CURRENTS SYSTEMS IN THE MEDITERRANEAN SEA

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Introduction

In the last two decades the Mediterranean Sea has been the object of renewed interest in the oceanographic community thanks to the formulation and execution of international collaborative programs, such as the UNESCO/IOC sponsored Programme de Recherche Internationale en Méditerranée Occidentale (PRIMO) in the Western basin and Physical Oceanography of the Eastern Mediterranean (POEM) Programme in the Eastern Mediterranean, followed up by the recent effort undertaken by the European community under the Marine Science and Technology (MAST) banner.

Two main reasons form the basis of this scientific effort. The Mediterranean is a midlatitude semi-enclosed sea, exchanging water and other properties with the North Atlantic Ocean, which plays a crucial role in the global thermohaline circulation through the formation of North Atlantic Deep Water (NADW) in the polar Greenland and Labrador Seas. The upper intermediate layer of the North Atlantic is replenished with a very salty water mass that spreads out from the Mediterranean through the connecting narrow Straits of Gibraltar. This salty water is formed in the easternmost Mediterranean, the Levantine basin, as Levantine Intermediate Water (LIW). The Gibraltar Straits are thus a point source of heat and salt for the North Atlantic at all depths from 1000 m to more than 2500 m. Tongues of this warm, salty water extend through the Atlantic interior, both northward along the coast of Europe and westward towards America on all isopycnals from $\sigma_1 = 31.938\,\mathrm{kg\,m^{-3}}$ to $\sigma_3 = 41.44\,\mathrm{kg\,m^{-3}}$, thus crucially preconditioning the NADW convective cells in the polar seas.

The second reason is that many dynamical processes which are fundamental to the world ocean circulation also occur within the Mediterranean, such as deep convection cells completely analogous to the NADW cell, with convective sites in both the Western and Eastern basins. Both of these basins are moreover endowed with a deep thermohaline circulation, the equivalent of the global conveyor belt. Thus the Mediterranean provides a laboratory basin for general circulation studies. The two basins, Western and Eastern, can be studied quite independently, as they are connected through the shallow Sicily Straits, with the deepest threshold at ~ 250 m, which prevents direct communication between the subsurface layers.

This paper first provides a short review of the climatology characterizing the entire basin. The western and eastern basins are then discussed separately. Particular attention is devoted to the Eastern Mediterranean, where a major transient has occurred in the last decade that documents the existence of multiple states for the Eastern Mediterranean internal thermohaline circulation.

Morphology and Climatology

The Mediterranean Sea (**Figure 1A**) is an enclosed basin connected to the Atlantic Ocean by the narrow and shallow Strait of Gibraltar (width ~13 km; sill depth ~300 m). It is composed of two similar size basins, western and eastern, connected by the Strait of Sicily (width ~35 km; sill depth ~250 m). The Western Mediterranean has a triangular shape, with the Ligurian Sea at its apex and a large topographic plateau in the Balearic Sea (**Figure 1B**). The islands of Corsica and Sardinia separate the Balearic Sea from the Tyrrhenian Sea, where the bottom relief has the more complex shape of a deep, corrugated valley. The Balearic and Tyrrhenian Seas join in the south in a wide passage between Sardinia and Sicily that leads to the Sicily Straits and the eastern basin.

The Eastern Mediterranean has a more complicated structure than the western, with a much more irregular, complex topography constituted by a succession of deep valleys, ridges, and localized pits (**Figure 1B**). Four sub-basins can be defined in the Eastern Mediterranean (**Figure 1A**): the Ionian, the Levantine, the Adriatic, and the Aegean Seas. The Ionian Sea is the deepest in its central part, ending in the shallow Gulf of Sirte at its southernmost end. The Cretan passage leads from the Ionian into the Levantine basin, that reaches its maximum depth in a localized depression south-east of the island of Rhodes.

The hydrology and the circulation of the Mediterranean Sea have been known in overall generality for some time. For instance it is well known that the

