Perhaps the extraordinary width and flatness of the original meddy has its explanation here: As the Coriolis parameter f decreases, a decrease in thickness h would indicate a tendency to conserve its potential vorticity $(f+\zeta)/h$. On a more speculative note, if the lens did indeed flatten and widen, this could help explain the extraordinary diameter of the original 'meddy' and simultaneously give it an additional lease of life against radial erosion.

The fact that subsurface eddies larger than $\sim 100\,\mathrm{km}$ in diameter have not been observed suggests an upper limit at formation time set by inertia. Meddies form at Cape St. Vincent at the south-west corner of Portugal where the Mediterranean Undercurrent must make a sharp turn to the north along the continental slope. Owing to inertia, the current may overshoot, becoming geostropically unbalanced where the bottom turns north. This causes the current to curve to the right owing to the Coriolis force. For faster than normal flow, this curving flow can almost fold back on itself, resulting in a closed loop leading to the genesis of a meddy. Given the frequent rate of formation of meddies at Cape St. Vincent site, this would be an excellent place to study the formation process in greater detail. Other sharp topographic features have been identified as sites for the formation of anticyclonic lenses. In contrast, remarkably little is known about how cyclonic lenses get spun up. Perhaps they result from instabilities of fronts and/or fission from larger eddies. No lower limit to the size of subsurface lenses has been established, but, at some limit, viscosity and double-diffusive processes will dissipate what is left. Before that limit is reached, however, the lenses can still remain remarkably energetic. But the very small pressure gradients needed to balance the cyclogeostrophic motion all but guarantees that they can only be detected and identified as such by Lagrangian means.

See also

Double-diffusive Convection. Drifters and Floats. Intrusions. Rossby Waves.

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MEDITERRANEAN SEA CIRCULATION

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Introduction

The Mediterranean Sea is a mid-latitude semi-enclosed sea, or almost isolated oceanic system. Many processes which are fundamental to the general circulation of the world ocean also occur within the Mediterranean, either identically or analogously. The Mediterranean Sea exchanges water, salt, heat, and other properties with the North Atlantic Ocean. The North Atlantic is known to play an important role in the global thermohaline circulation, as the major site of deep- and bottom-water formation for the global thermohaline cell (conveyor belt) which encompasses the Atlantic, Southern, Indian, and Pacific Oceans. The salty water of Mediterranean origin may affect water formation processes and variabilities and even the stability of the global thermohaline equilibrium state.

The geography of the entire Mediterranean is shown in **Figure 1A** and the distribution of deep-sea topography and the complex arrangement of coasts and islands in **Figure 1B**. The Mediterranean Sea is composed of two nearly equal size basins, connected by the Strait of Sicily. The Adriatic extends northward between Italy and the Balkans, communicating with the eastern Mediterranean basin through the Strait of Otranto. The Aegean lies between Greece and Turkey, connected to the eastern basin through the several straits of the Grecian Island Arc. The Mediterranean circulation is forced by water exchange through the various straits, by wind stress, and by buoyancy flux at the surface due to freshwater and heat fluxes. Evaporation 1.27 m/year, Precipitation 0.59 m/year, Mediterranean outflow (through the Gibraltar) ~1.0 Sv, the inflow exceeds outflow by 5% (0.05 Sv) to compensate the water deficit of the Mediterranean, fresh water input 0.67 m/year, which comprises precipitation, river runoff and the Black Sea input, Net salt flux towards the Atlantic ~2×10^6 kg/s.

Research on Mediterranean Sea general circulation and thermohaline circulations and their variabilities, and the identification and quantification of critical processes relevant to ocean and climate dynamics involves several issues. Conceptual, methodological, technical, and scientific issues include, for example, the formulation of multiscale (e.g., basin, sub-basin, mesoscale) interactive nonlinear dynamical models; the parametrization of air–sea interactions and fluxes; the determination of specific regional processes of water formation and transformations; the representation of convection and boundary conditions in general circulation models. A three-component nonlinear ocean system

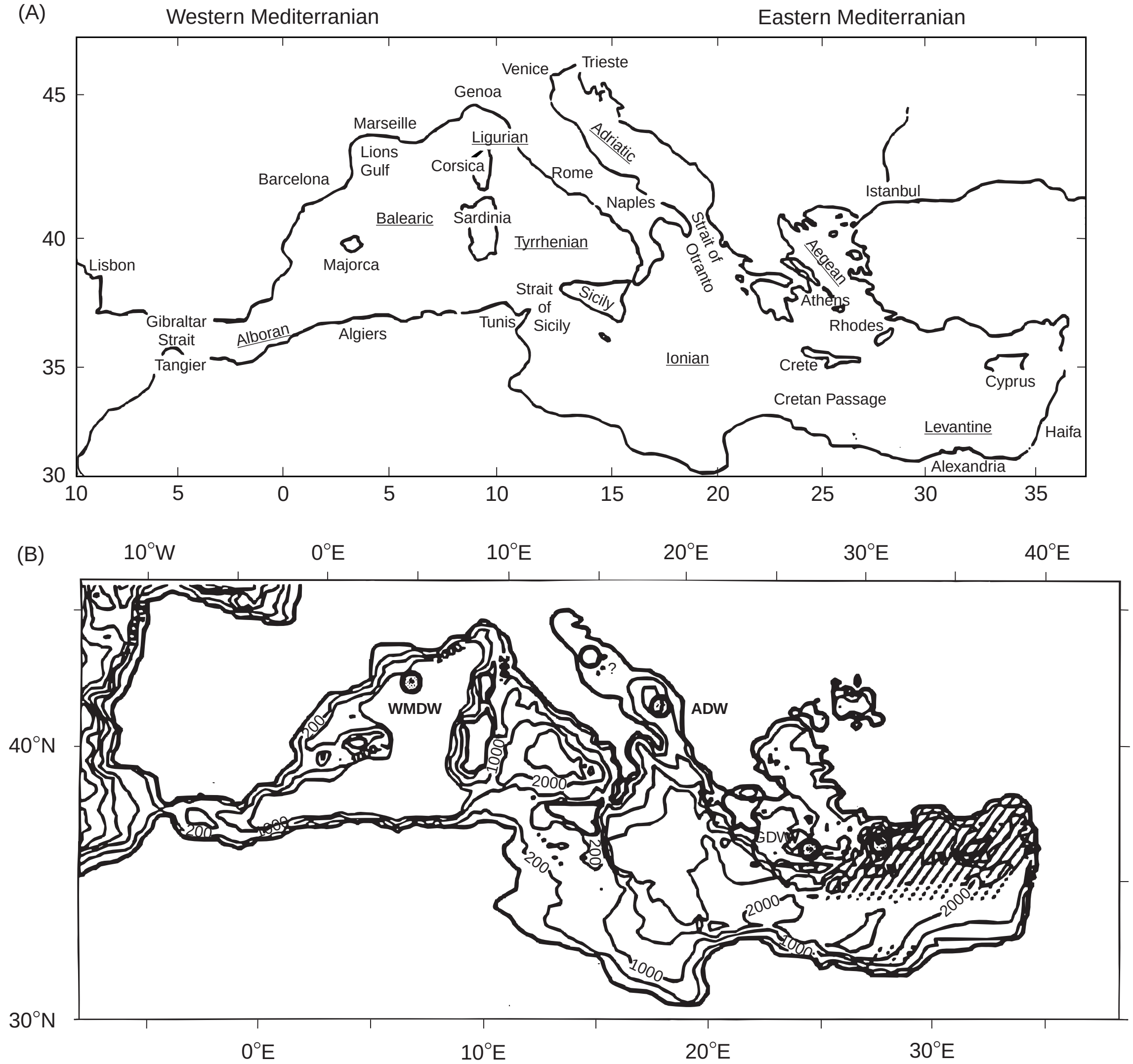


Figure 1 (A) The Mediterranean Sea geography and nomenclature of the major sub-basins and straits. (B) The bottom topography of the Mediterranean Sea (contour interval is 1000 m) and the locations of the different water mass formations.

is involved whose components are: (1) air–sea interactions, (2) water mass formations and transformations, and (3) circulation elements and structures. The focus here is on the circulation elements and their variabilities. However, in order to describe the circulation, water masses must be identified and described.

