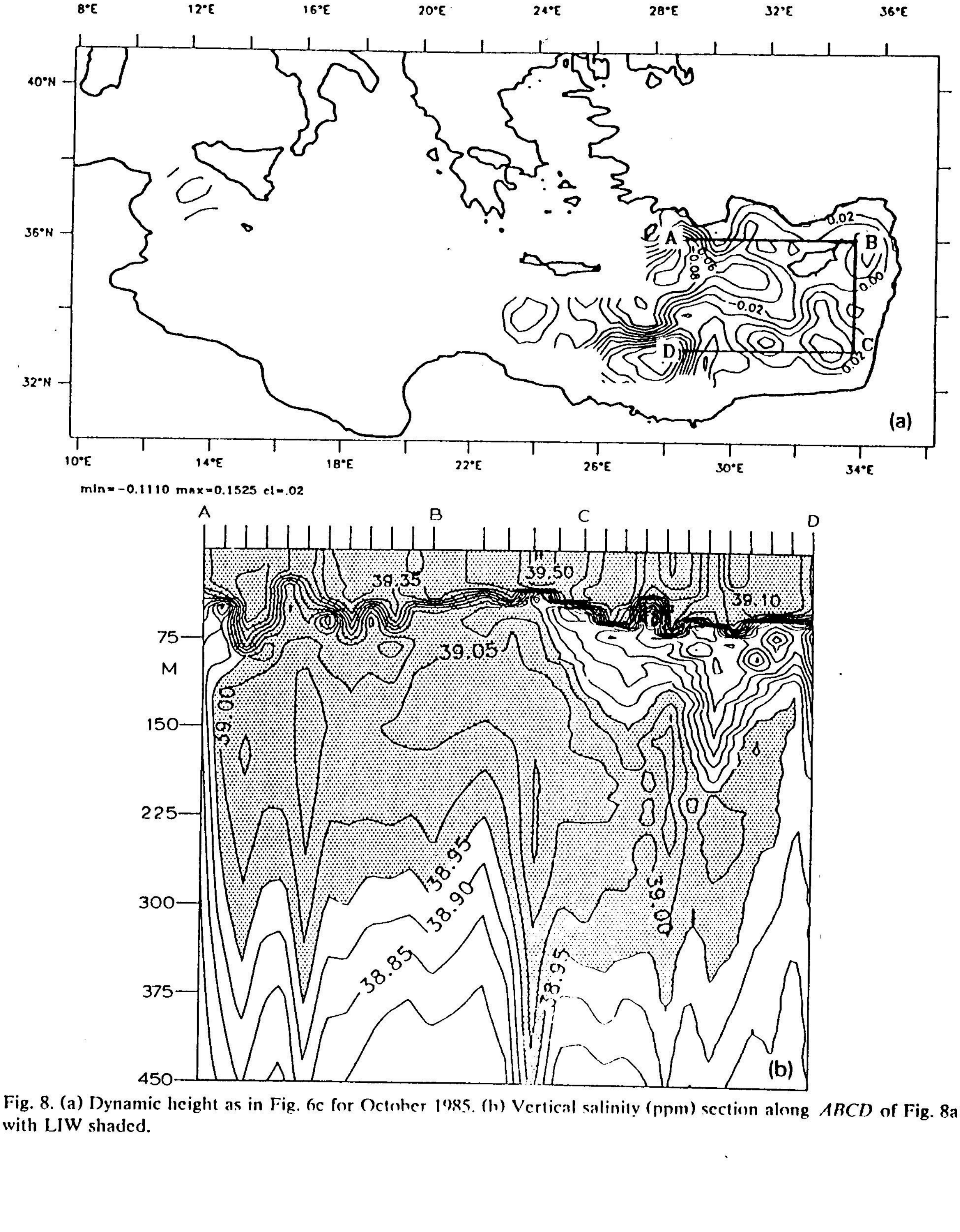


Fig. 8. (a) Dynamic height as in Fig. 6c for October 1985. (b) Vertical salinity (ppm) section along *ABCD* of Fig. 8a with LIW shaded.

dering into the Ionian Sea, we believe, continues to feed the Mid-Mediterranean Jet flowing in the central Levantine. One branch of the Mid-Mediterranean Jet flows to Cyprus and thence northward becoming the Asia Minor Current; a second branch separates, flows east and turns southward. Sometimes (Fig. 6c, d) a bifurcation occurs with flow around Cyprus into the Cilician Current. Subbasin features are the broad cyclonic region between Rhodes and Cyprus, comprised of two or three cyclonic centers including the Rhodes gyre (whose northern border is the Asia Minor current) and the strong anticyclonic Mersa Matruh gyre off the Egyptian coast which can be north–south (Fig. 6a, b) or east–west (Fig. 6c, d) elongated. Note the transient Southeastern Levantine eddies. The anticyclone south of Cyprus, the Shikmona eddy, has been shown to be quasipermanent for long time durations. Typical speeds of 20–30 cm/sec occur in the subbasin scale gyres and jets.

The results for the circulation and variabilities of all the surveys are summarized in the schematic of Fig. 7 and the companion Table 1. There are a number of permanent, albeit variable, subbasin scale features. Other features are recurrent, i.e. disappear but reappear similarly. Transient gyres and jets also occur randomly throughout the basin. Variabilities characterizing the permanent and recurrent structures include: the center, size and strength of gyres and their multi-lobe mesoscale instabilities; the axis location, meander pattern and bifurcation structure of jets. The time scales associated with the subbasin scale variabilities and mesoscale interactions are not yet well defined but appear to range from years (e.g., recurrence time of the Shikmona gyre) to days (mesoscale interactions). The general circulation modeling studies of Section 4 indicate that subbasin scale structures are the form of the Eastern Mediterranean's response to the large-scale forcing functions due to factors including topographic effects and the seasonal power in the wind-stress forcing. In Section 5 the subbasin scale features are shown to be remarkably robust and stable to the dynamical adjustment process.

### *3.3. Levantine Intermediate Water*

The formation of Levantine Intermediate Water was for many years believed to occur predominantly in a limited region between Rhodes, Cyprus and the Turkish coast and to involve a preconditioning process afforded by the domed pycnocline characteristic of the Rhodes gyre. Recent evidence, however, indicates that formation occurs over a much larger domain which could include the centers of anticyclonic gyres via a process related to thermocline deepening in warm core Gulf Stream rings (Dewar, 1986). The horizontal circulation structures and pattern, of Fig. 6c observed and first analyzed by Ozsoy et al. (1989) for the upper thermocline of the Levantine basin in October of 1985 is shown in Fig. 8a. A composite vertical salinity section around the basin (*ABCD* on Fig. 8a) is shown on Fig. 8b with LIW (salinity greater than 38.95 ppm) shaded. LIW is prevalent and ubiquitous throughout the basin including the southern sector.

### *3.4. Mesoscale variability*

The internal Rossby radius of deformation is the horizontal scale which characterizes mesoscale instabilities, meandering and eddying. It is essentially the vertical scale (e.g. thermocline depth) of the phenomenon amplified by the ratio of the Brunt–Väisälä buoyancy frequency to the Coriolis parameter. Since this length scale is only ~10–12 km in the Eastern Mediterranean, four times smaller than typical values for much of the worlds ocean, mesoscale phenomena were not defined in observations until recently when dedicated high resolution sampling was undertaken (Robinson et al., 1987).