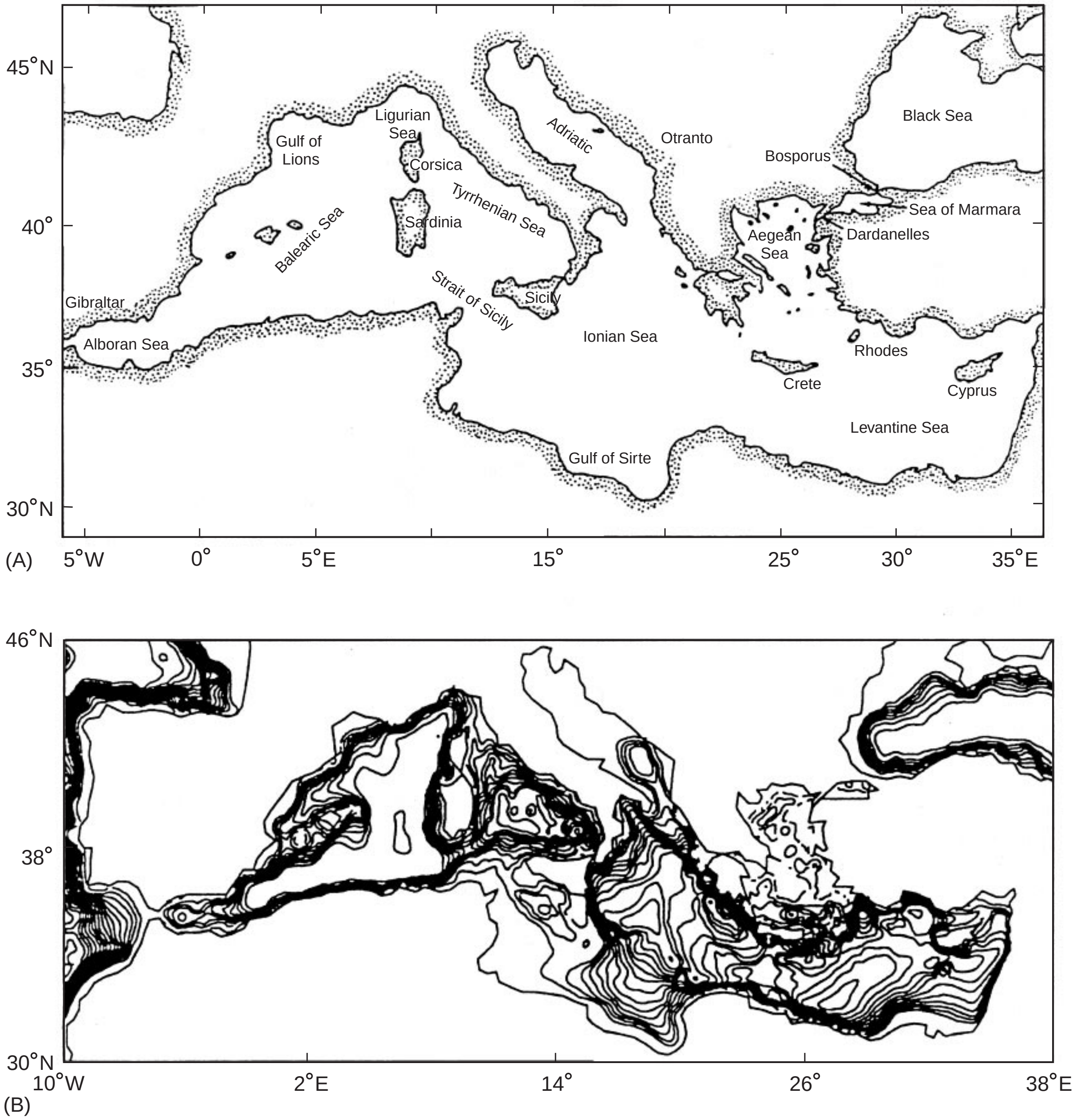

Figure 1 Morphology of the Mediterranean Sea: (A) geography of the basin; (B) bathymetry.

Mediterranean basins, both western and eastern, are evaporation basins (lagoons), with freshwater flux from the Atlantic through the Gibraltar Straits and into the Eastern Mediterranean through the Sicily Straits. The Atlantic Water (AW) mass entering through Gibraltar increases in density because evaporation exceeds precipitation and becomes Modified Atlantic Water (MAW) in its route to the Levantine basin. New water masses are formed here via convection events driven by intense local cooling and evaporation from winter storms. Bottom water is produced in localized convection sites, for the western basin in the Gulf of Lions (Western Mediterranean Deep Water, WMDW) and for the eastern basin in the southern Adriatic (Eastern Mediterranean Deep Water, EMDW). Recent observations also indicate Levantine Deep Water (LDW) formation in the north-eastern Levantine basin during exceptionally cold winters, where Levantine Intermediate Water (LIW) is regularly formed seasonally. Evidence has emerged that LIW formation occurs over much of the Levantine basin but preferentially in the north probably due to meteorological factors. The LIW is the important water mass which circulates westward through both the eastern and western basins and contributes predominantly to the efflux from Gibraltar to the Atlantic, mixed with some EMDW and WMDW.