Multiscale Circulation and Variabilities

The new picture of the general circulation in the Mediterranean Sea which is emerging is complex, and composed of three predominant and interacting spatial scales: basin scale (including the thermohaline (vertical) circulation), sub-basin scale, and mesoscale. Complexity and scales arise from the multiple driving forces, from strong topographic and coastal influences, and from internal dynamical processes. There exist: free and boundary currents and jets which bifurcate, meander and grow and shed ring vortices; permanent and recurrent sub-basin scale cyclonic and anticyclonic gyres; and small but energetic mesoscale eddies. As the scales are interacting, aspects of all are necessarily discussed when discussing any individual scale. The path for spreading of Levantine Intermediate Water (LIW) from the region of formation to adjacent seas together with the thermohaline circulations are shown in **Figure 2**; where the entire Mediterranean is schematically shown as two connected basins (western and eastern). The internal thermohaline cells existing in the western and eastern Mediterranean have interesting analogies and differences to each other and to the global thermohaline circulation. In the western basin (**Figure 3A**) the basin-scale thermohaline cell is driven by deep water formed in the Gulf of Lions and spreading from there. Important sub-basin scale gyres in the main thermocline in the Alboran and Balearic Seas have been identified. Intense mesoscale activity exists and is shown by instabilities along the coastal current, mid-sea eddies and along the outer rim swirl flow of a sub-basin scale gyre. The basin scale thermohaline cell of the eastern basin is depicted generically in **Figure 3B** and discussed in more detail in the next section. The basin scale general circulation of the main thermocline is composed of dominantly energetic sub-basin scale gyres linked by sub-basin scale jets. The active mesoscale is shown by a field of internal eddies, meanders along the border swirl flow of a sub-basin scale gyre, and as meandering jet segments. The Atlantic Water jet with its instabilities, bifurcations, and multiple pathways, which travels from Gibraltar to the Levantine is a basin scale feature not depicted in **Figure 3**; this also pertains to the intermediate water return flow.

Large-scale Circulation

Processes of global relevance for ocean climate dynamics include thermohaline circulation, water mass formation and transformation, dispersion, and mixing. These processes are schematically shown in **Figure 4A** and **B** for the western and the eastern basins. The Mediterranean basins are evaporation basins (lagoons), with freshwater flux from the Atlantic through the Gibraltar Straits and into the eastern Mediterranean through the Sicily Straits. Relatively fresh waters of Atlantic origin circulating in the Mediterranean increase in density because evaporation (E) exceeds precipitation (advective salinity preconditioning), and then form new water masses via convection events driven by intense local cooling (Q) from winter storms. Bottom water is produced: for the western basin (WMDW) in the Gulf of Lions (**Figure 4A**) and for the eastern basin (**Figure 4B**) in the southern Adriatic (EMDW, which plunges down through the Otranto Straits). Recent observations also indicate deep water (LDW)

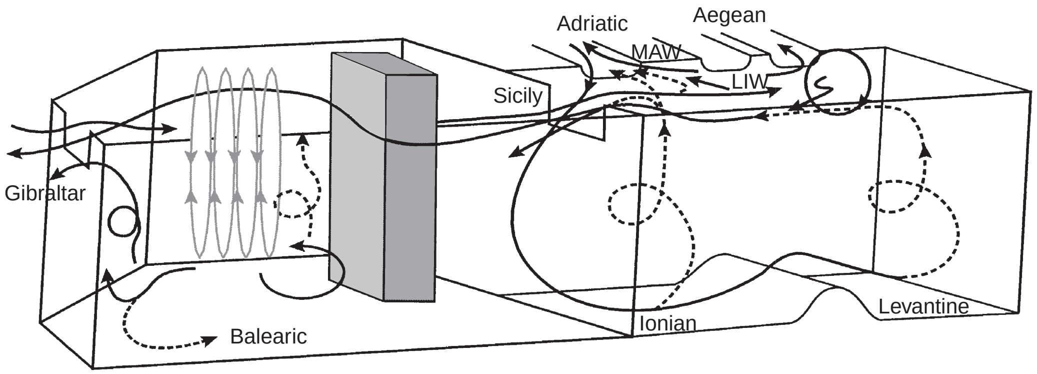


Figure 2 Schematic of thermohaline cells and path of Levantine Intermediate Water (LIW) in the entire Mediterranean.

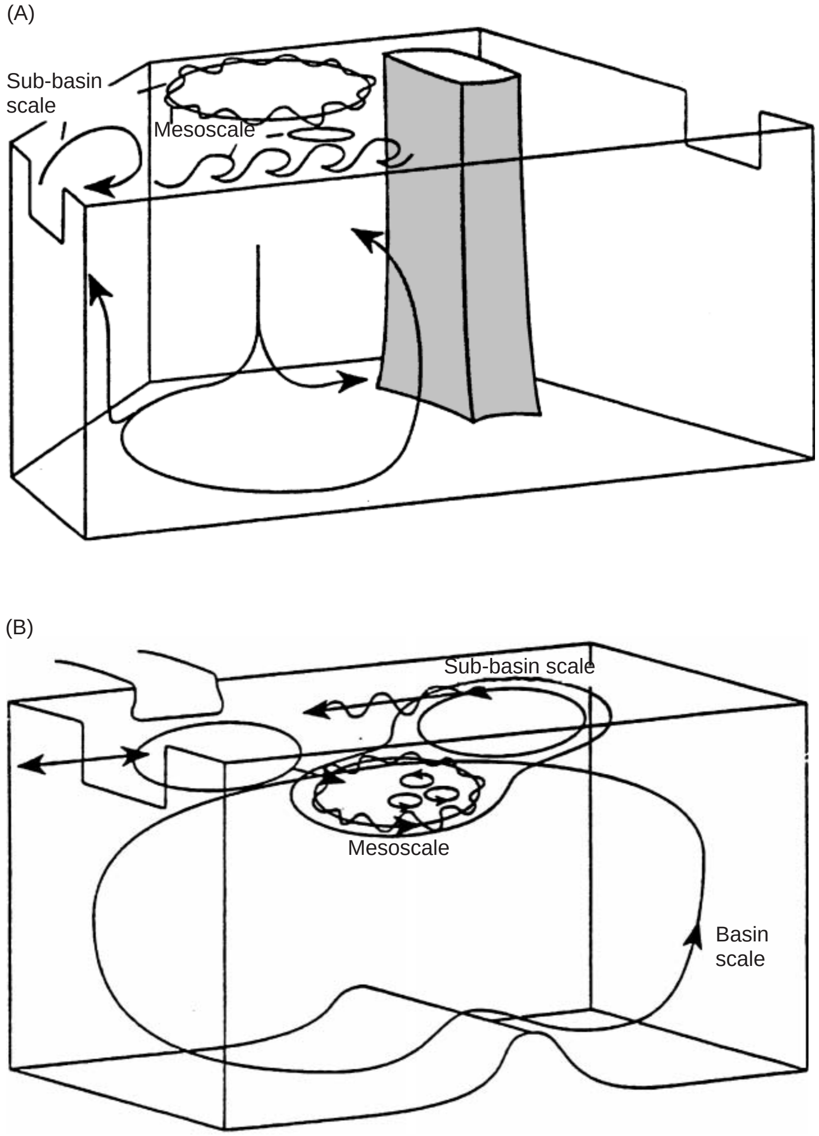


Figure 3 Schematic of the scales of circulation variabilities and interactions in (A) western Mediterranean, (B) eastern Mediterranean.

formation in the north-eastern Levantine basin during exceptionally cold winters, where intermediate water (LIW) is regularly formed seasonally. Evidence now shows that LIW formation occurs over much of the Levantine basin, but preferentially in the north, probably due to meteorological factors. The LIW is an important water mass which circulates through both the eastern and western basins and contributes predominantly to the efflux from Gibraltar to the Atlantic, mixed with some EMDW and together with WMDW. Additionally, intermediate and deep (but not bottom) waters formed in the Aegean (AGDW) are provided to the eastern basin through its straits. As will be seen below, that water formerly known as AGDW, is now identified as Cretan Intermediate Water (CIW) and Cretan Deep Water (CDW). Important research questions relate to the preconditioning, formation, spreading, dispersion, and mixing of these water masses. These include: sources of forced and internal variabilities; the spectrum and relative amounts of water types formed, recirculating within the Mediterranean basins, and fluxing through the straits, and the actual locations of upwelling.

A basin-wide qualitative description of the thermohaline circulation in the western basin of the Mediterranean Sea has recently been provided by Millot (see Further Reading). Results based on cruises in December 1988 and August 1989 indicated that the deep layer in the western Mediterra-

