Water masses and circulation patterns in the deep layer of the Eastern Mediterranean

Water masses
Mixing ratios
Circulation
Eastern Mediterranean
Masses d'eau
Proportions du mélange
Circulation
Méditerranée orientale

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ABSTRACT

Hydrographic data collected at deep stations during the cool and warm seasons from 1948 to 1972 were used for detailed analysis of the water masses and circulation patterns at and below 1 000 m depth, in the Eastern Mediterranean.
The potential temperature, salinity, potential density distributions and mixing ratios of Adriatic, Levantine and Cretan waters at 1 000 and 2 000 m depth were presented. Two water cores were found, one with low salinity and temperature and a significantly high percentage of Adriatic-type water (greater than 80%), less than 10% of deep Cretan Sea water, and 10 to less than 20% of Levantine-type water. The other is found near the Cretan Sea straits with an important contribution of deep Cretan Sea water (about 40-50%), 40-60% of Adriatic and 5-15% of Levantine-type water. The horizontal distributions showed the preferential paths of the water masses contributing to the formation of the deep water.
A cyclonic general circulation has been detected in the Levantine sea as well as in the Ionian sea.

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RÉSUMÉ

Les masses d'eau et la circulation profonde en Méditerranée orientale

Les masses d'eau et la circulation à 1 000 m de profondeur et au-delà ont été analysées en Méditerranée orientale, à partir des données hydrologiques de stations profondes effectuées durant les saisons froides et chaudes de 1948 à 1972 : température potentielle, salinité, densité potentielle, proportions du mélange des eaux adriatique, levantine et de la mer de Crête à 1 000 et 2 000 m de profondeur.
Deux veines d'eau ont été trouvées : l'une avec de faibles valeurs de salinité et température et une proportion élevée (80%) d'eau adriatique, moins de 10% d'eau de la mer de Crête, et de 10 à moins de 20% d'eau levantine; l'autre, proche des détroits de la mer de Crête, avec une proportion élevée (40 à 50%) d'eau profonde de la mer de Crête, 40 à 60% d'eau adriatique et de 5 à 15% d'eau levantine. Les répartitions horizontales montrent les circuits préférentiels des masses d'eaux profondes.
Un tourbillon cyclonique a été décelé dans la mer Levantine et dans la mer Ionienne.

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INTRODUCTION

The deep waters of the Eastern Mediterranean have been studied by Nielsen (1912), Pollak (1952), Lacombe and Tchernia (1958), Wüst (1961) and Borkova (1976). Lacombe and Tchernia (1958) have drawn a small number of isohalines and isotherms at 1 000, 1 500 and 2 000 m using data available for the period from June to October. Wüst (1961) has also presented the isotherms and isohalines of what is called the core of the deep water. Finally the Russian author Borkova (1976) has shown the horizontal distribution of temperature and salinity throughout the year. All these investigators agreed on the role of the Adriatic and Levantine water types in the formation of the deep waters of the Eastern Mediterranean, in addition to the remarkable effect of deep Cretan Sea water on the deep waters in the vicinity of the Cretan Sea straits. This latter effect was also confirmed by Miller (1972). However, Pollak disagreed with the other authors concerning the influence of the deep Cretan Sea waters. According to Borkova (1976), a water tongue of minimum temperature coming from the Ionian Sea towards the Levantine basin was noticed at the 2000 m level. This tongue indicated the deep Adriatic water flow direction. However, the data used in the above-mentioned studies were not abundant and it is useful to utilize the data now available from a great number of stations, to make a detailed analysis of the deep water and its circulation.

DATA AND METHODS OF ANALYSES

The hydrographic data collected from 1948 to 1972 (obtained from hydrographic data centres) were used in the study of the deep waters in the region delineated by (31° to 40°N) and (15° to 36°E). Vertically unstable stations were either corrected for temperature or salinity, or rejected if many instabilities were observed. The year was divided into two periods: the cool season, from November to April, and the warm season from May to October. In each season, the potential temperature, salinity and potential density were presented at 1000 and 2000 m depth. The mixing ratios of the main components of the deep waters in the Eastern Mediterranean have been determined at each station at the different depths. Their determination was based on the triangle of mixing formed by:

1) the Adriatic water type (13°C, 38.60), after Lacombe and Tchernia (1958);