The western and eastern basins are connected in the upper layer, ~ 200 m thick, through the 'open

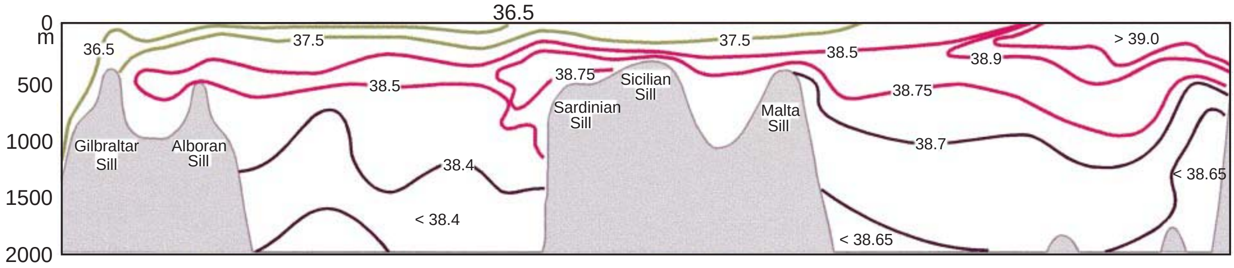

Figure 2 The open thermohaline cell of the Mediterranean upper layer.

thermohaline cell' of the basin, schematized in **Figure 2**.

While the entire Mediterranean is a 'lagoon' for the North Atlantic, the eastern basin itself is a 'lagoon' for the western one. The Atlantic Water (AW) mass enters the Mediterranean at Gibraltar with a typical salinity of $S = 36.15$ PSU and temperature $T = 15°C$. The AW becomes Modified Atlantic Water (MAW) through diffusive processes in its pathway eastward and can be identified as a subsurface salinity minimum below ~ 30 m depth. At the Sicily Straits, the saltier MAW has a salinity $S \leq 37.5$ PSU reaching a maximum of $S < 38.9$ PSU in the Levantine basin. Here in its northern part, winter episodes of cold, dry winds blowing from the mainland under surface cooling and evaporative fluxes lead to the formation of LIW, which has $39.0 \leq S \leq 39.2$ PSU and $15°C < \theta < 16°C$ at the formation sites, the most important of which is the well-known Rhodes gyre. The LIW return route is westward in the layer between 200 and 600 m depth. LIW becomes progressively colder and fresher. At the Sicily Straits typical LIW core values are $\theta = 14.3°C$ and $S \leq 38.8$ PSU. At the Gibraltar Straits LIW is diluted to $S \leq 38.5$ PSU, and spreads out in the North Atlantic, becoming Upper North Atlantic Intermediate Water. Secondary pathways of LIW will be discussed separately for the two basins.

The Western Mediterranean

The upper thermocline circulation (upper ~ 200 m) of the Western basin is schematized in **Figure 3A**.

The MAW in the Alboran Sea describes a quasi-permanent anticyclonic gyre in the west and a more variable circuit in the eastern Alboran. Further east, the MAW is entrained in the strong meandering Algerian current, whose instabilities lead to the formation of anticyclonic eddies (diameter $\sim$50–100 km) all along the coast of Algeria. These eddies grow in size; some may detach from the coast and drift into the interior of the Balearic Sea. A quasi-stationary cyclonic path of MAW has been observed around the Balearic Sea leading to the formation of the Western Corsican Current west of Corsica. A steady cyclonic path of MAW is also present in the Tyrrhenian Sea, that intrudes into Northern Ligurian Sea, where it joins the Western Corsican Current producing a return south-westward flow along the Italian, French, and Spanish coasts, towards the Alboran Sea, that is called the Northern Current. The latter shows strong seasonal variability, becoming more intense and narrower in wintertime when it develops intense meanders, and splits into multiple branches in the southern Balearic sea.

Figure 3B shows the pathway of LIW emerging from the Sicily Straits into the Western Mediterranean in the intermediate layer, 200–600 in depth.

LIW follows a cyclonic route all around the Tyrrhenian Sea, and splits into two branches at the northern tip of Corsica. One branch enters directly into the Ligurian Sea, the second circulates around Sardinia and Corsica, merges with the previous branch and successively flows cyclonically around the Balearic Sea. This major LIW branch enters the Gulf of Lions, where it plays a crucial role in preconditioning the winter convective cell of WMDW located here. WMDW has been observed to form in the Gulf of Lions basically every year, under winter episodes of cold, dry Mistral wind blowing from France. Here the mixed, ventilating chimney ($\sim$100 km in diameter) can reach 2000 m depth.