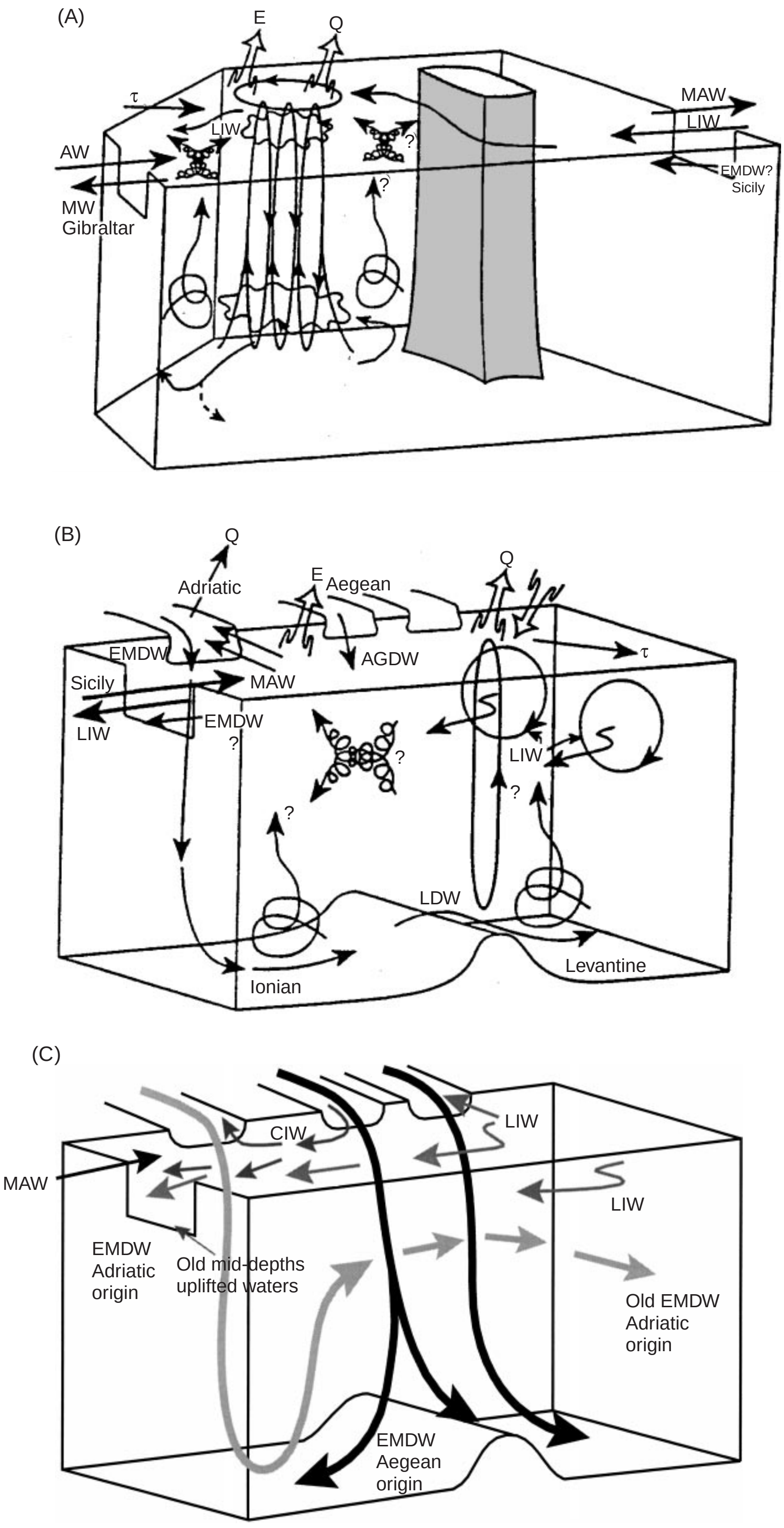


Figure 4 Processes of air–sea interaction, water mass formation, dispersion, and transformation. (A) western Mediterranean, (B) eastern Mediterranean, (C) eastern Mediterranean (post-eastern Mediterranean Transient).

nean was 0.12°C warmer and about 0.33 PSU more saline than in 1959. Analysis of these data together with those from earlier cruises has shown a trend of continuously increasing temperatures in recent decades. Based on the consideration of the heat and water budget in the Mediterranean, the deep-water temperature trend was originally speculated to be the result of greenhouse gas-included local warming. A more recent argument considers the anthropomorphic reduction of river water flux into the eastern basin to be the main cause of this warming trend.

During the 18th and 19th centuries a number of observations of temperature and salinity were made mostly in the surface down to intermediate layers, in certain areas of the Mediterranean. Progressively, the investigators extended their measurements into deeper layers to understand the distribution of the parameters, both horizontally and vertically. Sometimes the values were surprisingly close to the correct values but in other cases they presented significant differences due mainly to the primitive instrumentation and methods used by this time. Initially, some believed that the deep waters are motionless. Later the researchers noted the variations of the parameters occurring on a daily, monthly and seasonal basis in the upper layers and began to think about the movements and renewal of the deep waters. Regarding the distribution of salinity extremely confused and erroneous views prevailed up to 1870. However, it was already known by this time that the fresh water input is much lower and does not compensate evaporation from the sea surface. Furthermore, they noted that the source of the salt of the deep water is the surface layer. Several theories on the mechanisms governing the renewal and oxygenation of the deep layers were formulated. Moreover, they succeeded to measure currents and structure primitive maps showing prevailing circulation patterns, as the Atlantic Water inflow and the Black Sea outflow towards the Northeast Aegean.

Since the beginning of the twentieth century, when the first investigations in the Mediterranean Sea took place (1908), up to the mid-1980s, both the intermediate and deep conveyor belts of the eastern basin presented rather constant characteristics. The Adriatic has been historically considered as the main contributor to the deep and bottom waters of the Ionian and Levantine basins, thus indicating an almost perfectly repeating cycle in both water mass characteristics and formation rates during this long period. Roether and Schlitzer found in 1991 that the thermohaline circulation in the eastern basin consists of a single coherent convective cell which connects the Levantine and Ionian basins and has a turnover time of 125 years below 1200 m. Their results indicated that the water formed in the Adriatic is a mixture of surface water (AW) and intermediate Levantine water (LIW) from the Mediterranean. The Aegean has also been reported as a possible secondary source, providing dense waters to the lower intermediate and/or deep layers, namely Cretan Intermediate Water (CIW), that affected mainly the adjacent to the Cretan Arc region of the eastern Mediterranean. Since 1946 increased densities were observed in the southern Aegean Sea in 1959–65 and 1970–73. These events occurred under extreme meteorological conditions. However, the quantities of the dense water produced were never enough to affect the whole eastern Mediterranean. The traditional historical picture of water properties is illustrated in **Figure 5A** by a west–east vertical section of salinity through the eastern Mediterranean.

After 1987, the most important changes in the thermohaline circulation and water properties basin-wide ever detected in the Mediterranean occurred. The Aegean, which had only been a minor contributor to the deep waters, became more effective than the Adriatic as a new source of deep and bottom waters of the eastern Mediterranean. This source gradually provided a warmer, more saline, and denser deep-water mass than the previously existing Eastern Mediterranean Deep (and bottom) Water (EMDW) of Adriatic origin. Its overall production was estimated for the period 1989–95 at more than 7 Sv, which is three times higher than that of the Adriatic. After 1990, CIW appeared to be formed in the southern Aegean with modified characteristics. This warmer and more saline CIW (less dense than the older one) exits the Aegean mainly through the western Cretan Arc Straits and spreads in the intermediate layers, the so-called LIW horizons, in the major part of the Ionian Sea, blocking the westward route of the LIW.

These changes have altered the deep/internal and upper/open conveyor belts of the eastern Mediterranean. This abrupt shift in the Mediterranean ‘ocean climate’ has been named the Eastern Mediterranean Transient (EMT). Several hypotheses have been proposed concerning possible causes of this unique thermohaline event, including: (1) internal redistribution of salt, (2) changes in the local atmospheric forcing combined with long term salinity change, (3) changes in circulation patterns leading to blocking situations concerning the Modified Atlantic Water (MAW) and the LIW, and (4) variations in the fresher water of Black Sea origin input through the Strait of Dardanelles.