2) the Levantine water type (16.2°C, 39.12), after El-Gindy (1983); and

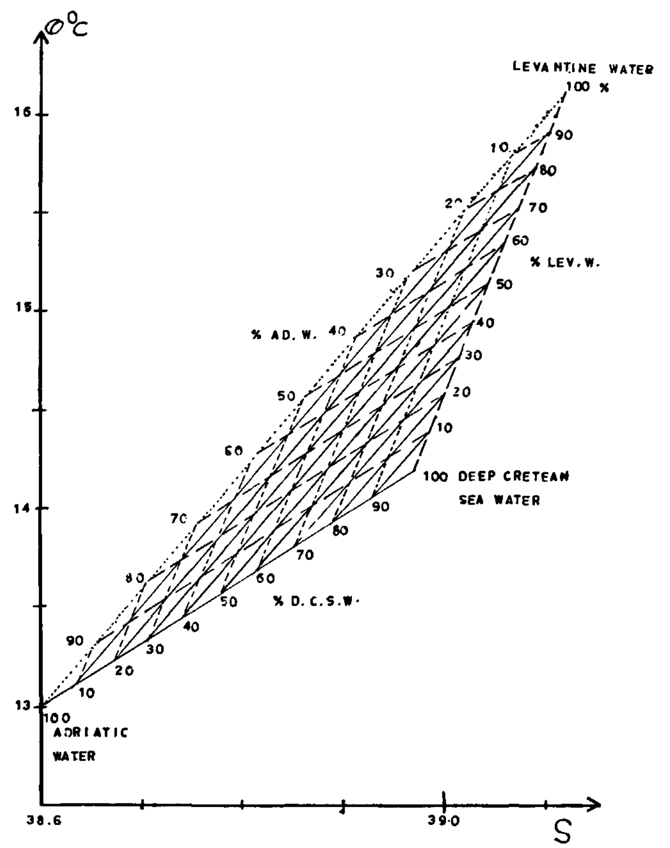


Figure 1

A nomogram for determination of percentages of Levantine, Adriatic and deep Cretan Sea waters in the deep Eastern Mediterranean. Lines of equal percentages in the triangle are indicated by: .... Adr. water, --- Lev. water, ——— D.G.S. waters.

3) the deep Cretan Sea water (14.2°C, 38.97), after Lacombe and Tchernia (1958).

The nomogram used for the determination of the mixing ratios of the different components is shown in Figure 1. The ratios of each of these components will also be presented on horizontal sections.

From the above distributions, the characteristics and the circulation patterns of the deep waters will be investigated.

DEEP WATER CHARACTERISTICS AT 1000 M DEPTH

The distribution of the potential temperature, salinity and potential density during the warm and cool seasons will be discussed in detail.

The potential temperature

In the warm season, the potential temperature distribution at this level (Fig. 2 *b*) shows that in the Ionian Sea there are waters with relatively low temperature (Ø < 13.50°C) lying between 34° and 35°N. In the Levantine Sea, the core of this cool water in the Ionian Sea flows along the North African coast, and moves to the NE in the SE of the basin. The trend of the isotherms near the Cretan Sea straits indicates the outflows from the Aegean Sea. In the Cretan Sea, the potential temperature at the 1000 m level is higher than that in the Ionian and Levantine basins, lying between 13.70°C in the east and 14.3°C in the west.

In the cool season (Fig. 2 *a*) the tongue of cold water is again obvious in the Levantine Sea. Considering the area covered by Ø > 13.50°C, in the Ionian Sea, the deep Cretan Sea water seems to have a more extensive effect on the deep waters out of the straits during the cool season. This could indicate a more active outflow from the Cretan Sea to the Ionian basin during the cool period.

Salinity

During the warm season, the salinity distribution, Figure 3 *b*, indicates that two regions of high salinity are found in the Ionian Sea: one in the SW of the Sea (with S > 38.72), the other occupying a wide area shown by two tongues originating in the Western Cretan Sea straits, with salinity up to 38.75. A relatively low salinity (S < 38.70) is located between these two maxima. In the Levantine Sea, a low saline water is detectable along the southern and northern Levantine coast and intruding into higher salinity waters. The high salinities reflect the influence of deep Cretan Sea waters. In the Aegean Sea the salinity is higher than in the Ionian and Levantine Seas; it reaches 38.95 near the eastern Peloponnesus coast, and 38.80 near the SE Cretan Sea straits.

Figure 2*a*
Distribution of potential temperature at 1 000 m depth in the Eastern Mediterranean during the cool season.

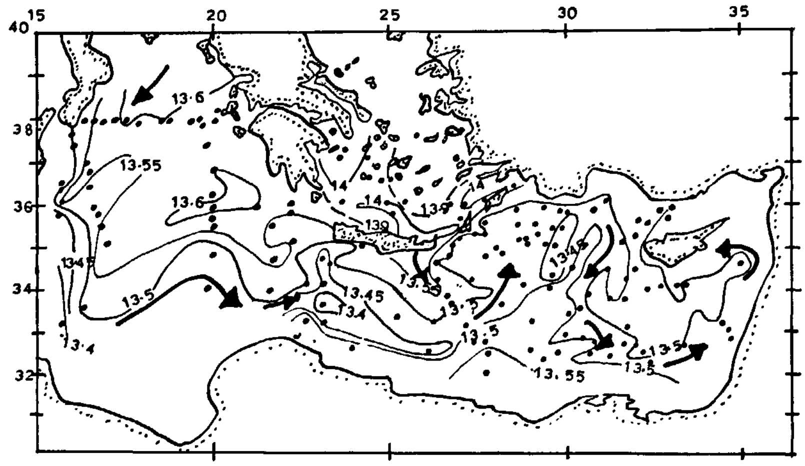
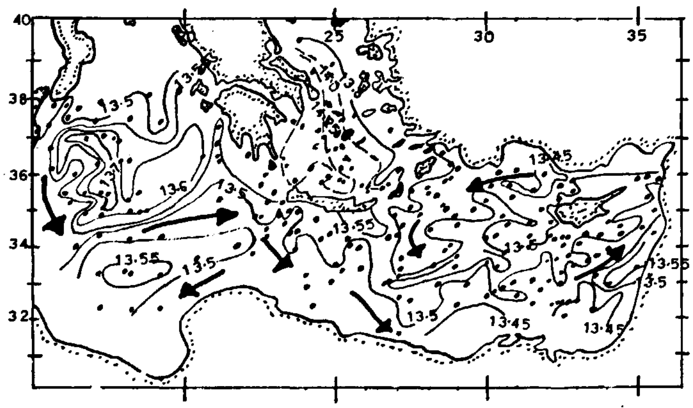


Figure 2*b*
Distribution of potential temperature at 1 000 m depth in the Eastern Mediterranean during the warm season.