The mesoscale experiment conducted in 1987 by A.R. Robinson, W.G. Leslie and N. Pinardi took 620 XBT samples at nominal 10

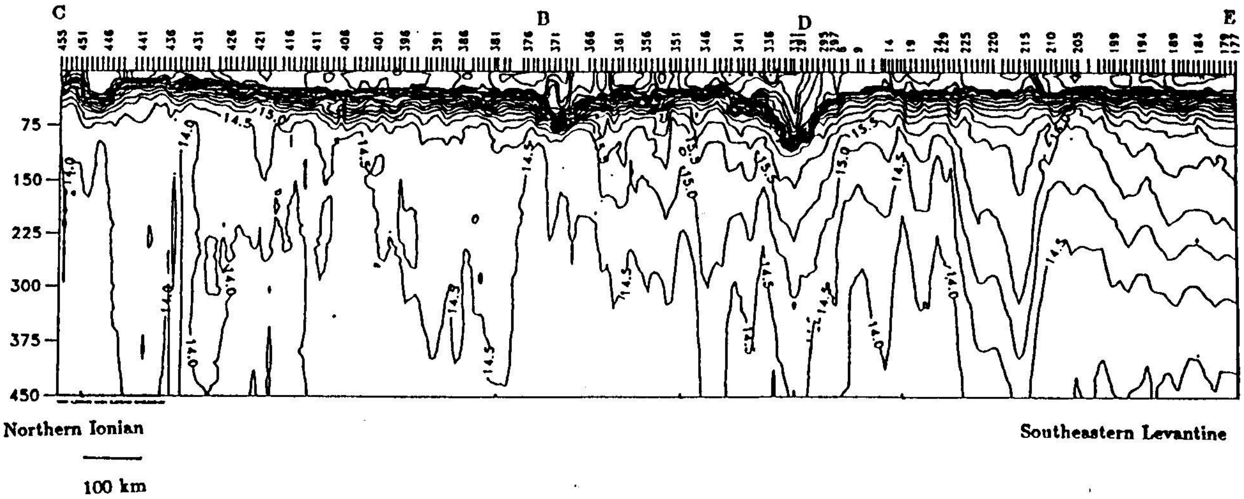


Fig. 9. Composite XBT derived temperature section along track *CBDE* of Fig. 4 (from RG91, fig. 5).

km spacing along the entire F/S *Meteor* ship track. A composite section across the basin from the mouth of the Adriatic Sea to the southeastern Levantine corner (*CBDE* in Fig. 4) is shown on Fig. 9. A number of interesting features are present which characterize the highly resolved structures of the subbasin scale gyres and jets (e.g. the eddy south of Crete in the vicinity of *D*). Mesoscale eddies exist in the open sea (e.g. northwest of *E*) and interactively with the subbasin scale features. The Levantine basin appears more energetic in the mesoscale, with the Ionian (*C–B*) characterized by a remarkable thermostad at 14.0–14.5 °C from 75 to 450 m.

## 4. MODELING THE GENERAL CIRCULATION

Three types of ongoing modeling efforts in the Mediterranean Sea will be presented in this section. The first effort consists of a series of idealized numerical experiments aimed at investigating the purely wind-driven circulation in the entire Mediterranean. The second, and more realistic, effort is focused mainly on the Eastern Basin, with the objectives of investigating both the wind-driven and thermohaline components of the circulation under climatological conditions and understanding the relative importance of the different forcing functions in the different subbasins of the Eastern Mediterranean. Three methodologies have been simultaneously used: (i) inverse techniques, (ii) prognostic calculations with a numerical circulation model and (iii) a variational data assimilation approach based upon the adjoint method of control theory. The third effort focuses on understanding the thermohaline cell of the Eastern Mediterranean with a conceptual box model that simultaneously uses chlorofluoromethane (CFM) and tritium data obtained during the POEM-V survey in summer 1987.

In the first approach Pinardi and Navarra (1992) use the Geophysical Fluid Dynamics Laboratory (GFDL) model of Cox (1984) adapted to the Mediterranean geometry. The model uses 1/4° coarse resolution (the baroclinic Rossby radius of the Mediterranean is ~ 12 km) and eight levels in the vertical. Except for near the coasts, the basin is flat bottomed in its western and eastern basins (separated by the Sicily Straits) and the Gibraltar Strait is closed. The vertical density structure is initialized with annual average data and the temperature and salinity fields are fixed at the surface to simulate perpetual annual mean conditions. The purely wind-driven circulation is forced by monthly mean climatological stresses. A typical result is shown in Fig. 10, which presents the transport streamfunctions in the months of January (upper panel) and July (lower panel) at the end of the month. The response is clearly seasonal, with a winter-to-summer change in flow features including reversals induced by the wind stress curl annual harmonics. This seasonal response of the purely wind-driven circulation over the flat-bottomed basin is in large part constituted by Rossby waves as evident from Fig. 10.

The second modeling effort is the one undertaken by Malanotte-Rizzoli and collaborators in which three approaches have been used simultaneously. In the first study, Tziperman and Malanotte-Rizzoli (1991) use a simple inverse model to calculate the horizontal circulation of the upper 800 m of the entire Mediterranean Sea for a seasonal climatological hydrographic dataset. The inverse results were used to address three main aspects of the general Mediterranean circulation, namely the seasonality of the surface circulation; the shape of the general circulation of the Eastern basin and the shape of the deep circulation of the entire Mediterranean. Figure 11 shows the winter circulation (upper panel) and the summer one (lower panel) in the surface layer, at a depth of 10 m. A fairly steady yearly pattern of the surface circulation in the Western basin emerges from an examination of Fig. 11. The seasonal signal is somewhat stronger in the