It must be pointed out that the mean LIW pathway is still controversial. Numerical simulations as well as data analysis indicate a major direct route of LIW from the Sicily Straits to Gibraltar. On the other hand, strong observational evidence suggests the pattern presented in **Figure 3B**, with the LIW cyclonic circuit around the Tyrrhenian, the islands of Sardinia and Corsica and finally the Balearic Sea. Here, in the southern, eastern part, the LIW pathway bifurcates, with one branch proceeding towards and exiting from Gibraltar and a second returning eastward along the Algerian coast.

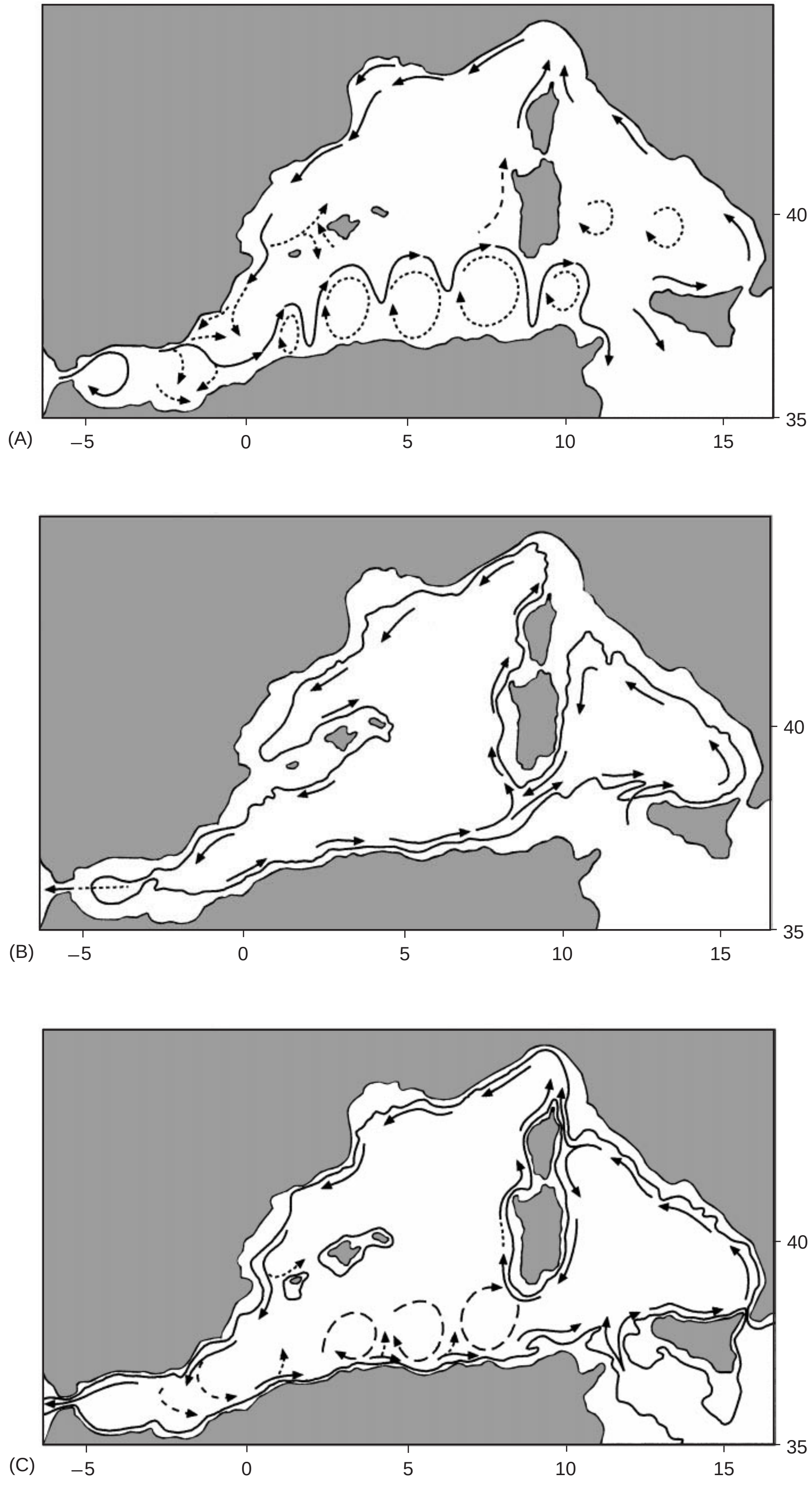

Figure 3 Circulation of the Western Mediterranean: (A) upper thermocline circulation; (B) intermediate layer circulation with LIW pathways; (C) deep thermohaline circulation with WMDW pathways.