In the cool season (Fig. 3*a*), the salinity at 1 000 m depth shows similar distributions, with high salinity near Cretan Sea straits and low saline waters in the south of the Levantine and Ionian Seas. This low salinity has northward veins at different longitudes, from 23°E-26°E and 30°-32°. This should generate deep eddies. Salinities lower than 38.70 in this tongue were found at about 11 stations.

Figure 3*a*
Distribution of salinity at 1 000 m depth in the Eastern Mediterranean during the cool season.

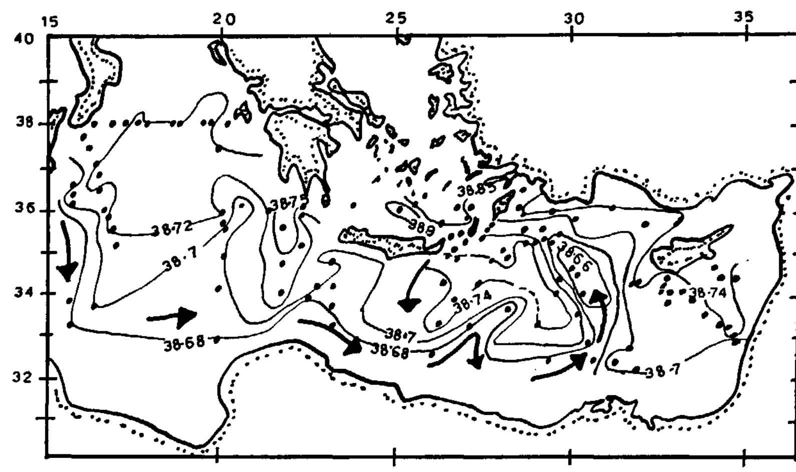
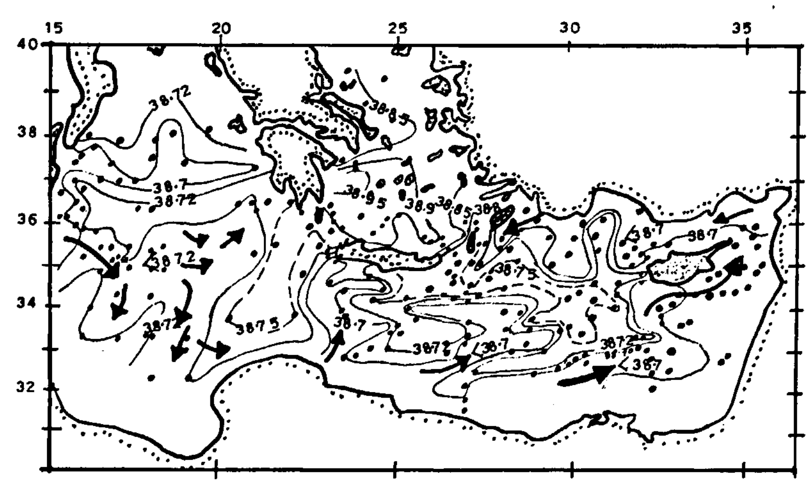


Figure 3*b*
Distribution of salinity at 1 000 m depth in the Eastern Mediterranean during the warm season.



Potential density

The distribution of the potential density (Fig. 4 *b* and 4 a) shows that in the warm season, the density lies between 29.15 and 29.22.

Low densities exist west of the Ionian Sea (between 34°-37°N) and along the Levantine coast while the higher ones are near the Cretan Sea straits. The path of the low saline cool water along the African coast could be followed by the isopycnal of 29.17.

Mixing ratios

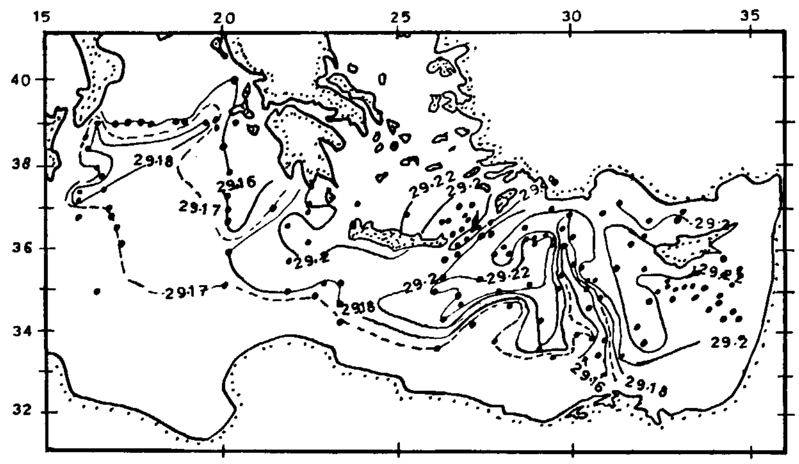
In the warm season, the percentages of the Adriatic, Levantine and deep Cretan Sea water masses at 1 000 m depth (Fig. 5 *b*, 6 *b*, 7 *b*) show a region, nearly along 18°E, characterized by an important contribution of Adriatic water (%> 80). In the Levantine Sea, although the isohaline of 80% follows the North African coast, it intrudes northward at 23°E, at 27°-28°E and at 32°E. A tongue of Levantine water of relatively important percentage (> 20%) is nearly between the latitudes of 35° and 37°N in the Ionian Sea. This tongue is nearly parallel to that of the core of the intermediate water (El-Gindy, 1983). Hence the higher ratio of Levantine water could be attributed to the influence of vertical mixing with the above intermediate layer. The contribution of the deep Cretan Sea water is pronounced in the Ionian and Levantine basins near the Cretan Sea straits where it may exceed 40%. In the cool season the mixing ratios at 1 000 m depth (Fig. 5 *a*, 6 *a* and 7 *a*) are shown to be similar to those of the warm season.