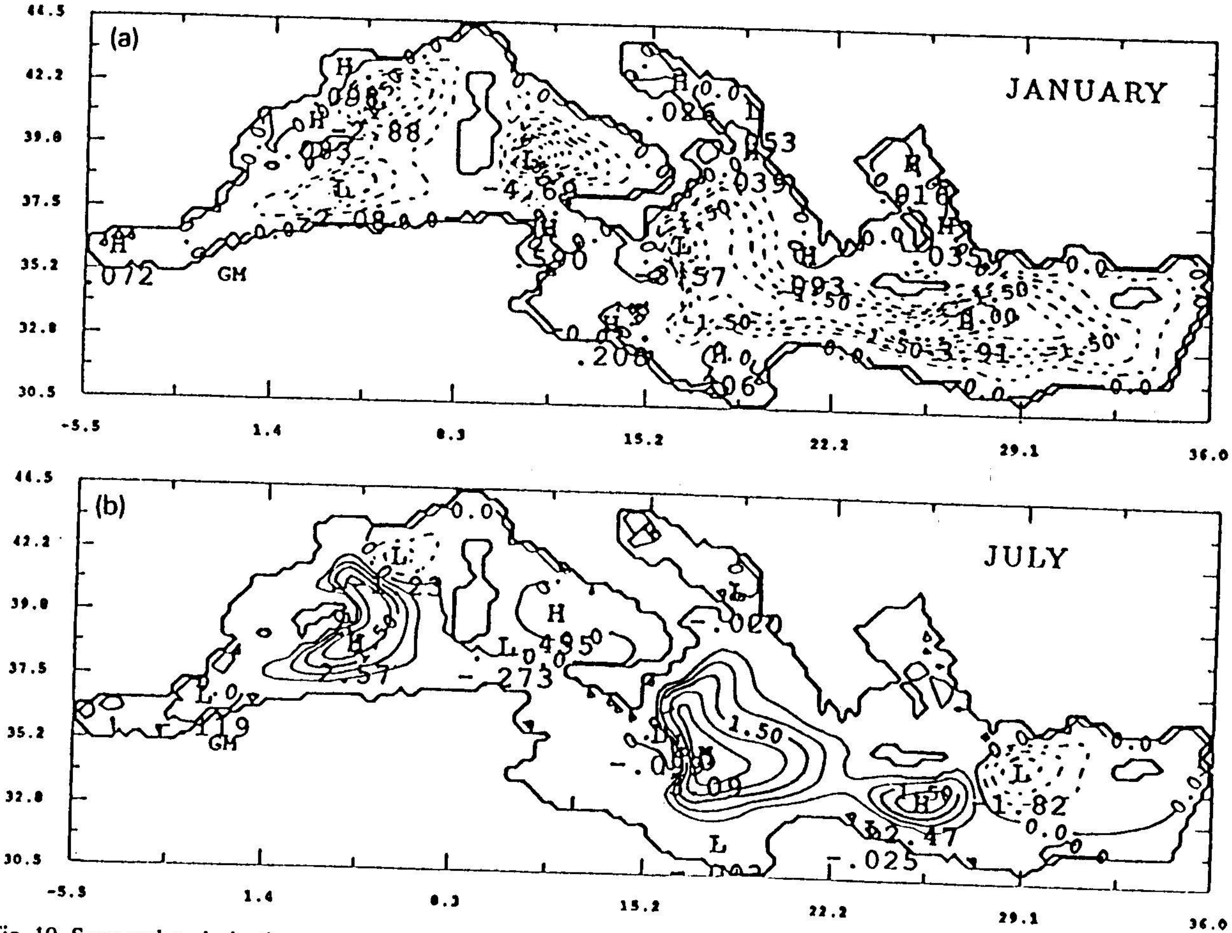


Fig. 10. Seasonal cycle in the transport streamfunction. The pictures are instantaneous fields taken at the end of the month indicated in the upper right corner of each plot. Units are Sverdrup and the contour interval is 0.5 Sv (from Pinardi and Navarra, 1992, fig. 8).

Eastern basin and especially in the Ionian Sea where the jet of Atlantic water entering the Sicily Straits shoots south-eastward in winter (Fig. 11a) while forming an intense meander that protrudes into the Northern Ionian in summer (Fig. 11b). Also, Fig. 11 clearly shows the Eastern Mediterranean circulation to be constituted by a succession of subbasin scale gyres.

In a parallel study, Malanotte-Rizzoli and Bergamasco (1991) carried out an intensive series of numerical experiments investigating the wind-driven and thermohaline components of the Eastern Mediterranean circulation and the relative importance of the different forcing functions under climatological conditions in the different regions of the Eastern basin. They used a linearized, primitive equation level model with coarse resolution but with active thermodynamics and realistic topography with the Sicily Straits open. The model is forced by the monthly climatological means of: wind stress; heat fluxes (incoming solar radiation, backscatter, latent and sensible heat); and evaporation minus precipitation fluxes. The inflow imposed at the Sicily Straits is derived from real data and the hydrographic temperature and salinity dataset is the same used by Tziperman and Malanotte-Rizzoli (1991).

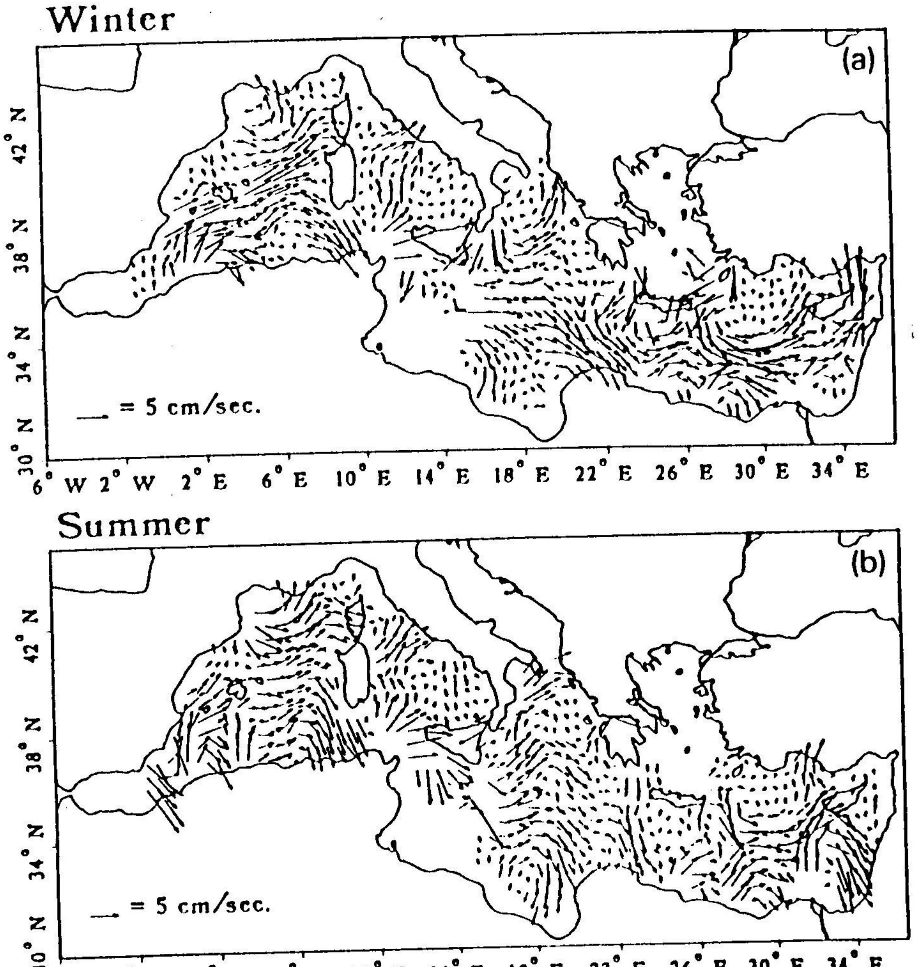


Fig. 11. (a) The winter circulation at 10 m depth. (b) The summary circulation at 10 m depth. The velocity vector scales are indicated (from Tziperman and Malanotte-Rizzoli 1991, fig. 4 winter, fig. 6 summer).