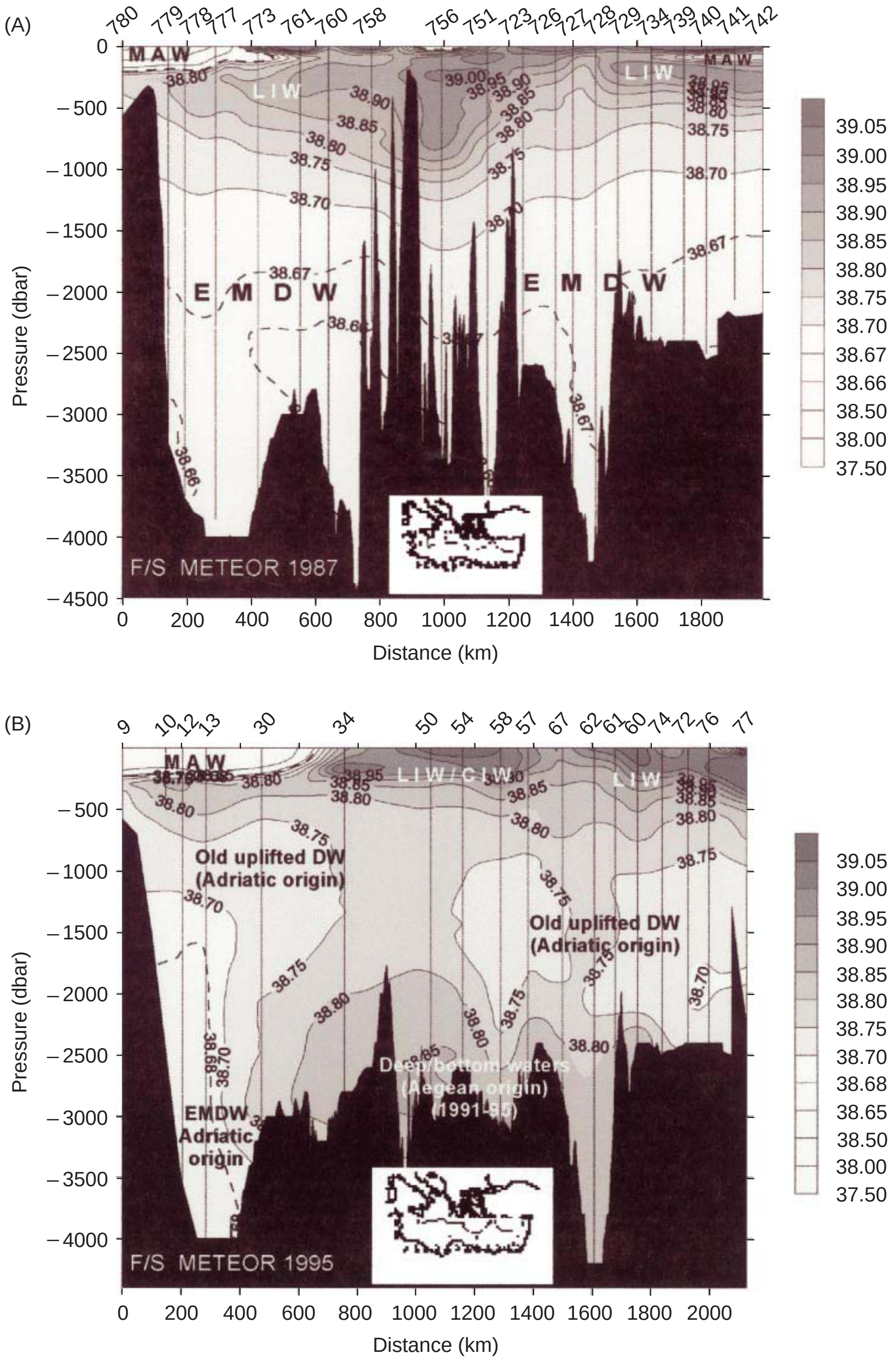


Figure 5 West–east vertical sections of salinity through the eastern Mediterranean: (A) 1987, (B) 1995, (C) 1999.

The production of denser than usual local deep water started in winter 1987, in the Kiklades plateau of the southern Aegean. The combination of continuous salinity increase in the southern Aegean during the period 1987–92, followed by significant temperature drop in 1992 and 1993 caused massive dense water formation. The overall salinity increase in the Cretan Sea was about 0.1 PSU, due to a persistent period of reduced precipitation over the Aegean and the eastern Mediterranean. This meteorological event might be attributed to larger scale atmospheric variability as the North Atlantic Oscillation. Moreover, the net upper layer (0–200 m) salt transport into the Aegean from the Levantine was increased one to four times within the period 1987–94 due not only to the dry period but also to

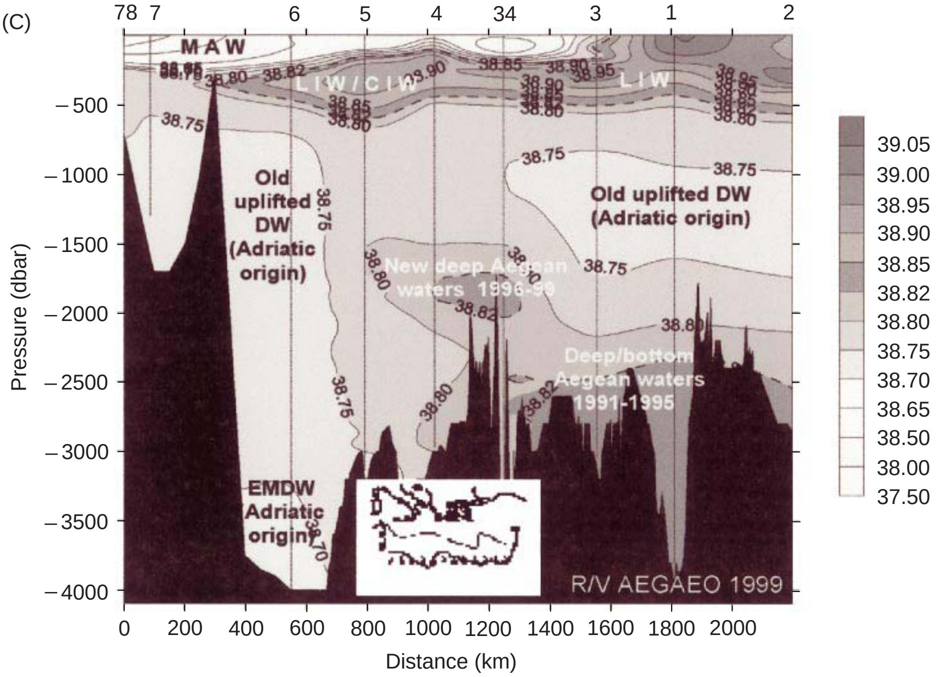


Figure 5 *Continued*

significant changes of the characteristic water mass pathways. This was a secondary source of salt for the south Aegean that has further preconditioned dense water formation. The second period is characterized by cooling of the deep waters by about 0.35°C, related to the exceptionally cold winters of 1992 and 1993. The strongest winter heat loss since 1985 in the Adriatic and since 1979 in the Aegean was observed in 1992. During this winter an almost complete overturning of the water column occurred in the Cretan Sea. The density of the newly formed water, namely Cretan Deep Water (CDW), reached its maximum value in 1994–95 in the Cretan Sea of the southern Aegean. The massive dense water production caused a strong deep outflow through the Cretan Arc Straits towards the Ionian and Levantine basins. Interestingly, the peak of the production rate, about 3 Sv, occurred in 1991–92 when the 29.2 σ_T isopycnal was raised up to the surface layer. While its deep-water production in the Aegean is becoming more effective with time, that in the Adriatic stopped after 1992. Conditions in 1995 are illustrated in **Figure 5B** by a west–east vertical section of salinity through the eastern Mediterranean.

The period 1995–98 is characterized by continuous decrease of CDW production, from 1 to 0.3 Sv. The level of the CDW at the area of the deep Cretan Arc Straits (i.e. Antikithira in the West and Kassos in the East) is found approximately at the sill depths (800–1000 m). The deep outflow has also been weakened, especially from the western Cretan Straits. Moreover, the density of the outflowing water is no longer sufficient to sink to the bottom and therefore the water coming from the recent Aegean outflow has settled above the old Aegean bottom-water mass, in layers between 1500 and 2500 m. On the other hand, the Aegean continues to contribute the CIW to the intermediate layers of the eastern Mediterranean. Salinity in the eastern Mediterranean in 1999 is shown in **Figure 5C**.

The intrusion of the dense Aegean waters has initiated a series of modifications not only in the hydrology and the dynamics of the entire basin, but also in the chemical structure and some biological parameters of the ecosystem. The dense, highly oxygenated CDW has filled the deep and bottom parts of the eastern Mediterranean, replacing the old EMDW of Adriatic origin, which has been uplifted several hundred meters. This process brought the oxygen-poor, nutrient-rich waters closer to the surface, so that in some regions winter mixing might bring extra nutrients to the euphotic zone, enhancing the biological production. Since 1991, the above mentioned uplifted old EMDW of Adriatic origin has reached shallow enough depths, outside the Aegean and especially in the vicinity of the Straits of the Cretan Arc, to intrude the Aegean (Cretan Sea) and compensate its deep outflow (CDW outflow). These waters, namely Transitional Mediterranean

Water (TMW), gradually formed a distinct intermediate layer (150–500 m) in the south Aegean, characterized by temperature, salinity and oxygen minima, and nutrient maxima. This has enhanced the previously weak stratification and enriched with nutrients one of the most oligotrophic seas in the world. This new structure prevents winter convection deeper than 250 m. Finally, in 1998–99, the presence of the TMW was much reduced, mainly as a result of mixing.

The simultaneous changes in both the upper and deep conveyor belts of the eastern Mediterranean may affect the processes and the water characteristics of the neighboring seas. The contribution of the Aegean to the intermediate and deep layers is still active. The variability in the intermediate waters can alter the preconditioning of dense water formation in the Adriatic as well as in the western Mediterranean. On the other hand, the changes in the deep waters can affect the LIW formation characteristics. Whether the present thermohaline regime will eventually return to its previous state or arrive at a new equilibrium is still an open question.

Sub-basin Scale Circulation

Figure 6 shows the patterns of circulation in the western Mediterranean for the various water types. The Atlantic Water in the Alboran Sea flows anticyclonically in the western portion of the western basin, while a more variable pattern occurs in the eastern portion. The vein flowing from Spain to Algeria is named the Almeria-Oran Jet. Further east, the MAW is transported by the Algerian Current, which is relatively narrow (30–50 km) and deep (200–400 m) in the west, but it becomes wider and thinner while progressing eastwards along the Algerian slope till the Channel of Sardinia. Meanders of few tens of kilometers, often 'coastal eddies' (**Figure 7**), are generated due to the unstable character of the current. The cyclonic eddies are relatively superficial and short-lived, while the anticyclones last for weeks or months. The current and its associated mesoscale phenomena can be disturbed by the 'open sea eddies.' The buffer zone that is formed by the MAW reservoir in the Algerian Basin disconnects the inflow from the outflow at relatively short timescales typically.

Large mesoscale variability characterizes the Channel of Sicily. In the Tyrrhenian Sea both the flow along Sicily and the Italian peninsula and the mesoscale activity in the open sea are the dominant features. The flows of MAW west and east of Corsica join and form the so-called Liguro-Provenco-Catalan Current, which is the 'Northern Current' of the Basin along the south-west European coasts. Mesoscale activity is more intense in winter, when this current becomes thicker and narrower than in summer. There is also strong seasonal variability in the mesoscale in the Balearic Sea. Intense barotropic mesoscale eddy activity propagates seaward from the coastline around the sea from winter to spring, and induces a seasonal variability in the open sea.