DEEP WATER CHARACTERISTICS AT 2 000 M DEPTH

At 2 000 m depth, in the warm season, an obvious core of water having (Ø < 13.5°C, S < 38.67) is observed (Fig. 8 *b* and 9 *b*). The density distribution (Fig. 10 *b*) indicates the highest density within a tongue originating from the Cretan Sea Straits to the central parts of the Ionian and the Levantine Seas. The general trend of the isohalines of the hydrographic parameters and the mixing ratios of the three water masses contributing to the deep water (Fig. 11 *b*, 12 *b*, 13 *b*) is similar at 1 000 and 2 000 m depth, although the mixing ratios are different at the two levels. The core of low salinity and temperature passes nearly along 17-18°E in the Ionian Sea. Near the Cretan Sea straits, the deep Cretan Sea water makes an important contribution, about 20-30%. This ratio is less than that in the same region at 1 000 m depth, which is more affected by the deep Cretan Sea waters flowing over the Cretan Sea sills to the east.

In the cool season (Fig. 8 *a*, 9 *a* and 10 *a*), the distributions of temperature, salinity, density and the mixing ratios of Levantine, Adriatic and deep Cretan Sea waters, give the same features as at 1 000 m. However, from the mixing ratios (Fig. 12 *a* and 13 *a*), the preferred path of Adriatic water can be followed by the isohalines of 90% of Adriatic water type. The deep Cretan Sea water has its highest ratios of 30-40% near the Cretan Sea straits.

Figure 4 *a*
Distribution of potential density at 1 000 m depth in the Eastern Mediterranean during the cool season.



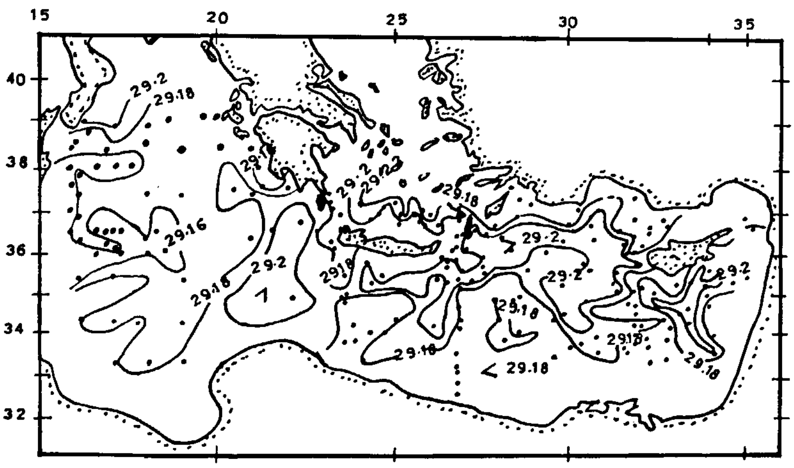


Figure 4 *b*
Distribution of potential density at 1 000 m depth in the Eastern Mediterranean during the warm season.

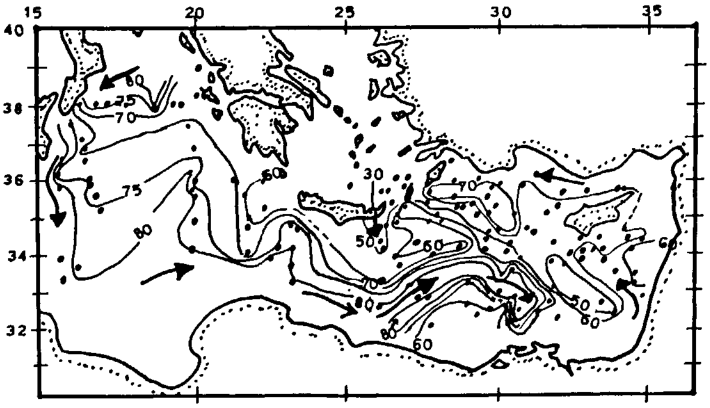


Figure 5*a*

Percentages of Adriatic water in deep Eastern Mediterranean water at 1 000 m depth during the cool season.

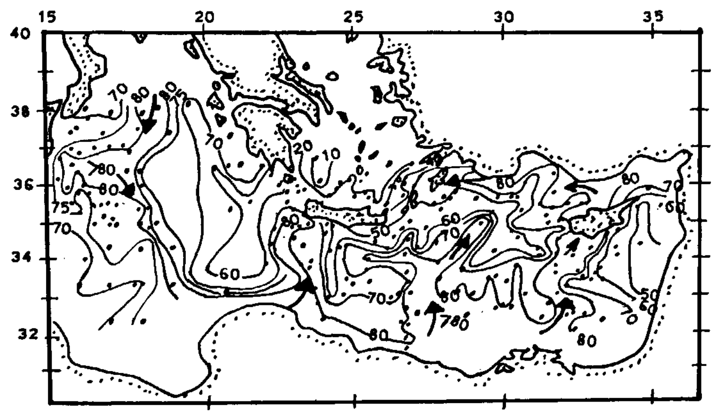


Figure 5*b*

Percentages of Adriatic water in deep Eastern Mediterranean water at 1 000 m depth during the warm season.