The numerical results indicate that the inflow at Sicily is the dominant driving mechanism in the Ionian Sea, with a strong seasonal modulation imposed by the change in polarity of the wind-stress curl from winter to summer over the Ionian. However, the thermohaline fluxes emerge to be the dominant driving mechanism for the circulation in the Eastern Levantine, where the seasonal signal is greatly attenuated. Figure 12 shows the total transport streamfunction in the Central Experiment, the one both wind and thermally forced in which all the fields are evaluated prognostically, respectively for January (upper panel) and September (lower panel). Examination of Fig. 12 shows the circulation to be quasi-steady in the Eastern Levantine. In the Ionian Sea, the jet of Atlantic water entering through the Sicily Straits is deflected southward towards the African coast in winter (upper panel) while forming a big, northward protruding meander in summer (lower panel). The similarity of Fig. 12 with the inverse results of Fig. 11 is striking and also shows the importance of the barotropic, forced component of the circulation in the Eastern basin. A final result is that many of the persistent features found in

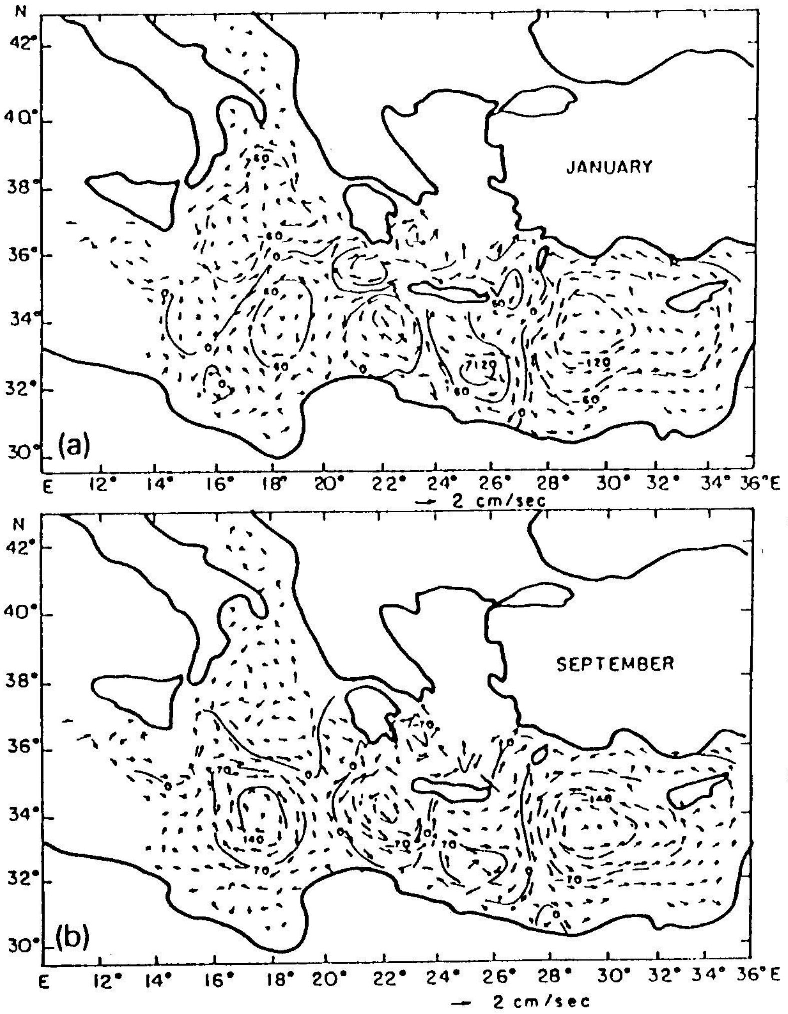


Fig. 12. Total average transport in January (a) and September (b). Transport vectors are normalized by the maximum value. Transport streamlines are superimposed with a contour interval 0.6 (a) and 0.7 (b) Sverdrups (normalized by $10^2$). Corresponding maximum depth-averaged velocities are annotated (from Malanotte-Rizzoli and Bergamasco, 1991, fig. 16).

the model circulation patterns can be related to the strong control exerted by the ambient potential vorticity ($f/H$) upon the circulation (compare, for instance, the patterns of Fig. 12 with Fig. 15 which shows the bottom relief).

In a final approach, the adjoint method of control theory is used to determine the seasonal circulations of the Eastern basin (Bergamasco et al., 1992). The GFDL model, adapted to the Eastern basin, has been coupled with its adjoint developed by collaborators Long and Thacker. The prognostic model is forced with the climatological wind stress field and the hydrological data set of temperature and salinity is used to constrain the model predicted fields as part of the cost function of the adjoint. The cost function also includes terms penalizing the tendencies of the prognostic fields, i.e. horizontal velocities, temperature and salinity. The GFDL model and its adjoint are used with 1/4° coarse resolution but with 17 vertical levels, thus allowing for a realistic topography in the Eastern basin. The Sicily Straits are also open with the same forcing inflow of Malanotte-Rizzoli and Bergamasco (1991). Thus, a seasonal circulation of the Eastern Mediterranean is reconstructed that is consistent both with the model dynamics and the climatological hydrographic dataset. A preliminary result in Fig. 13 shows the circulation pattern in the surface layer, 1 to 50 m depth, for the winter season. Again, the similarity is striking between the winter circulation and the corresponding patterns obtained through the independent inverse method (Fig. 11a) and the prognostic calculations (Fig. 12a).

The final modeling effort is the one followed by Roether and Schlitzer (1991) and aimed at understanding the pathways of the Eastern Mediterranean deep circulation. They use the box model shown in Fig. 14, where the deep water regime is represented

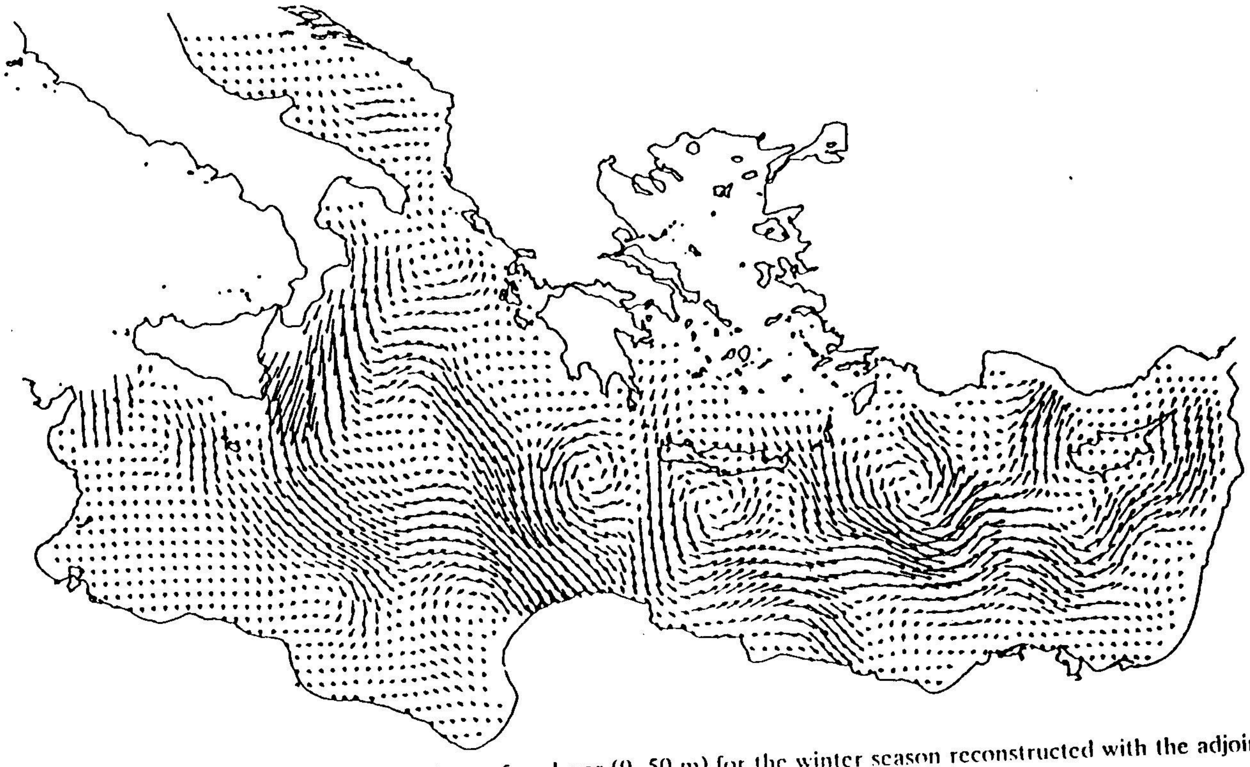

Fig. 13. Steady circulation pattern in the surface layer (0–50 m) for the winter season reconstructed with the adjoint approach (from Bergamasco et al., 1992).