Figure 3C schematizes the thermohaline cell of the Western Mediterranean, driven by the winter convection in the Gulf of Lions.

Even though the exact routes of WMDW are also under debate, the pattern of **Figure 3C** is based on available observations and indicates spreading at depth of WMDW both towards the Sicily and the Gibraltar Straits, following a circuitous cyclonic route that leads it throughout the Balearic and Tyrrhenian Seas. The deep WMDW flow is obviously affected by topography. In the Tyrrhenian Sea, the WMDW joins the Tyrrhenian Dense Water present in the deep layers. At Gibraltar, upwelling of WMDW occurs, mixing with the overlying LIW, and contributing (what it is believed to be a small proportion) to the outflow from Gibraltar into the northern Atlantic.

The Eastern Mediterranean

The field work for the POEM program which was carried out in the period 1985–95, has definitively established the existence of three dominant scales interacting in the general circulation pattern; the basin-scale, i.e. the intermediate and deep thermohaline circulation; the sub-basin scale, characterizing the upper thermocline; and the mesoscale, defined by a ubiquitous and energetic eddy field. The POEM observational evidence has moreover shown that the Eastern Mediterranean has undergone a startling transition in the intermediate and deep basin circulations between the 1980s and the 1990s, the first documented example of the existence of multiple thermohaline states.

The upper thermocline circulation, on the other side, which is embedded in the Mediterranean open thermohaline cell, has remained very consistent throughout the two decades. The building blocks of the upper thermocline circulation are sub-basin-scale gyres and permanent, or quasi-permanent, cyclonic and anticyclonic structures interconnected by intense jets and meandering currents. The schematic representation of the upper thermocline circulation is given in **Figure 4**.

All the structures depicted in **Figure 4** are robust and persisted in the 1980s and the 1990s, albeit with modulations in strength and areal extension. Some differences were present but only in the Levantine Sea. At the Sicily Straits, the entering MAW is advected by the strong Atlantic Ionian Stream (AIS) jet, which forms a broad meander in the Ionian Sea, bifurcating into two main branches. One branch turns directly southward towards the African coast enclosing an intense anticyclonic area with multiple centers, the Ionian anticyclones (IA)