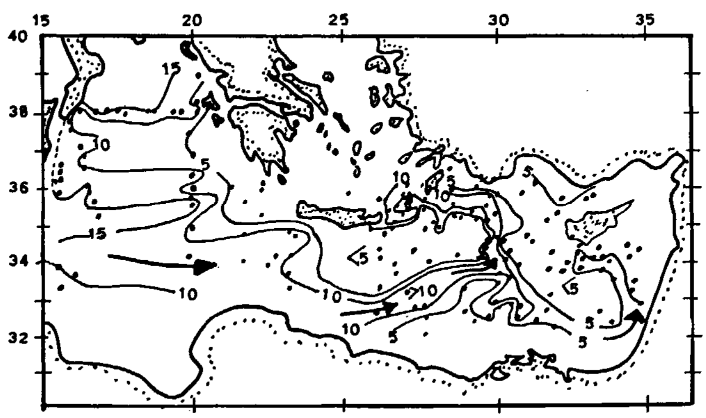


Figure 6*a*

Percentages of Levantine water in deep Eastern Mediterranean water at 1 000 m depth during the cool season.

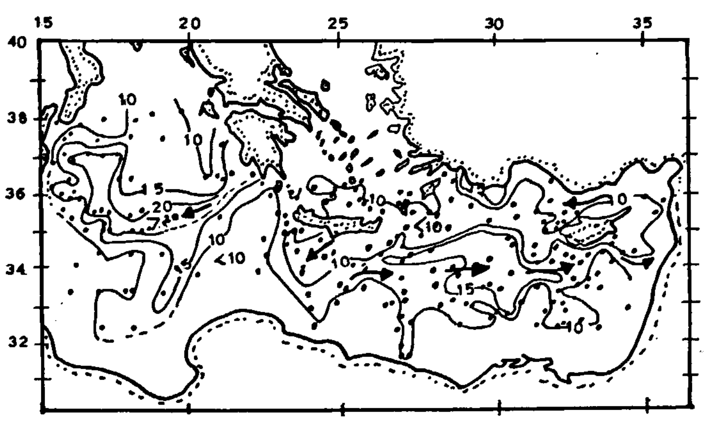


Figure 6*b*

Percentages of Levantine water in deep Eastern Mediterranean water at 1 000 m depth during the warm season.

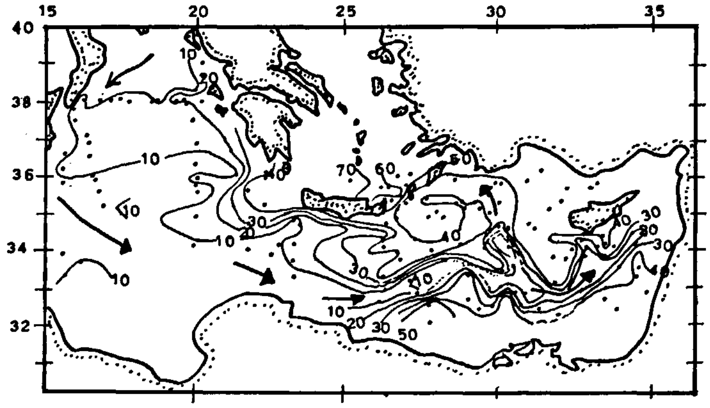


Figure 7 *a*

Percentages of deep Cretan Sea water in deep Eastern Mediterranean water at 1 000 m depth during the cool season.

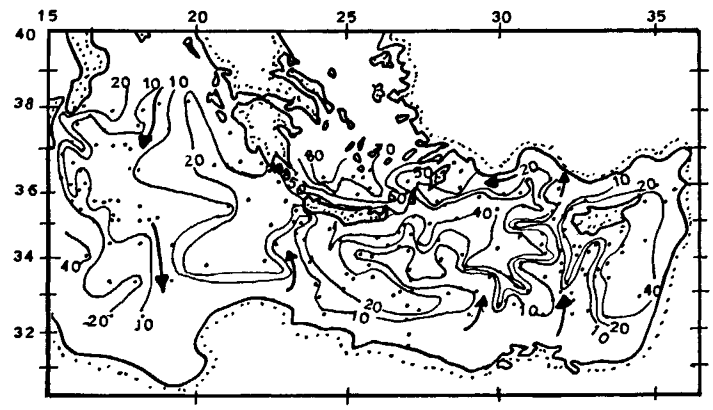


Figure 7 *b*

Percentages of deep Cretan Sea water in deep Eastern Mediterranean water at 1 000 m depth during the warm season.

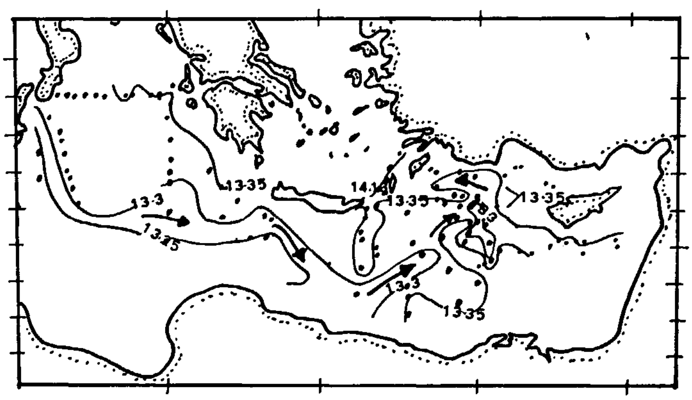


Figure 8 *a*

Distribution of potential temperature at 2 000 m depth in the Eastern Mediterranean during the cool season.

Figure 8 *b*

Distribution of potential temperature at 2 000 m depth in the Eastern Mediterranean during the warm season.