by boxes no. 1 to 16 and the boundary regime by boxes *a* to *f*. Boxes *b* through *f* represent near surface water in the Ionian preconditioned as intermediate water, which mixes in the Adriatic with surface water when deep water is formed. They simultaneously use the CFM and tritium measurements obtained during the general survey of the summer of 1987. The data are interpreted by means of the conceptual model of Fig. 14 to quantify the renewal, recirculation and mixing of the waters below ~1000 m depth. The model gives a replacement of the waters below 1400 m depth by waters above 1000 m, converted by way of the Adriatic, at the rate of $2.9 \pm 0.9 \times 10^5$ $m^3$ $s^{-1}$. The results indicate that the deep water of the Eastern Mediterranean below ~1200 m forms a coherent thermohaline convective system (see also Fig. 5).

## 5. DATA ASSIMILATION INTO DYNAMICAL MODELS

Dynamical studies and dynamically adjusted field estimates are being carried out by the Harvard group and collaborators involving the initialization of dynamical models with the POEM synoptic data sets. The studies address: the structure, dynamics and instabilities of the circulation and its components; nonlinear scale interactions; the relative role of external forcing vs. internal dynamical processes; and the construction of transport fields for air–sea interactions and water mass research.

### 5.1. *Methodology*

The Harvard dynamical model hierarchy consists of a set of compatible and intercom-

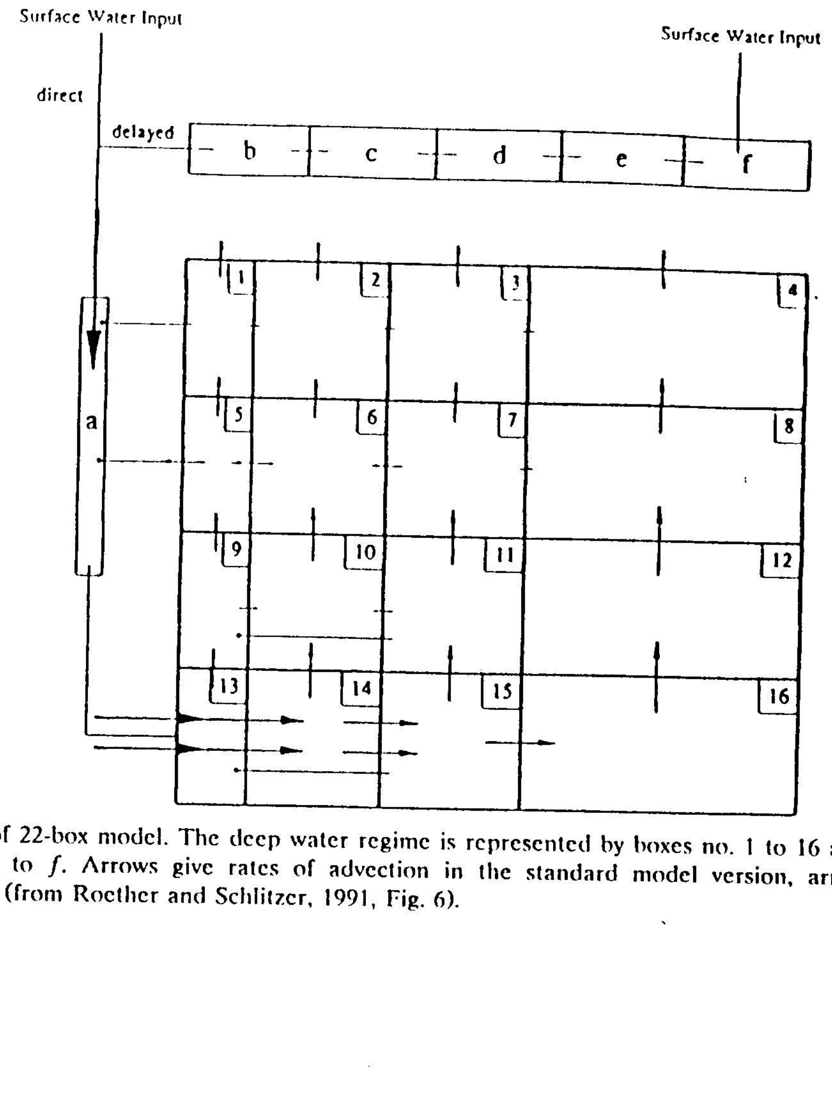


Fig. 14. Geometry of 22-box model. The deep water regime is represented by boxes no. 1 to 16 and the boundary regime by boxes *a* to *f*. Arrows give rates of advection in the standard model version, arrow length being proportional to rate (from Roether and Schlitzer, 1991, Fig. 6).

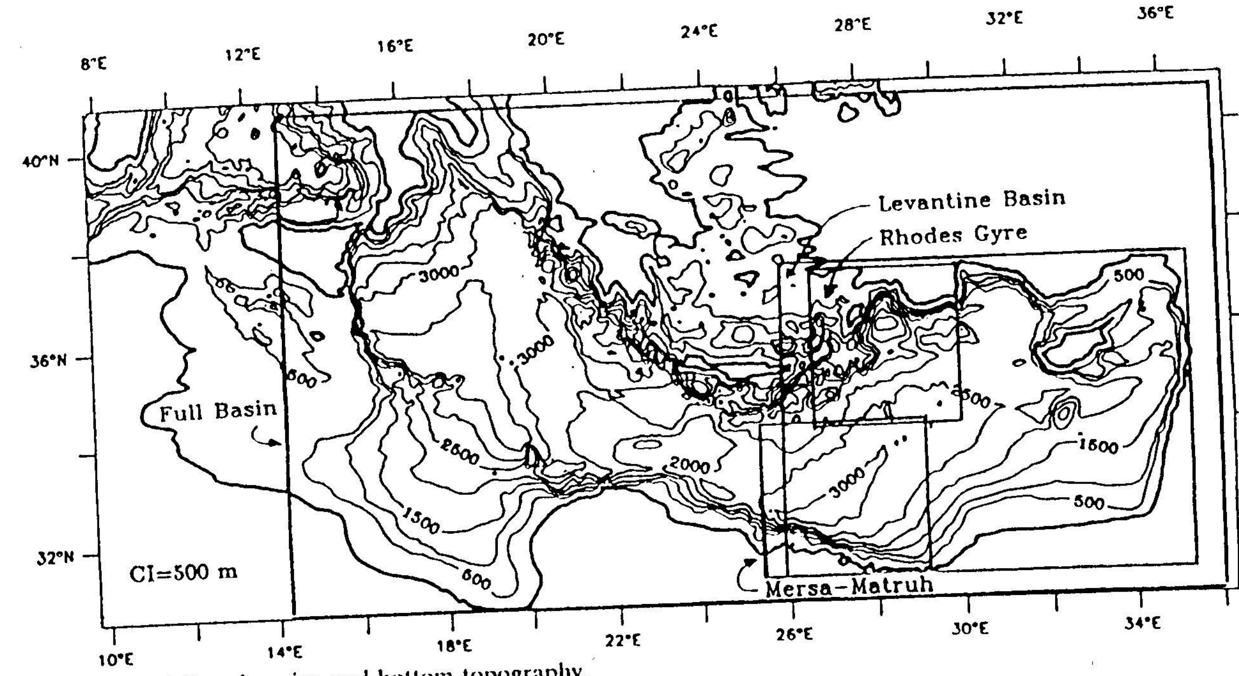


Fig. 15. Modeling domains and bottom topography.