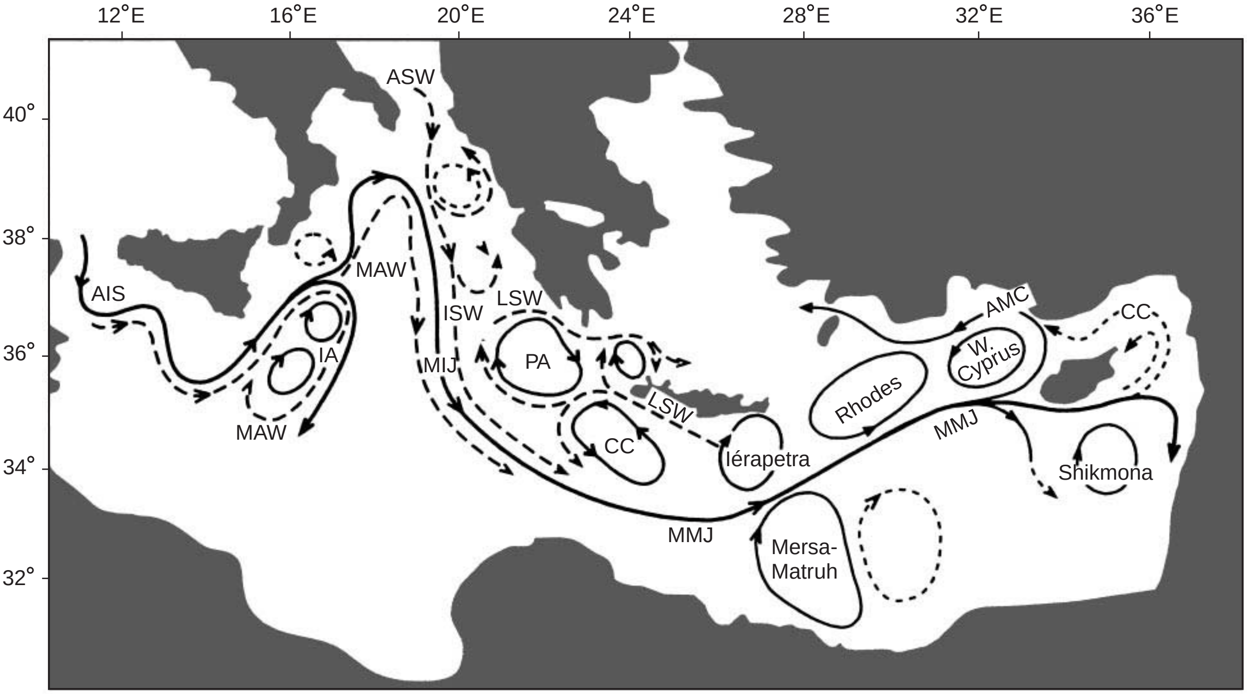

Figure 4 Eastern Mediterranean: Schematic representation of the upper thermocline circulation. AIS, Atlantic Ionian Stream; AMC, Asia Minor Current; ASW, Adriatic Surface Water; CC, Cretan Cyclone; IA; Ionian anticyclones; ISW, Ionian Surface Water; LSW, Levantine Surface Water; MAW, Modified Atlantic Water; MIJ, Mid-Ionian Jet; MMJ, Mid-Mediterranean Jet; PA, Pelops anticyclone.

which penetrate deeply into the intermediate layer. The second AIS branch protrudes into the north-eastern extremity, then turns southward forming the strong Mid-Ionian Jet (MIJ) that crosses the entire Ionian sea meridionally, thereafter veering eastward through the Cretan channel where it becomes the Mid-Mediterranean Jet (MMJ). Strong permanent features are the Pelops anticyclone (PA) that has a strong barotropic component and penetrates to 800–1000 m depth. The Cretan cyclone, located south of Crete, is on the other side confined to the upper thermocline. A further permanent structure in