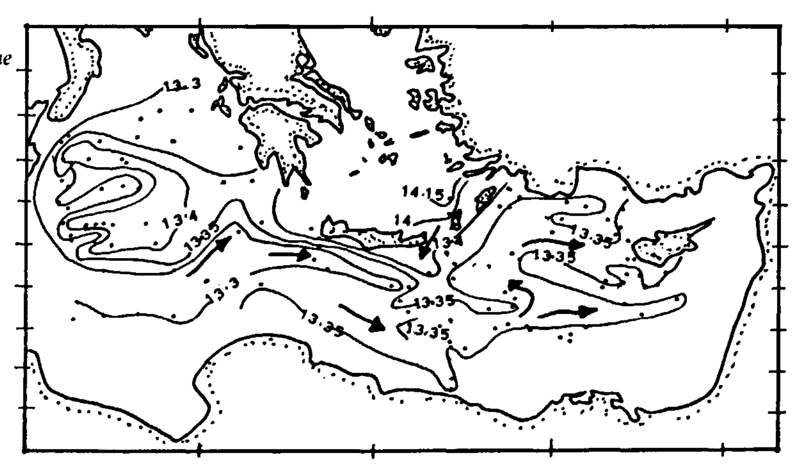
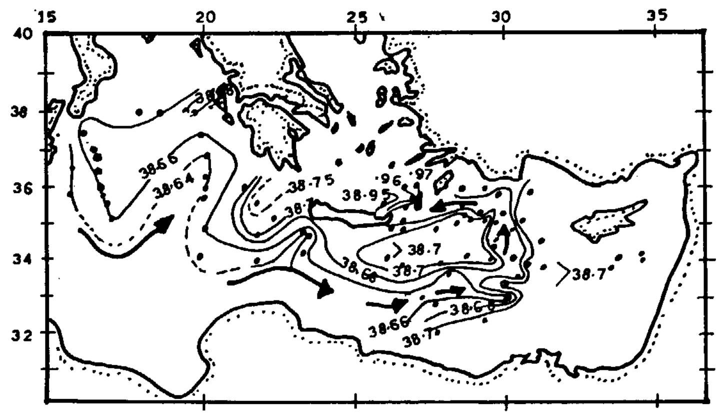


Figure 9 *a*
Distribution of salinity at 2 000 m depth in the Eastern Mediterranean during the cool season.



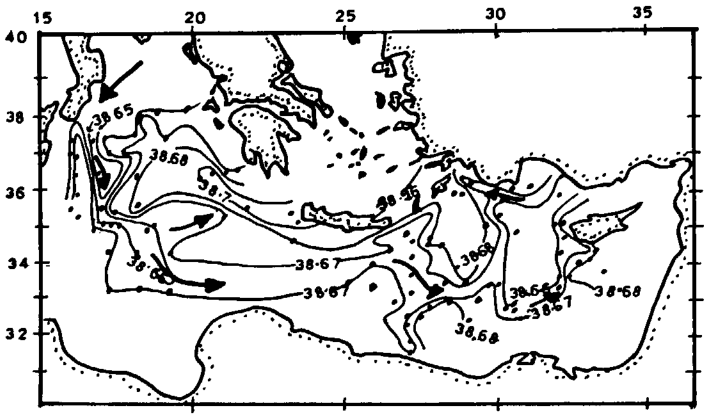


Figure 9 *b*
Distribution of salinity at 2 000 m depth in the Eastern Mediterranean during the warm season.

Figure 10 *a*
Distribution of potential density at 2 000 m depth in the Eastern Mediterranean during the cool season.

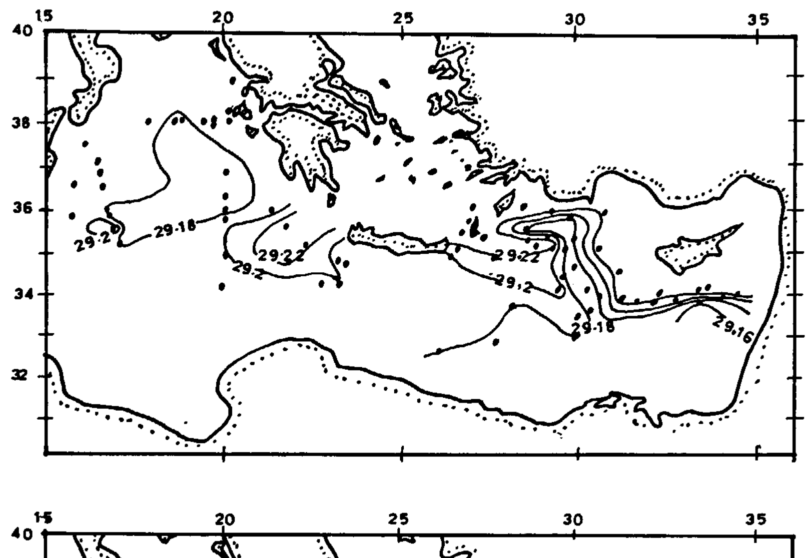
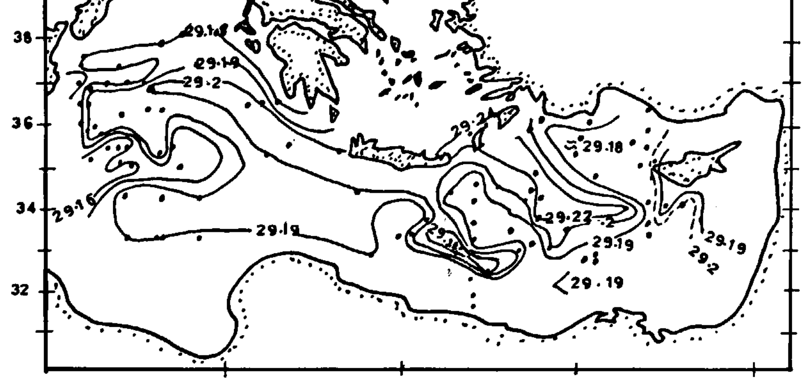


Figure 10 *b*
Distribution of potential density in the Eastern Mediterranean at 2 000 m depth during the warm season.