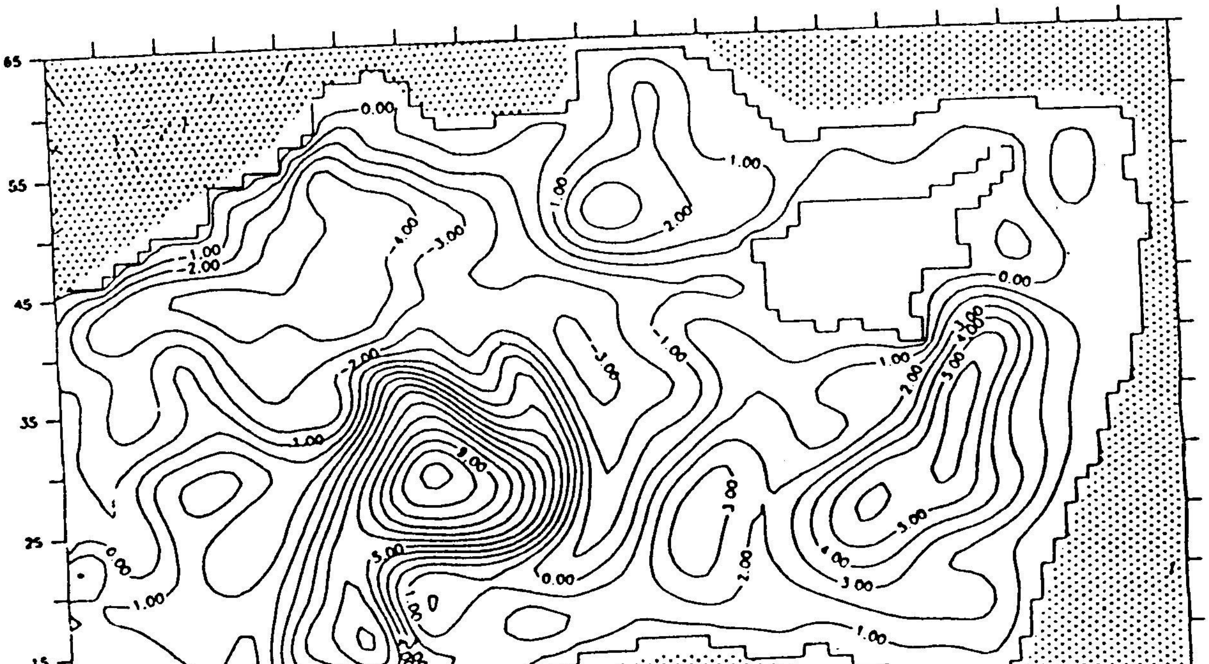


Fig. 16. Streamfunction field at 40 m depth 14 days after initialization. The streamfunction is proportional to dynamic height (nondimensional units) (from RG91, fig. 8).

parable numerical dynamical ocean models constructed under physical assumptions suitable for various regions and phenomena in the oceans. Domains and geometries are general, ranging from an arbitrary piece of open ocean (water-water boundaries) to an entire basin scale. The model hierarchy approach was adopted in order: to achieve the closest possible relationships of modeling to experimental data bases; to allow the focus of computing resources and scientific effort on regions of special interest; and to facilitate the physical interpretation of results via utilization of the simplest physical model required for a simulation of specified accuracy.

The present model hierarchy consists of a quasigeostrophic model for a block of open ocean (Robinson and Walstad, 1987) or for a region (partially) bounded by an arbitrary coastline (Milliff, 1990) which contains islands (Özsoy et al., 1992). A surface boundary layer may be attached (Walstad and Robinson, 1992). More general primitive equation dynamics may be utilized with arbitrary open boundary conditions (Spall and Robinson, 1989).

The POEM data sets have been assimilated into the dynamical models and studies are continuing. Initialization of the dynamical model with a real ocean data set serves to dynamically adjust the data and generally improves the field estimates. Data gaps can be interpolated dynamically. Dynamics together with hydrography yields absolute flow estimates; dynamics provides the consistent barotropic mode. Four dimensional field estimates best suitable for the transport flows necessary as input to interdisciplinary and applied studies are provided. Furthermore, the results of simulations based on real data sets can be analyzed in detail qualitatively and quantitatively in order to reveal real physical processes operative in the ocean. Four examples of the Eastern Mediterranean will be briefly described for the regions shown in Fig. 15: the full basin, the eastern Levantine basin and the Mersa Matruh and Rhodes gyres.

### 5.2. *Results*

Figure 16 shows the streamfunction field (proportional to upper thermocline dynamic height) for the winter 1986 POEM quasisynoptic survey after fourteen days of dynamical adjustment. The assimilation is remarkably robust. Overall, the features resemble the objective analysis initialization (not shown). There has been dynamical smoothing and natural variabilities (meandering of the mid-Mediterranean jet) are occurring. The remarkable robustness of the subbasin scale features to dynamical assimilation in this data set is characteristic of all the data sets.

Dynamical interpolation is illustrated for the Mersa Matruh gyre in the region indi-

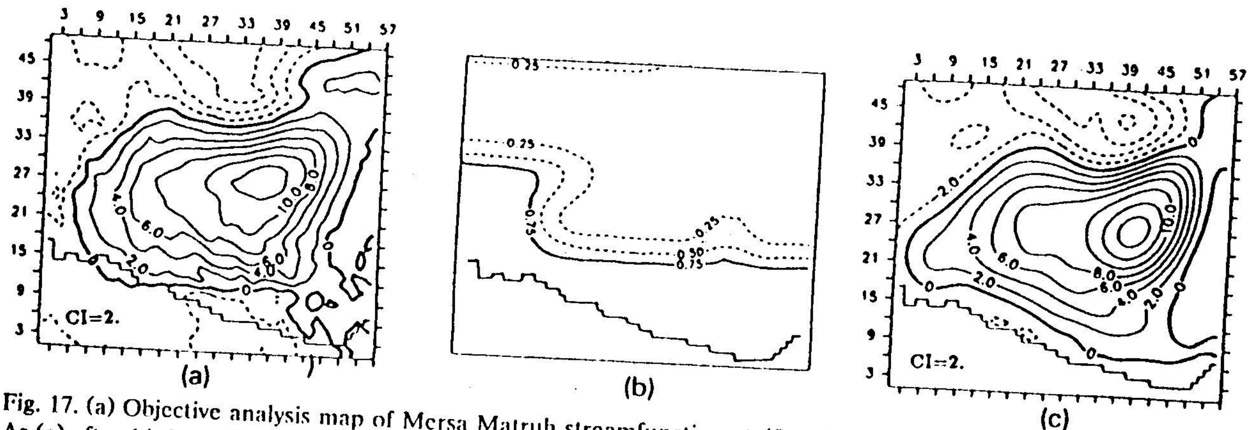


Fig. 17. (a) Objective analysis map of Mersa Matruh streamfunction at 40 m (b) Associated expected error map. (c) As (a) after 14 days of dynamical run (from RG91, fig. 7).