There is evidence that the Winter Intermediate Water (WIW) formed in the Ligurian Sea and the Gulf of Lions can be in larger amounts than that of Western Mediterranean Deep Water (WMDW). Because of their appropriate or shallower depths, these WIW can flow out at Gibraltar with LIW more easily than the WMDW. Furthermore, apart from the LIW there are also other intermediate waters of eastern Mediterranean origin that circulate and participate in the processes of the western topography. After filling the Algero–Provencal Basin up to depths ~2000 m, the WMDW intrudes into the deep Tyrrhenian (~3000 m). The amount of unmixed WMDW in the western Mediterranean and especially in the south Tyrrhenian Sea is automatically controlled by the density of the cascading flow from the Channel of Sicily and thus from the dense water formation processes in the eastern Mediterranean. The south Tyrrhenian is a key place for the mixing and transformation of the water masses; the processes within the eastern Mediterranean play a dominant role in the entire Mediterranean Basin.

In the eastern basin energetic sub-basin scale features (jets and gyres) are linked to construct the basin-wide circulation. Important variabilities exist and include: (1) shape, position, and strength of permanent sub-basin gyres and their unstable lobes, multi-centers, mesoscale meanders, and swirls; (2) meander pattern, bifurcation structure, and strength of permanent jets; and (3) occurrence of transient eddies and aperiodic eddies, jets, and filaments. **Figure 8** shows a conceptual model in which a jet of Atlantic Water enters the eastern basin through the Straits of Sicily, meanders through the interior of the Ionian Sea, which is believed to feed the Mid-Mediterranean Jet, and continues to flow through the central Levantine all the way to the shores of Israel. In the Levantine basin, this Mid-Mediterranean Jet bifurcates, one branch flows towards Cyprus and then northward to feed the Asia Minor Current, and a second branch separates, flows eastward, and then turns southward. Important sub-basin features include: the Rhodes cyclonic gyre, the

Mersa Matruh anticyclonic gyre, and the south-eastern Levantine system of anticyclonic eddies, among which is the recurrent Shikmona eddy south of Cyprus. The diameter of the gyres is generally between 200 and 350 km. Flow in the upper thermocline is in the order of 10–20 cm s^{-1}. A tabulation of circulation features in the eastern Mediterranean and their characteristics is presented in **Table 1**.

Figure 7 shows the upper-thermocline main circulation features and surface waters' pathways. **Figure** 4 presents the thermohaline (intermediate and deep) circulation, which has a significant vertical component. Finally, **Figure 5** presents the vertical structure of the water masses in three different periods in order to follow/show the continuous transformation of the water mass structure and characteristics in the recent 13 years, that is the period of the Eastern Mediterranean Transient.

During the period 1991–95, a large three-lobe anticyclonic feature developed in the south-western Levantine (from the eastern end of the Cretan Passage, 26°E up to 31°E), blocking the free westward

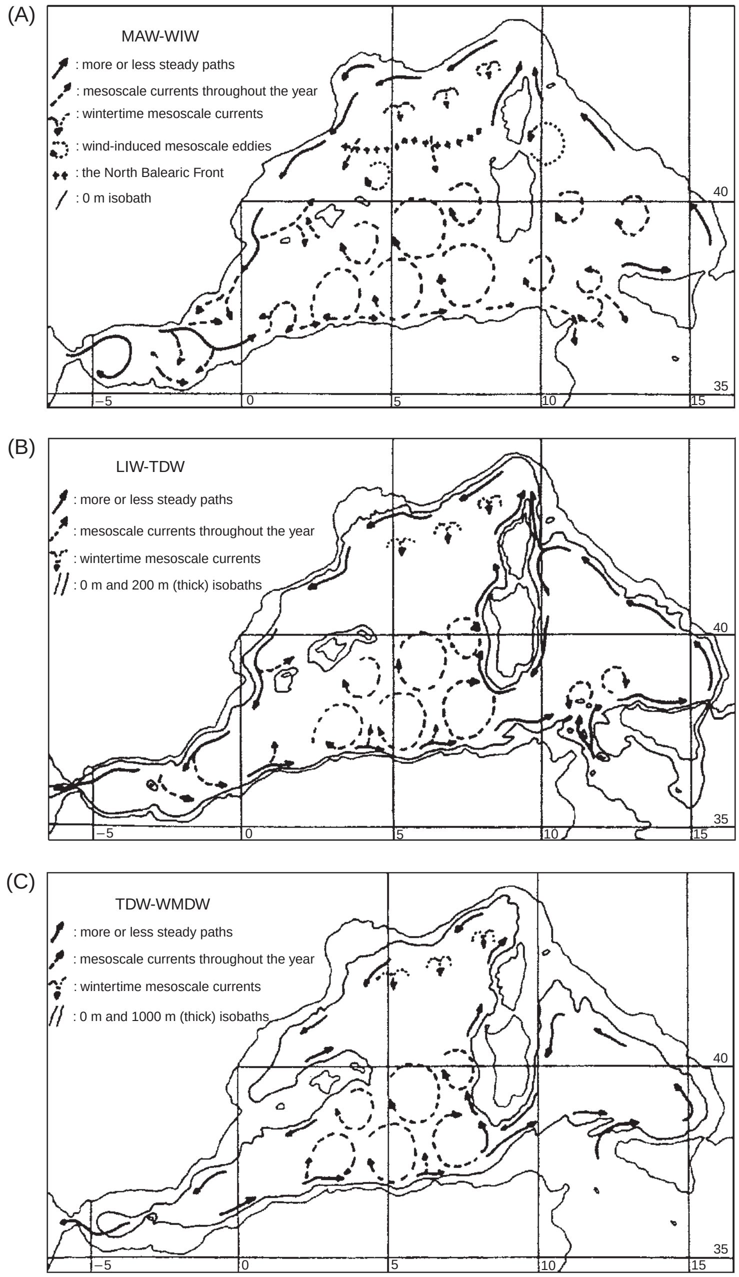


Figure 6 Schematics of the circulation of water masses in the western Mediterranean. (A) MAW–WIW; (B) LIW–TDW; (C) TDW–WMDW (Reproduced with permission from Millot, 1999).

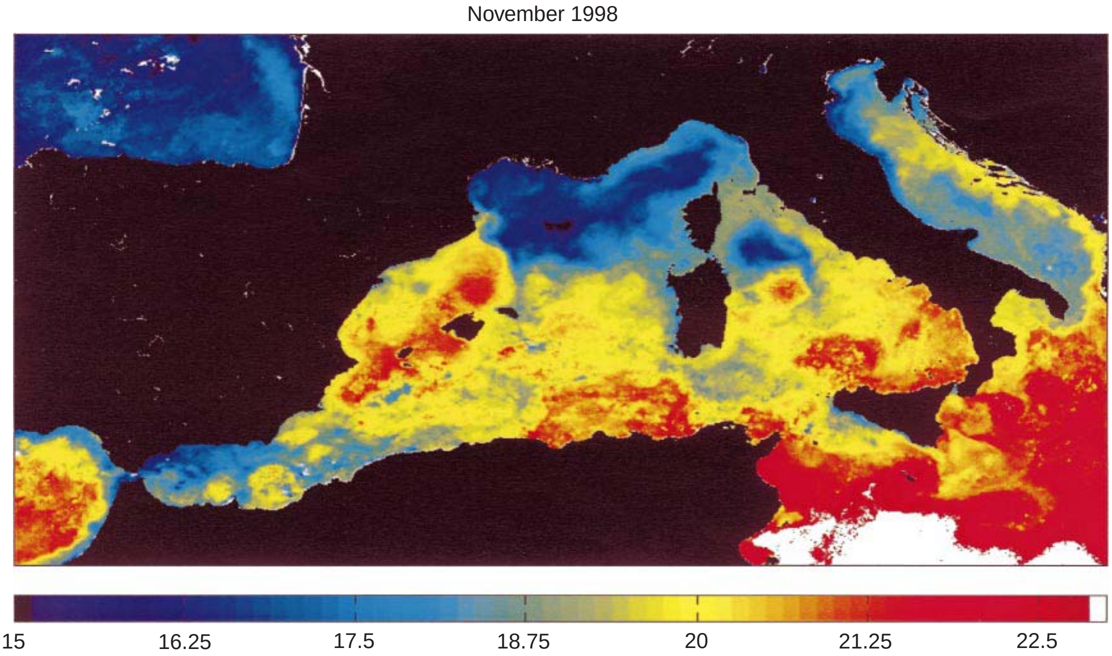
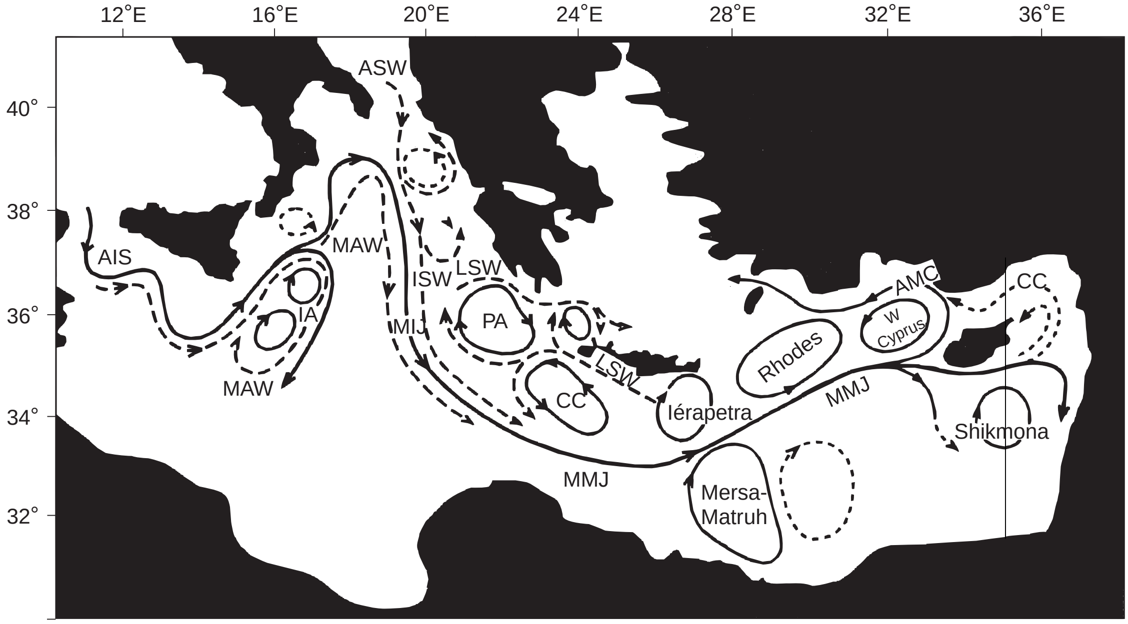