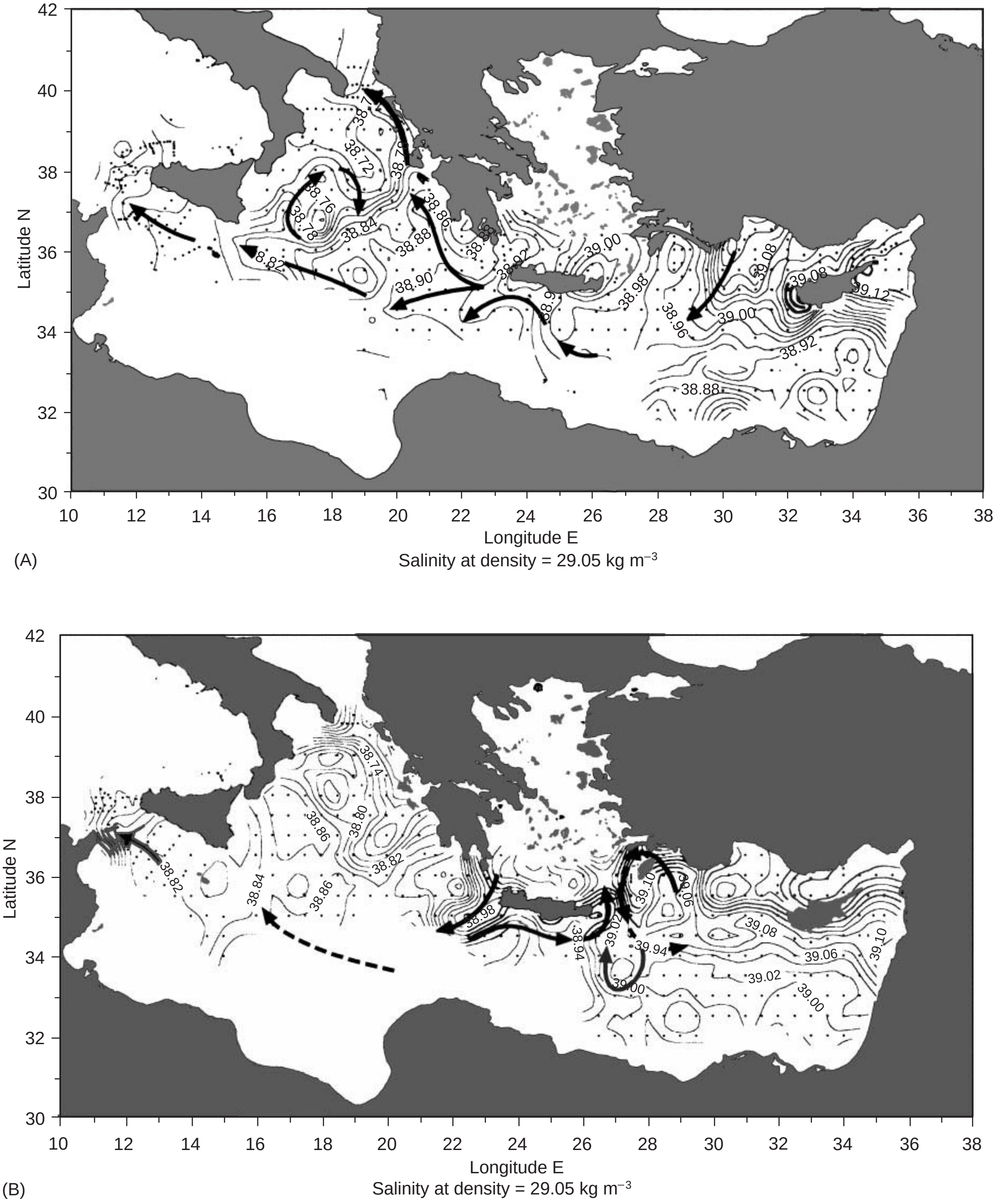

Figure 5 Intermediate layer circulation: (A) circulation in 1987 with LIW pathways; (B) circulation in 1991 with LIW and CIW pathways.

the Cretan passage is the strong Ierapetra anticyclone, also South of Crete. The MMJ from the Cretan passage intrudes into the Eastern Levantine where it separates a northern overall cyclonic region from a southern anticyclonic region. The northern region comprises two well defined, permanent cyclones, the Rhodes gyre, site of LIW and LDW formation, and the western Cyprus cyclone. The southern anticyclonic area also comprises multiple centers, the strongest and most robust of which is the Mersa-Matruh anticyclone, located just south of the Rhodes gyre. A quasi-permanent structure, the Shikmona anticyclone, is present in the easternmost Levantine. In the 1990s, the only major difference was constituted by the appearance of a third anticyclonic center in the southern Levantine, of which the MMJ constituted the Northern rim. This anticyclone pushed westward the Mersa-Matruh anticyclone, thus forming with the Ierapetra gyre a three-lobed intense anticyclonic area that induced a stronger meandering in the MMJ, confining it to its northern rim.