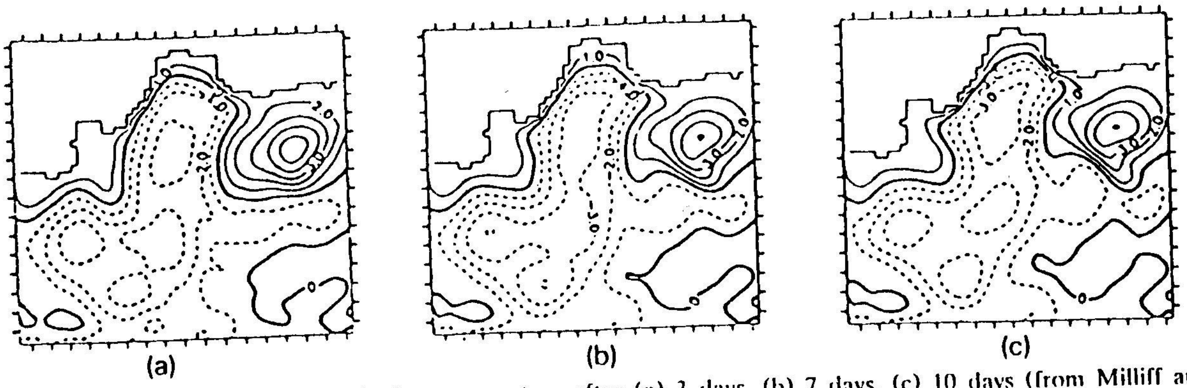


Fig. 18. Mesoscale simulation of Rhodes gyre system after (a) 3 days, (b) 7 days, (c) 10 days (from Milliff and Robinson, 1991, fig. 6).

cated in Fig. 15 (which is to appear in the doctoral dissertation of Ms. M. Golnaraghi of Harvard University). The objective analysis initialization of Fig. 17a can be seen from the expected error maps of Fig. 17b to suffer from an absence of data in approximately one third of the domain of interest north of the Egyptian coastline. After fourteen days (Fig. 17c) dynamics provides a consistent complete gyre circulation.

The 1987 mesoscale experiment accomplished a mapping pattern in the region of the Rhodes gyre as evidenced by the zig-zag ship track in that region in Fig. 4. This served as the basis of a simulation and dynamical process study of mesoscale-subbasin scale interactions for the gyre system (Milliff and Robinson, 1991). The main thermocline streamfunction for three, seven and ten days into the simulation are shown in Fig. 18. There is a four-lobed oscillation of the gyre center with a period of about a week. This appears to be driven by intermittent bursts of baroclinic instability associated with the tightening of the jet between the cyclonic Rhodes gyre and the anticyclonic gyre to its

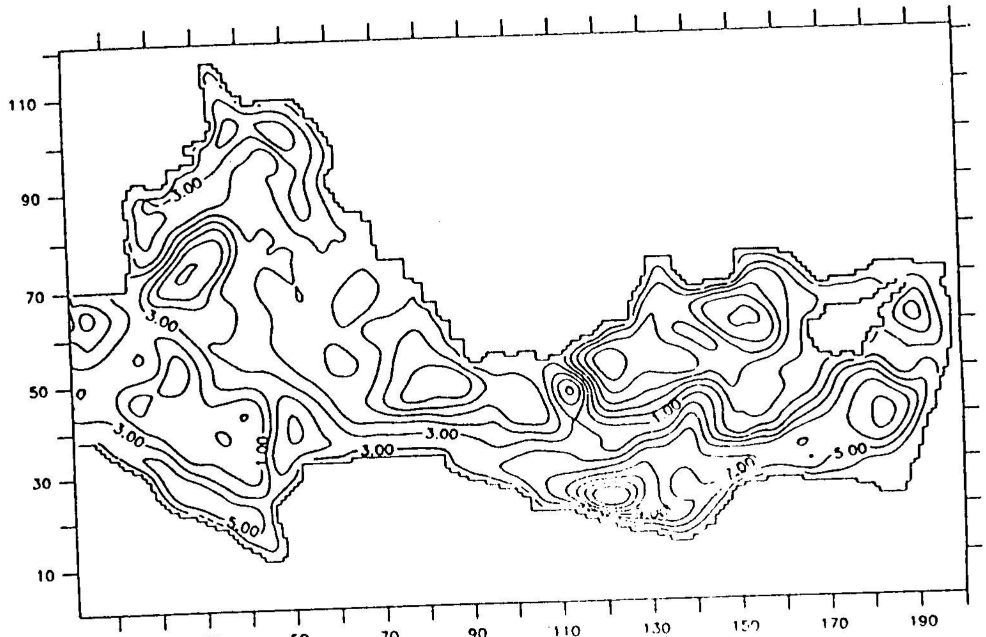


Fig. 19. Full basin simulation 45 days after initialization. Upper thermocline streamfunction.

northeast, which can be seen most intensively in Fig. 18c.

A full basin assimilation of the summer 1987 data shown in Fig. 6a, b is presented in Fig. 19. Dynamical interpolation and wind forcing have filled in the large data gap in the southern Ionian and also the gaps south of Crete and the mid-Levantine basin. The flow depicted as forty-five days into a dynamical run initialized with the objective analysis of Fig. 6a and also driven by the August–September climatological mean winds. The Atlantic Ionian Stream which projects to the northeast into the Ionian threads its way across the basin continuously to the Mid-Mediterranean Jet. This is, to our knowledge, the first time that observations and dynamics have been combined to produce a quasisynoptic realization of a full basin circulation with subbasin scale resolution.

## 6. SUMMARY AND CONCLUSIONS

The Eastern Mediterranean Sea is an open but isolated basin of interest as a laboratory basin for global ocean general circulation processes including oceanic climate dynamical processes. The circulation and variabilities of the Eastern Mediterranean Sea are known to be constituted from multiple and interactive space and time scales. A single full basin scale thermohaline cell exists with a turnover time of one and one quarter centuries. The main thermoclinic general circulation is built up from subbasin scale features, cyclonic and anticyclonic gyres linked by interconnecting jets. Variabilities include fluctuations in the characteristics of the permanent features as well as the occurrence of recurrent and transient features. Mesoscale eddies, meanders and oscillations occur and interact with the subbasin scale circulation, most energetically in the Levantine basin (in the summer 1987 data set).

Important climate processes include the formation, dispersion, transformation, mixing and circulation of both intermediate and deep water masses. The basin wide deep thermohaline circulation has both an internal cell, confined to the Eastern Mediterranean, and an external cell which communicates with the world ocean through the Western Mediterranean. The internal cell, whose deep water formation involves preconditioning via salt concentration, may present interesting analogies to the global conveyor belt.

Results of the different modeling efforts aimed at studying the general circulation of the Eastern Mediterranean consistently show that subbasin scale gyres are the "building blocks" of this circulation. Thermal/evaporation fluxes are particularly crucial in driving the circulation of the Eastern Levantine, while the seasonal modulation imposed by the wind-stress curl is much stronger in the Ionian basin. This leads to different paths of the Atlantic water jet entering the Sicily Straits. The jet follows a northeastward course in the winter, but deflects northward into the Ionian interior and forms a large meander in the summertime. The final result is the strong control exerted by topography upon the circulation that influences some of the permanent features of the circulation such as the Rhodes gyre and the mid-Mediterranean jet of the Levantine basin.