Figure 7 Satellite imagery of sea surface temperature during November 1998 in the Western Mediterranean.



AIS = Atlantic-Ionian Stream
MIJ = Mid Ionian Jet
MAW = Modified Atlantic Water
ISW = Ionian Surface Water
IA = Ionian Anticyclones
MMJ = Mid-Mediterranean Jet
ASW = Adriatic Surface Water
LSW = Levantine Surface Water
PA = Pelops Anticyclone
CC = Cretan Cyclone
AMC = Asia Minor Current

Figure 8 Sub-basin scale and mesoscale circulation features in the eastern Mediterranean (Reproduced with permission from Malanotte-Rizzoli et al., 1997 after Robinson and Golnaraghi, 1994).

LIW flow, from the Levantine to the Ionian, and causing a recirculation of the LIW within the west Levantine Basin. Although, multiple, coherent anticyclonic eddies were also quite common in the area before 1991 (as the Ierapetra and Mersa-Matruh), the 1991–95 pattern differs significantly, with three anticyclones of relatively larger size covering the entire area. This feature seems to comprise the

Table 1 Upper thermocline circulation features

Feature	*Type*	*ON85*	*MA86*	*MA87*	*AS87*	*SO91*	*JA95*	*S97*	*ON98*
AIS	P	–	–	Y	Y	Y	Y	Y	N
MMC	P	Y	Y	–	Y	Y	Y	–	Y
AMC	P	Y	Y	–	Y	Y	Y	–	Y
CC	R	Y	N	Y	N	–	–	–	–
Se Lev. Jets	T	Y	Y	–	Y	–	–	–	–
Rhodes C	P	Y	Y	–	Y	Y	Y	–	Y
West Cyprus C	P	Y	Y	–	Y	Y	Y	–	–
MMA	P	Y	Y	–	Y	Y	Y	–	Y
Cretan C	P	Y	?	–	Y	Y	–	Y	Y
Shikmona AC	R	Y	Y	–	Y	Y	–	–	–
Latakia C	R	Y	N	N	Y	–	–	–	–
Antalya AC	R	?	Y	–	N	–	–	–	–
Pelops AC	P	–	Y	Y	Y	Y	–	Y	Y
Ionian eddies AC	T	–	–	–	Y	Y	–	Y	N
Cretan Sea eddies	T	Y	Y	–	Y	–	Y	–	Y
Ierapetra	R	Y	N	Y	Y	Y	Y	–	Y

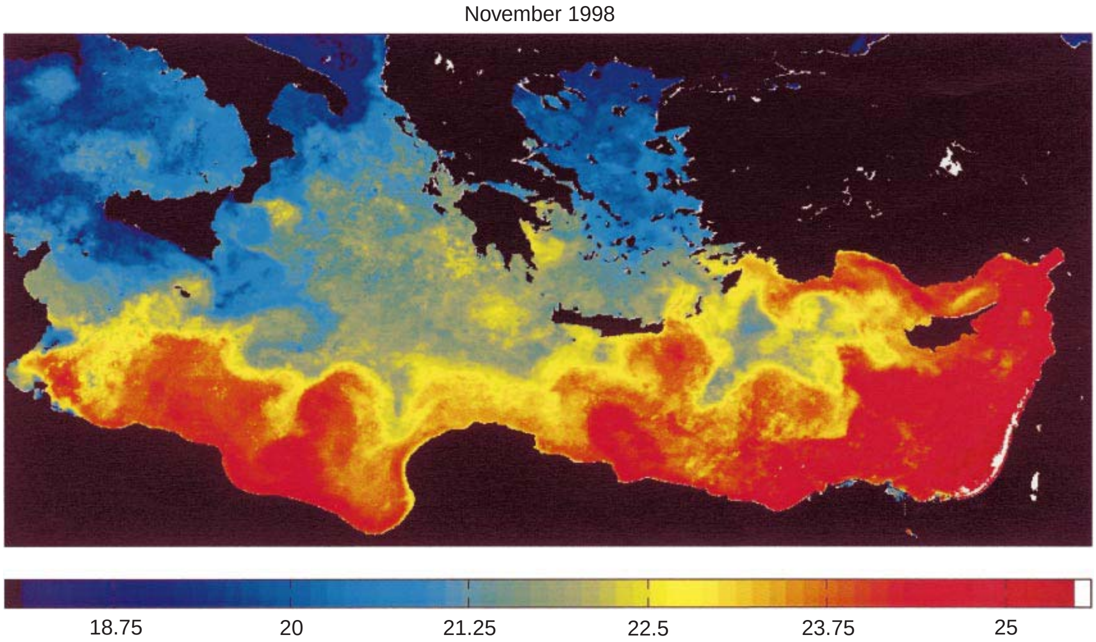


Figure 9 Satellite imagery of sea surface temperature during November 1998 in the Eastern Mediterranean.

Mersa-Matruh and the Ierapetra Anticyclone. Moreover, the 1998–99 infrared SST images (**Figure 9**) indicated that the area was still occupied by large anticyclonic structures. The data sets collected in late 1998 and early 1999 indicated that this circulation pattern had been reversed to cyclonic, confirming the transient nature of these eddies. Consequently, the Atlantic Ionian Stream (AIS) was not flowing from Sicily towards the northern Ionian, but directly eastwards crossing the central Ionian towards the Cretan Passage (**Table 2**).

The seasonal variability of the circulation of the late 1980s in the south Aegean Sea has been replaced by a rather constant pattern in the period of the EMT (1991–98). Therefore, the Cretan Sea eddies were in a seasonal evolution in the 1980s (always present), while in the 1990s there was a constant succession of three main eddies (one cyclone in the west, one anticyclone in the central region and again one cyclone in the east) that presented spatial variability.

Mesoscale Circulation

The horizontal scale of mesoscale eddies is generally related to, but somewhat larger than, the Rossby

Table 2 Mediterranean water masses

Water mass name	*Acronym*
Aegean Deep Water	AGDW
Adriatic Water	ASW
Cretan Deep Water	CDW
Cretan Intermediate Water	CIW
Eastern Mediterranean Deep Water	EMDW
Eastern Mediterranean Transient	EMT
Levantine Deep Water	LDW
Levantine Intermediate Water	LIW
Modified Atlantic Water	MAW
Transitional Mediterranean Water	TMW
Winter Intermediate Water	WIW
Western Mediterranean Deep Water	WMDW

radius of deformation. In the Mediterranean the internal radius is O(10–14) km or four times smaller than the typical values for much of the world ocean. The study of mesoscale instabilities, meandering, and eddying thus requires a very fine resolution sampling. For this reason, only recently different mesoscale features were found in both the western and eastern basins including the mesoscale variabilities associated with the coastal currents in the western basin and open sea mesoscale energetic eddies in the Levantine basin.

In the western basin, intense mesoscale phenomena (**Figure 6**) have been detected using satellite information and current measurements. Mesoscale activity occurs as instabilities along the coastal currents (i.e., the Algerian Current) leading to the formation of mesoscale eddies which can eventually move across the basin or interact with the current itself. Along the Algerian Current cyclonic and anticyclonic eddies develop and evolve over several months as they slowly drift eastward (a few kilometers per day). The anticyclonic eddies generally increase in size and detach from the coast. Some may drift near the continental slope of Sardinia, where a well-defined flow of LIW exists. Here they are able to pull fragments of LIW seaward. Old offshore eddies extend deep in the water column and last from several months to as much as a year. They sometimes enter the coastal regions and interact with the Algerian Current. In the coastal zones the mesoscale currents appear to be strongly sheared in the vertical.