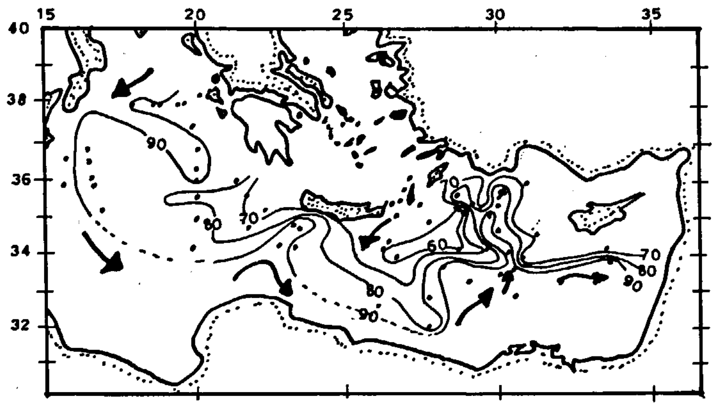


Figure 11 *a*

Percentages of Adriatic water in deep Eastern Mediterranean water at 2000 m depth during the cool season.

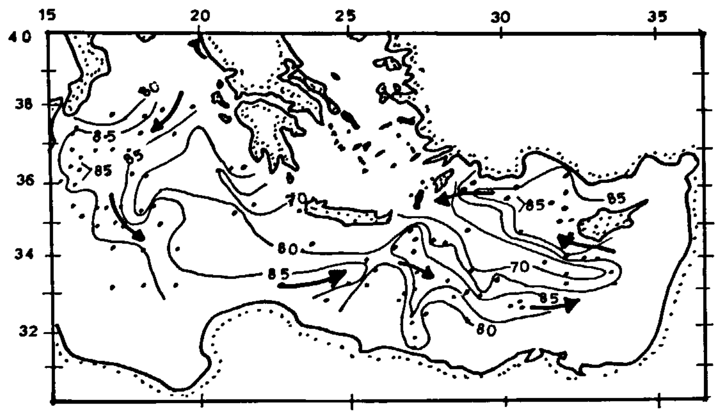
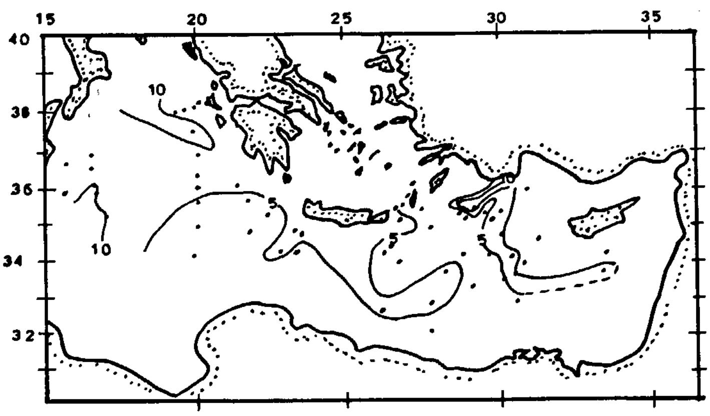


Figure 11 *b*

Percentages of Adriatic water in deep Eastern Mediterranean water at 2000 m depth during the warm season.

Figure 12 *a*

Percentages of Levantine water in deep Eastern Mediterranean water at 2000 m depth during the cool season.



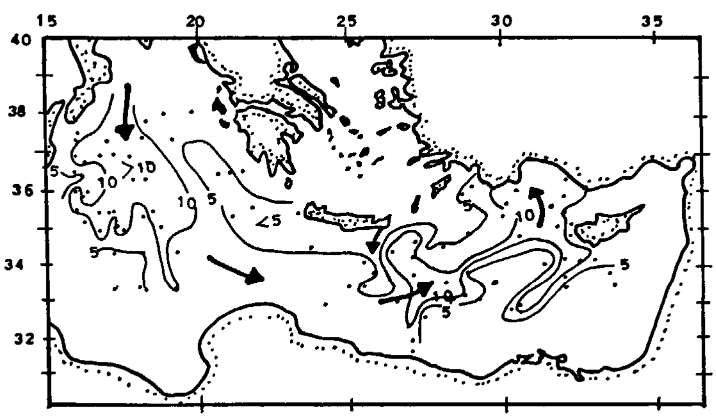


Figure 12 *b*

Percentages of Levantine water in deep water of the Eastern Mediterranean at 2000 m depth during the warm season.

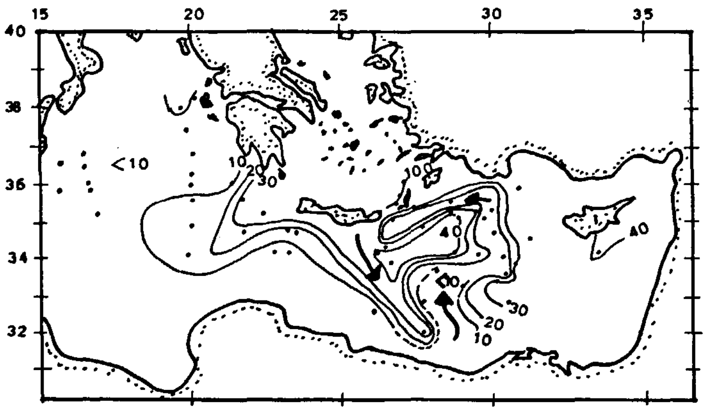
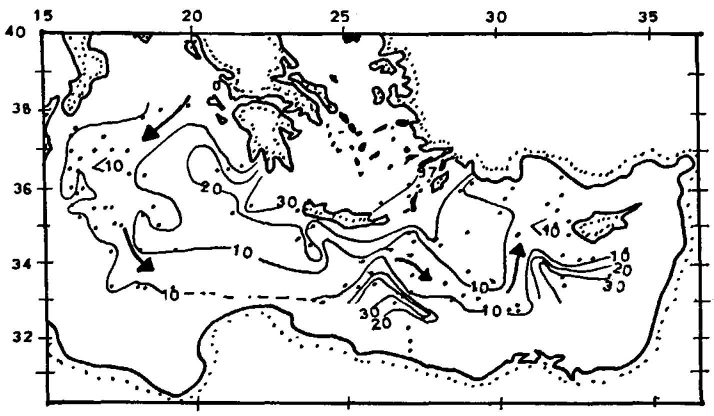