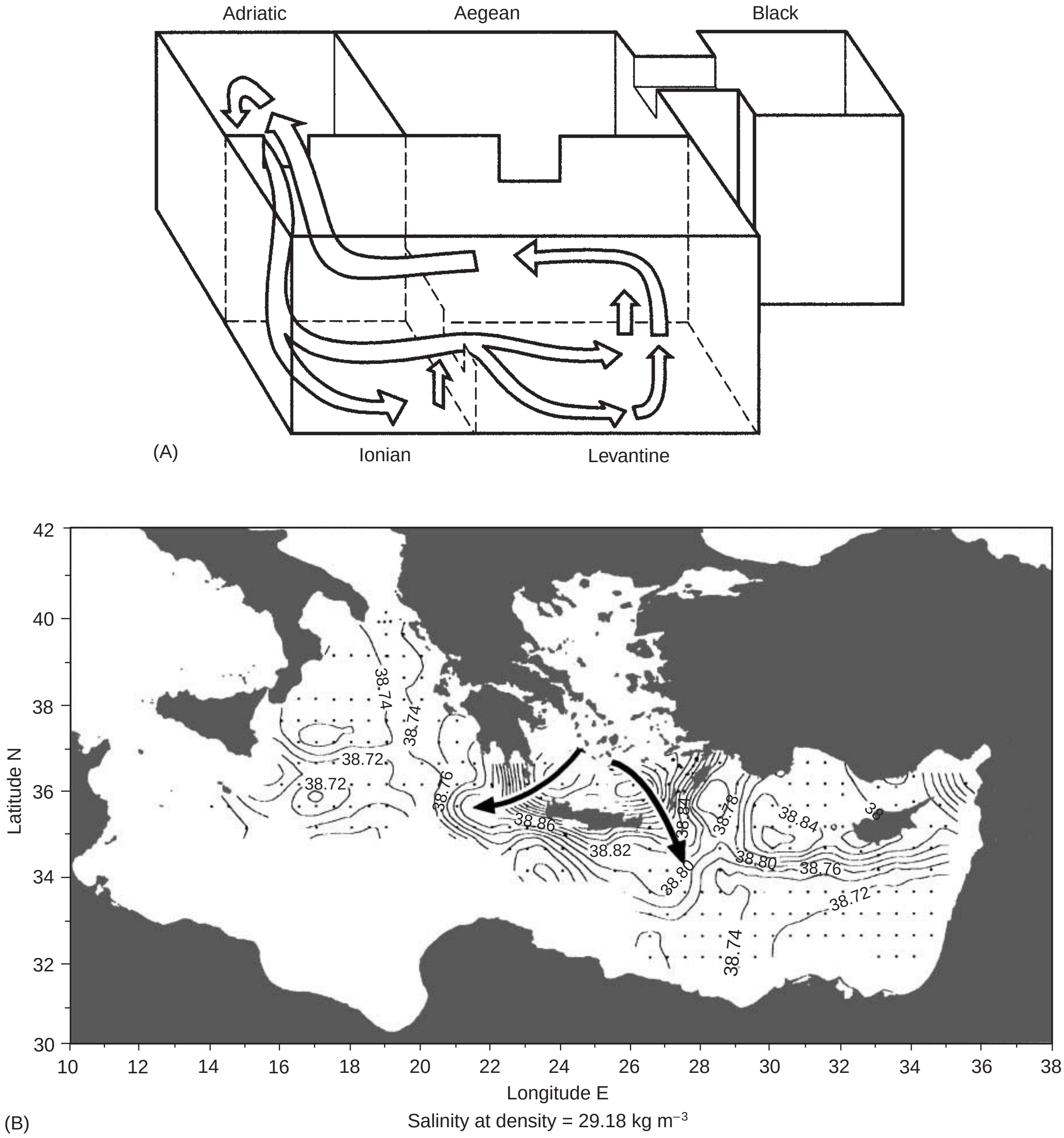

Figure 6 Deep thermohaline circulation: (A) schematic representation of the deep thermohaline cell in 1987; (B) deep pathways of CDW in 1991.

The dramatic transition occurred in the intermediate and deep layer circulations. Definitive observational evidence has been presented that this change was already present in 1991 and persisted through 1995–96, while the 1985–87 situation was completely different. In the intermediate layer, 250–600 dbar depth, characterized by LIW spreading on the isopycnal horizons $\sigma_\theta = 29.00–29.05–29.10\,\mathrm{kg\,m^{-3}}$, the 1987 LIW circulation is depicted in **Figure 5A** for $\sigma_\theta = 29.05\,\mathrm{kg\,m^{-3}}$.

LIW, formed in the northern Levantine in the Rhodes gyre, follows its 'classical' pathway, spreading towards the Sicily Straits through the Cretan channel and the Ionian interior. A second major route produced by the veering by the Pelops anticyclone is northward along the Greek coastline towards the Otranto Straits. Here LIW enters the southern Adriatic Sea to precondition the deep convective cell where Adriatic Deep Water (ADW) occurs. ADW spreads at depth out of the Otranto Strait to become EMDW.

The situation in 1991 (shown in **Figure 5B**, again the salinity distribution on $\sigma_\theta = 29.05$ to $\mathrm{kg\,m^{-3}}$) is completely different. Now Cretan Intermediate Water (CIW) formed inside the Cretan/Aegean sea, substitutes for LIW, exiting from the western Cretan Arc Straits in a well defined tongue and filling the Ionian interior. The LIW is still formed in the northern Levantine, but its westbound pathway is blocked by the three-lobed anticyclonic region now present in the southern Levantine, which induces a local LIW cyclonic recirculation inside the Levantine itself.

This startling change is due to the fact that in the 1990s the 'driving engine' of the intermediate, transitional and deep layer circulations became the interior of the Cretan/Aegean Sea, with CIW and Cretan Deep Water (CDW) forming there, spreading out and filling the abyssal layers of the entire Eastern Mediterranean. In 1987, the EMDW was formed in the southern Adriatic as ADW, spread out from the Otranto Strait into the entire Eastern Mediterranean, upwelled to the transitional/intermediate layers and returned as LIW in the upper warm pathway to the southern Adriatic, thus closing the internal thermohaline cell. The 1987 'conveyor belt' of the basin is schematized in **Figure 6A**.

In 1991 the transitional and deep water masses were also formed in the Cretan/Aegean Sea, and they spread out from the western and eastern Cretan Arc Straits on all the horizons $\sigma_\theta \geq 29.15\,\mathrm{kg\,m^{-3}}$, as shown in **Figure 6B**.

These denser isopycnals rose to much shallower depths in 1991 than in 1987, thus greatly increasing by advection the salt content of the intermediate layer. In the Ionian Sea, CDW pushes the old and slightly denser EMDW of southern Adriatic origin to the west and downward to the near bottom layer. However, the closing pathways of the Eastern Mediterranean deep thermohaline cell in the 1990s are not yet clearly identified.

See also

Mediterranean Sea Circulation. Thermohaline Circulation.

Further Reading

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CURRENT SYSTEMS IN THE PACIFIC OCEAN

See **CALIFORNIA AND ALASKA CURRENTS; EAST AUSTRALIAN CURRENT; KUROSHIO AND OYASHIO CURRENTS; PACIFIC OCEAN EQUATORIAL CURRENTS**