This clearly indicates that eddies can modify the circulation over a relatively wide area and for relatively long periods of time. The coastal eddies along the Algerian coast can be especially vigorous, inducing currents of 20–30 $\mathrm{cm\,s^{-1}}$ strength for periods of a few weeks. More complicated variations of the currents have also been measured at 300 m and sometimes at 1000 m.

Mesoscale activity has been observed in the northern basin (i.e., along the western and northern Corsican Currents). Coastal Corsican eddies are typically anticyclonic and located either offshore or along the coast of Corsica. A number of experiments were conducted to investigate the mesoscale phenomena in the Ligurian Sea. The results of a 1-year current meter array are shown for the southern coastal zone in the Corsican Channel (**Figure 10D**). Mesoscale currents are characterized by permanent occurrence and by a baroclinic structure with relatively large amplitude at the surface, moderate at the intermediate level and still noticeable at depth, thus indicating large vertical shear of the horizontal currents.

Dedicated high-resolution sampling in the Levantine basin led to the discovery of open ocean mesoscale energetic eddies, as well as jets and filaments. This was confirmed by a mesoscale experiment in August–September 1987 in the eastern basin. Mesoscale eddies dynamically interacting with the general circulation occur with diameters in the order of 40–80 km. From this analysis a notable energetic sub-basin/mesoscale interaction in the Levantine basin and a remarkable thermostad in the Ionian have been revealed.

Figure 10A shows a temperature cross-section from XBT profiles collected in summer 1987 across the Mid-Mediterranean Jet, West Cyprus Gyre, MMJ, and the northern border of the Shikmona eddy (section ABCD shown in **Figure 10C**). **Figure 10B** shows the identical XBT section after a pyramid filter, with horizontal influential distance of 50 km. The filter has removed very small scale features while maintaining the mesoscale structure.

Modeling

Vigorous research in the 1980s and the developing picture of the multiscale Mediterranean circulation were accompanied by a new era of numerical modeling on all scales. Modeling efforts included: water mass models, general circulation models, and data assimilative models. Dynamics in the models include: primitive equations, non-hydrostatic formulations, and quasi-geostrophy. The assimilation of the cooperative eastern Mediterranean surveys of the 1980s and 1990s into dynamical models played a significant role in the identification of sub-basin scale features. The numerical model results shown in **Figure 11** depict the existence of numerous sub-basin scale features, as schematized in **Figure 7**.

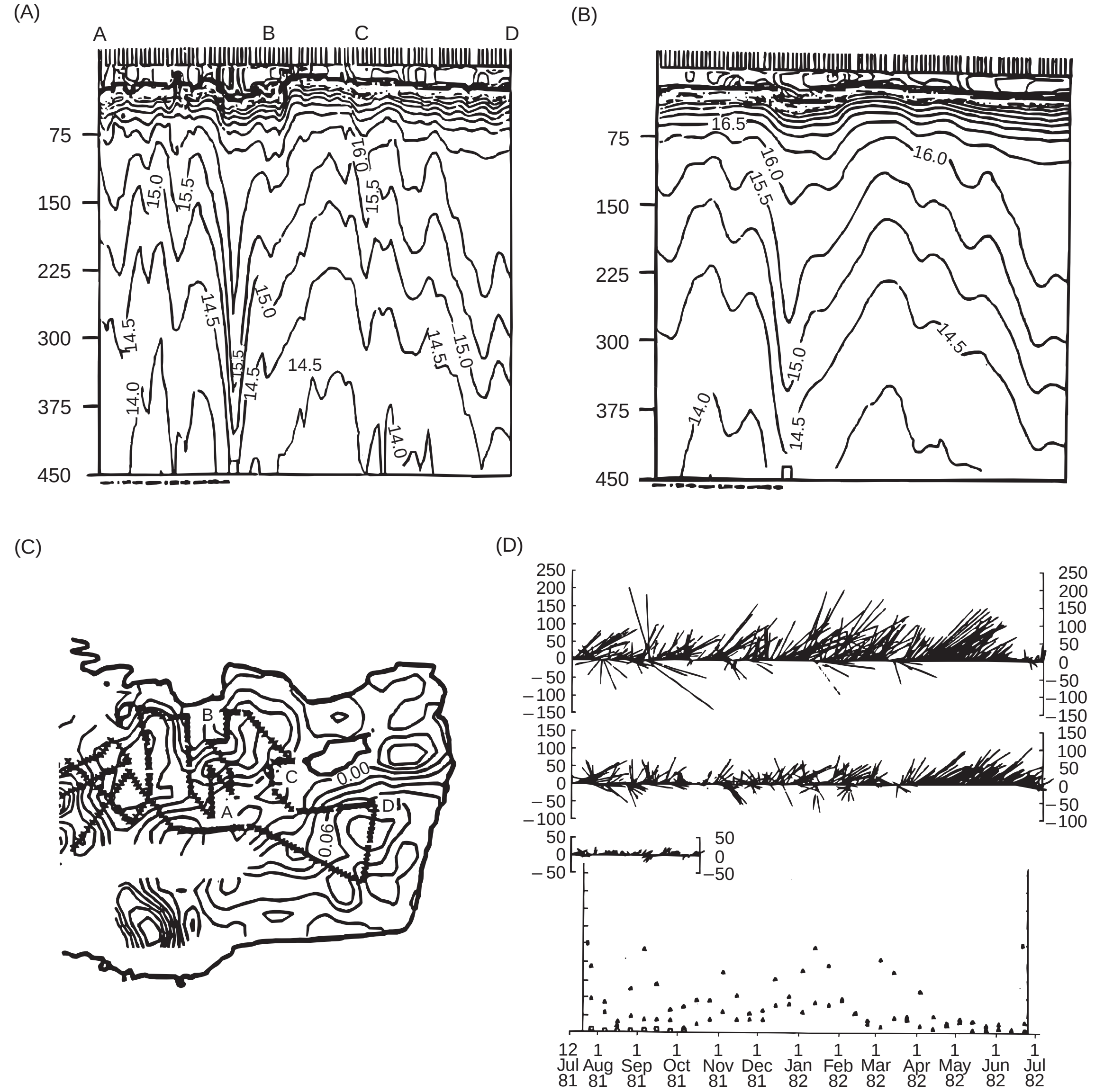


Figure 10 (A) Mesoscale temperature cross-section from XBTs in AS87 POEM cruise along section ABCD. (B) Filtered temperature cross-section using a pyramid filter with 50 km influential radius. (C) Location of the cross-section superimposed on the dynamic height anomaly from AS87 survey (excluding XBTs). (D) Velocities from a current meter array in the Corsican Channel.

In recent years numerical modeling of the general circulation of the Mediterranean Sea has advanced greatly. Increased computer power has allowed the design of eddy resolving models with grid spacing of one-eighth and one-sixteenth of a degree for the whole basin and higher for parts of it. An example output from such a model, forced with perpetual year atmospheric forcing, which includes the seasonal cycle but not interannual variability, is shown in **Figure 12**. Many of these models incorporate sophisticated atmospheric forcing parameterizations (e.g., interactive schemes) which successfully mimic existing feedback mechanisms between the atmosphere and the ocean. Studies have been carried out using perpetual year atmospheric forcing, mostly aimed at studying the seasonal cycle, as well as interannual atmospheric forcing. Studies have mainly focused on reproducing and understanding the seasonal cycle, the deep- and intermediate-water formation processes and the interannual variability of the Mediterranean. They have shown the existence of a strong response of the Mediterranean Sea to seasonal and interannual atmospheric forcing. Both seasonal and interannual variability of the Mediterranean seems to occur on the sub-basin gyre scale. The Ionian and eastern Levantine areas

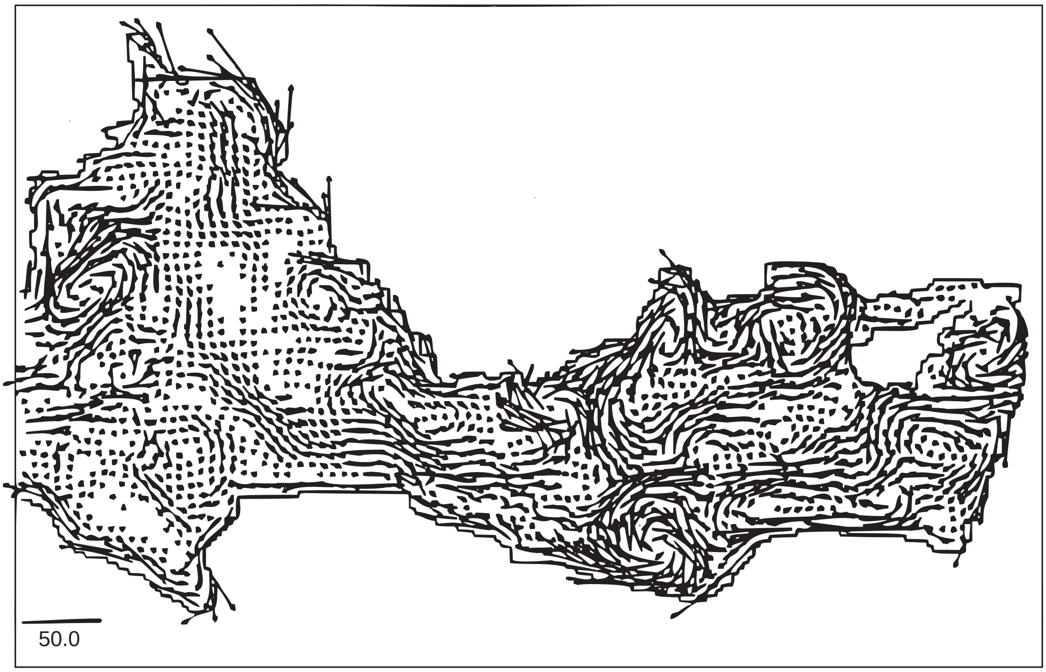


Figure 11 Velocity field for the eastern Mediterranean at 10 m depth from an eddy-resolving primitive equation dynamical model.