The assimilation of the new data sets into models provides absolute flow from hydrographic data plus dynamics, and improves the data via processes of dynamical adjustment and dynamical interpolation. The subbasin scale general circulation features are stable and robust under assimilation. Data driven extended simulations and process studies for both internal dynamics, general circulation forcings and multiscale nonlinear interactions are in progress. The realistic synoptic time series of fields estimates, provided regionally or basin wide by such models, also provide best estimate transport fields for biological, chemical and management studies and applications.

The research progress reported here provides the basis for definitive dynamical processes, air–sea interaction and water mass studies, and for interdisciplinary ocean science research. The first basin wide quasisynoptic combined biological, chemical and physical circulation survey was carried out by an expanded multidisciplinary POEM group in the fall of 1991.

## ACKNOWLEDGEMENTS

The POEM Group acknowledges with sincere thanks the essential support of many scientific, technical, logistical and administrative colleagues, students and friends. The coordinated and cooperative scientific effort sustained over seven years of planning, field work, analysis and synthesis were made possible by the endorsement and support of the Intergovernmental Oceanographic Commission and the UNESCO Division of Marine Sciences with additional support from the US National Science Foundation. It is with pleasure that we thank Dr. Gunnar Kullenberg and Dr. Gualter Soares of IOC. We are grateful to Dr. Mario Ruivo and Dr. Dale Krauss for initiating IOC and UNESCO support. We especially thank Dr. Selim Morcos (UNESCO) for his scientific interest and help and Professors Henry Charnock and Henri Lacombe for their insights and guidance. The executive assistance was provided by Ms. Marsha Glass-Cormier. The research was supported by the following national agencies and institutions: Germany – the Deutsche Forschungsgemeinschaft; Greece – the Ministry of Research and Technology; Israel – the Israel Oceanographic and Limnological Research, the Ministry of Energy and Infrastructure of Israel, the Cohan Marine Climates Research Center; Italy – Consiglio Nazionale delle Ricerche, Osservatorio Geofisico Sperimentale, Instituto Universitario Navale; Turkey – the Turkish Scientific and Technical Council (TÜBITAK) under the National Oceanography Program; United States – the National Science Foundation, the Office of Naval Research and the San Diego supercomputer Center; Croatia – Institute of Oceanography and Fisheries and Hydrographic Institute.

## REFERENCES

Bergamasco, A., Malanotte-Rizzoli, P., Long, R.B. and Thacker, W.C., 1992. The seasonal circulation of the Eastern Mediterranean investigated with the adjoint method in prep.

Broecker, W.S., 1987. The biggest chill. Nag. Hist. Mag., October 74–82.

Cox, M.D., 1984. A primitive equation three dimensional model of the ocean. GFDL Ocean Group Tech. Rep. no. 1. GFDL/NOAA, Princeton University.

Dewar, W.K., 1986. Mixed layers in Gulf Stream rings. Dyn. Atmos. Oceans, 10: 1–29.

Gordon, A., 1986. Interocean exchange of thermocline water. J. Geophys. Res., 91: 5037–5046.

Lacombe, H. and Tchernia, P. 1972. In: D.J.Stanley (editor), The Mediterranean Sea: A Natural Sedimentation Laboratory, Dowden, Hutchinson and Ross, Stroudsberg, PA., pp. 25–36.

Malanotte-Rizzoli, P. and Bergamasco, A., 1991. The wind and thermally driven circulation of the Eastern Mediterranean Sea. Dyn. Atmos. Oceans, 15: 355–420.

Malanotte-Rizzoli, P. and Hecht, A., 1988. Large-scale properties of the Eastern Mediterranean: a review. Oceanol. Acta, 11 (4): 323–335.

Malanotte-Rizzoli, P. and Robinson, A.R., 1988. POEM: Physical oceanography of the Eastern Mediterranean. EOS The Oceanogr. Rep., 69 (14): 194–203.

Milliff, R.F., 1990. A modified capacitance matrix method to implement coastal boundaries in the Harvard Open Ocean Model. Math. Comput. Simulations, 31: 541–564.

Miliff, R.F. and Robinson, A.R. 1992. Structure and dynamics of the Rhodes Gyre System and its dynamical interpolation for estimates of the mesoscale variability. J. Phys. Oceanogr., 22(4): 317–337.

Özsoy, E., A. Hecht and Ünlüata, Ü. 1989. Circulation and hydrography of the Levantine Basin: Results of POEM coordinated experiments 1985–1986. Prog. Oceanogr., 22: 125–170.

Özsoy, E., Ünlüata, Ü., Oğuz, T., Latif, M.A., Hecht, A., Brenner, S., Bishop, J. and Rozentroub, Z. 1991. A review of the Levantine Basin circulation and its variabilities during 1985–1988. Dyn. Atmos. Oceans, 15: 421–456.

Özsoy, E., Lozano, C.J. and Robinson, A.R. 1992. A baroclinic quasigeostrophic model for closed basins or semi-enclosed seas with islands. Math. Comput. Simulations, 34(1): 51–79.

Pinardi, N. and Navarra, A. 1992. Baroclinic wind adjustment processes in the Mediterranean Sea, submitted manuscript.

Robinson, A.R., 1992. The Eastern Mediterranean as a laboratory for ocean climate processes. Proc. San

Paolo Int. Conf. Oceans, Climate and Man, Torino, Italy, in press.

Robinson, A.R. and Golnaraghi, M., 1991. Progress in understanding the Eastern Mediterranean Sea. IC-SEM Proc., Perpignan, France 1990.

Robinson, A.R., Golnaraghi, M., Leslie, W.G., Artegiani, A., Hecht, A., Lazzoni, E., Michelato, A., Sansone, E., Theocharis, A. and Ünlüata, Ü., 1991. Structure and variability of the Eastern Mediterranean general circulation. Dyn. Atmos. Oceans 15, (3–5): 215–240.

Robinson, A.R., Hecht, A., Pinardi, N., Bishop, J., Leslie, W.G., Rozentroub, Z., Mariano, A.J. and Brenner, S., 1987. Small synoptic/mesoscale eddies: The energetic variability of the Eastern Levantine Basin. Nature, 327 (6118): 131–134.

Robinson, A.R. and Walstad, L.J., 1987. The Harvard Open Ocean Model: Calibration and application to dynamical process, forecasting, and data assimilation studies. Appl. Numer. Math., 3 (1–2): 89–131.

Roether, W. and Schlitzer, R., 1991. Eastern Mediterranean deep water renewal on the basis of chlorofluoromethane and tritium data. Dyn. Atmos. Oceans, 15 (3–5): 333–354.

Schlitzer, R., Roether, W., Oster, H., Junghans, H-G., Hausmann, M., Hohannsen, H. and Michelato, A., 1991. Chlorofluoromethane and oxygen in the Eastern Mediterranean. Deep-Sea Res., 38(12): 1531–1551.

Spall, M.A. and Robinson, A.R., 1989. A new open ocean, hybrid coordinate primitive equation model. Math. Comput. Simulations, 31: 241–269.

Tziperman, E. and Malanotte-Rizzoli, P., 1991. The climatological seasonal circulation of the Mediterranean Sea. J. Mar. Res., 49: 1–25.

Walstad, L.J. and Robinson, A.R., 1992. A coupled surface boundary layer quasigeostrophic model for mesoscale mixed layer dynamics. Dyn. Atmos. Oceans, in press.