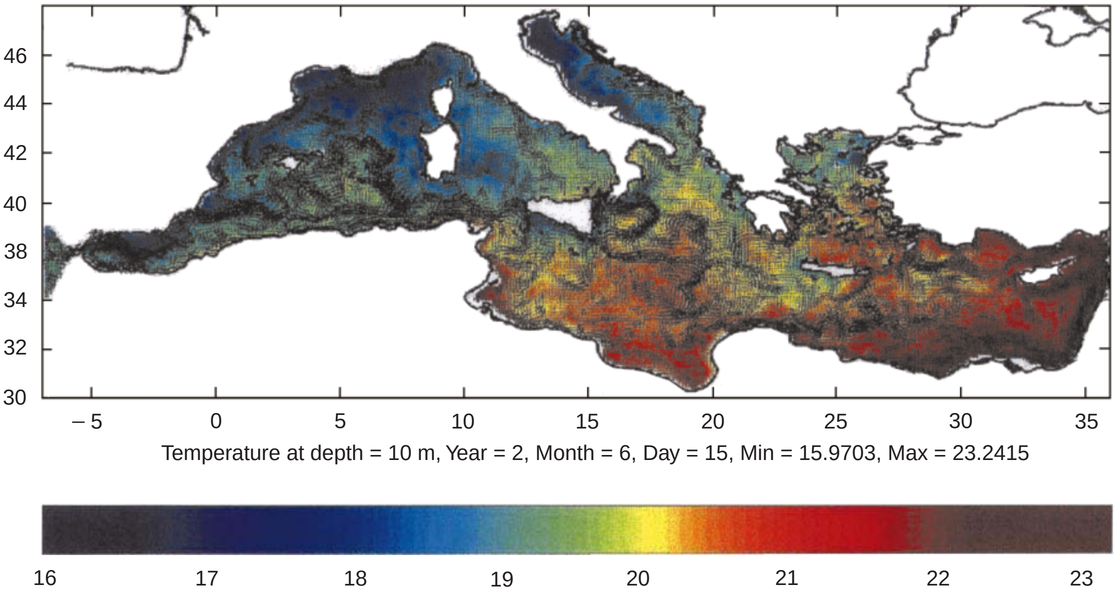


Figure 12 Temperature and superimposed velocity vectors at 10 m depth from a numerical simulation of the entire Mediterranean Sea.

are found to be more prone to interannual changes than the rest of the Mediterranean. Sensitivity experiments to atmospheric forcing show that large anomalies in winter wind events can shift the time of occurrence of the seasonal cycle. This introduces the concept of a 'memory' of the system which 'preconditions' the sea at timescales of the order of one season to 1 year.

In the deep- and intermediate-water formation studies, the use of high frequency (6 h) atmospheric forcing (in contrast to previously used monthly forcing) in correctly reproducing the observed convection depths and formation rates was found to be crucial. This shows the intermittent and often violent nature of the convention process, which is linked to a series of specific storm events that occur during each winter rather than to a gradual and continuous cooling over winter. The use of high-resolution numerical models in both the western and the eastern Mediterranean allowed the study of the role of baroclinic eddies, which are formed at the periphery of the chimney within the cyclonic gyre by instabilities of the meandering rim current, in open ocean convection. These eddies were shown to advect buoyancy horizontally towards the center of the chimney, thus reducing the effectiveness of the atmospheric cooling in producing a deep convected mixed layer. These results are in agreement with previous theoretical and laboratory work.

The LIW layer which extends over the whole Mediterranean was found to play an important role both in the western (Gulf of Lions) and the eastern (Adriatic) deep-water formation sites and more specifically in 'preconditioning' the formation process. It was shown that the existence of this layer greatly influences the depth of the winter convection penetration in these areas. This is related to the fact that the LIW layer with its high salt content decreases the density contrast at intermediate layers, thus allowing convection to penetrate deeper. This result shows the existence of teleconnections and inter-dependencies between sub-basins of the Mediterranean.

A number of numerical models have been developed to simulate and understand the origins and the evolution of the Eastern Mediterranean Transient. These models indicate that the observed changes can be at least partially explained as a response to variability in atmospheric forcing. Sensitivity experiments, in which the observed precipitation anomaly of 1989–90 and 1992–93 was not included, did not reproduce properly the EMT. This confirms that this factor was a significant contributor to the occurrence and evolution of the Eastern Mediterranean Transient, since it acted as a 'preconditioner' to the latter by importantly increasing the salinity in the area.

The enhanced deep water production in the Aegean has implied a deposition of salt in the deep and bottom layers with a simultaneous decrease higher up. As the turnover rate for waters below 1200 m has been estimated to exceed 100 years, this extra salt will take many decades to return into the upper waters. Its return, however, might well induce changes in the thermohaline circulation, considering the dependence of the two potential sources of deep water on the salinity preconditioning. It will therefore take many decades before the eastern Mediterranean returns to a new quasi-steady state. An interesting question in this connection is whether the system will recover its previous mode of operation with a single source of deep-water production in the Adriatic or evolve into an entirely different, perhaps even an unanticipated direction.

Conclusion

The Mediterranean Sea is now known to have a complex thermohaline, wind, and water flux-driven multi-scale circulation with interactive variabilities. Recent vigorous research, both experimental and modeling, has led to this interesting and complex picture. However, the complete story has not yet been told. We must wait to see the story unfold and see how many states of the circulation exist, what changes occur and whether or not conditions repeat.

See also

Coastal Circulation Models. Current Systems in the Mediterranean Sea. Data Assimilation in Models. Deep Convection. Elemental Distribution: Overview. Forward Problem in Numerical Models. Heat and Momentum Fluxes at the Sea Surface. Meddies and Sub-surface Eddies. Mesoscale Eddies. Ocean Circulation. Open Ocean Convection. Regional and Shelf Sea Models. Thermohaline Circulation. Upper Ocean Time and Space Variability. Water Types and Water Masses. Wind Driven Circulation.

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MEIOBENTHOS

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Introduction

Meiobenthos live in all aquatic environments. They are important for the remineralization of organic matter, and they are crucial members of marine food chains. These small (less than 1 mm) invertebrates have representatives from 20 metazoan (multicellular) phyla and three protistan (unicellular) phyla. With their ubiquitous distribution in nature, high abundances (millions per square meter), intimate association with sediments, rapid reproduction and rapid life histories, the meiobenthos have also emerged as valuable sentinels of pollution.

Definitions and Included Taxa

Meio (Greek, pronounced 'myo') means smaller, thus meiobenthos are the smaller benthos. They are smaller than the more visually obvious macrobenthos (e.g., segmented worms, echinoderms, clams, snails, etc.). Conversely, they are larger than the microbenthos – a term restricted primarily to Protista, unicellular algae, and bacteria. Meiofauna are small invertebrate animals that live in or on sediments, or on structures attached to substrates in aquatic environments. Meiobenthos (*benthos* = bottom living) refers specifically to those meiofauna that live on or in sediments. Meiofauna is the more encompassing word. By size, meiofauna are traditionally defined as invertebrates less than 1 mm in size and able to be retained on sieve meshes of 31–64 μm.

Nineteen of the 34 multicellular animal phyla (**Table 1**) and three protistan (unicellular) phyla, i.e., Foraminifera, Rhizopoda, and Ciliophora, have meiofaunal representatives. Of these multicellular (metazoan) phyla, some are always meiofaunal in size (permanent meiofauna), whereas others are meiofaunal in size only during the early part of their life (temporary meiofauna) (**Table 2**). These are the larvae and/or juveniles of macrobenthic species (e.g., Annelida, Mollusca, Echinodermata). Members of the phylum Nematoda are the most abundant meiofaunal organisms, and copepods (Arthropoda, Crustacea) or Foraminifera are typically second in abundance worldwide. Representative meiofauna taxa are illustrated schematically in **Figure 1**.

The books listed under Further Reading by Higgins and Theil and by Giere, and any invertebrate zoology text, should allow one to identify