Figure 13 *a*
Percentages of deep Cretan Sea waters in deep Eastern Mediterranean water at 2 000 m depth during the cool season.

Figure 13 *b*
Percentages of deep Cretan Sea water in deep Eastern Mediterranean water at 2 000 m depth during the warm season.



DEEP WATER MASSES IN THE EASTERN MEDITERRANEAN

The distribution of the hydrographic parameters indicates two important water cores in the deep zone. One of them is identified by low salinity and temperature associated with a tongue coming from the north of the Ionian Sea. This tongue has a significantly high ratio of Adriatic water. The characteristics of this water are shown in the Table, from which it can be seen that both salinities and temperatures are decreasing with increasing depth. The Adriatic water type in this core has a mixing ratio greater than 80%, while the deep Cretan Sea water has the least contribution (< 10%). The other core is found near the Cretan Sea straits in the Levantine and Ionian basins. It has high salinity and temperature and these are sometimes different at the western and the eastern straits; this may be due to different rates of water exchange on the two sides of the Cretan Sea. From the Table, the percentage of Adriatic water is seen to increase at greater depths, while the ratios of Levantine and deep Cretan Sea waters are decreasing in the same direction. At 1 500 and 2 000 m, the salinities and temperatures are similar in the cool and warm seasons, while at 1 000 m depth, salinity is higher in the warm season (38.75-38.80) than in the cool season (38.72-38.75). These higher salinities could be due to active exchange of deep Cretan Sea water during later Winter and early Spring.

CIRCULATION OF DEEP WATERS

The horizontal distribution of the different hydrographic parameters (Fig. 2-13) clarify the general circulation pattern in the deep Eastern Mediterranean water. The cool and low saline water comes from the north of the Ionian Sea, toward the south. These waters are deflected to the right hand side to the west of the Ionian Sea. In the Ionian Sea there may be a cyclonic gyre in the central part of the basin, but in the Levantine Sea this cyclonic gyre is well confirmed (Fig. 5 and 11). This conclusion in the Levantine basin agrees with that given by Wüst (1961). Unfortunately the available direct currentmeter data are very few and are of short duration, and consequently not comparable with the current directions deduced from hydrographic evidences. However, the absolute geostrophic current at 1 000 m depth in the Ionian Sea calculated using Stommel and Schott method (1977), considering the data of the Origny Cruise during May (1969; Fig. 14) shows a reasonable agreement with the direction of the salinity tongues and the expected flow from the distribution of the hydrographic parameters during the warm season (Fig. 3 *b*).

SUMMARY AND CONCLUSIONS

The distributions of the potential temperatures, salinity, density and the mixing ratios of Adriatic, Levantine and deep Cretan Sea water types at 1 000 and 2 000 m, during the cool and warm seasons indicate two cores of deep water. One could be identified by low temperature and salinity as well as by a significantly high ratio of Adriatic water type (⩾ 80%), less than 10% of deep Cretan Sea water and 10 to 20% of Levantine water type, while the other exists near the Cretan Sea straits with relatively high ratios of deep Cretan Sea water (about 20-40%), 40-60% of Adriatic water and 5 to 15% of Levantine water type.

However, even in the later water mass, the Adriatic water type is a dominant component. The characteristics of these two water cores at 1 000, 1 500 and 2 000 m depth are defined in Table 1. The cyclonic gyre in the deep water of the Levantine basin is well confirmed, and there may be a cyclonic movement of waters in the central part of the Ionian Sea.

Table
Characteristics of deep water masses in the Eastern Mediterranean.

Season \ Depth (m)	1000					1500					2000				
	T°C	S	* % Ad.	** % D.C.	*** % Lev.	T°C	S	% Ad.	% D.C.	% Lev.	T°C	S	% Ad.	% D.C.	% Lev.
A - Core of Adriatic water flow (Min.S°/₀₀ and Temp.)															
1. Warm Season	13.45	38.68				13.35	38.66				13.30	38.64			10
	1	1			≤10	1					1	1	>85		1
	13.50	38.70				13.45	38.68				13.35	38.66			<15
2. Cool season	13.50	38.62	≥80	≤10	10	13.30	38.65	≥80	≤10	10-20	13.25	38.64		<10	5
	1	1			1	1						1	>90		1
	13.55	38.68			<20	13.35	38.67				13.35	38.66			10
B - Near Cretan Sea straits												38.68			
1. Warm season															
Eastern Straits				40-	≤10	13.40						38.70			
	13.55	38.75	40	50		13.45	38.70	60	20		13.35		60	10	5
	1	1	1				1	1	1	<10	1		1	to	1
Western Straits	13.60	38.80	60	20-30	≤15	13.50	38.75	70	40		13.45	38.70	80	<40	10
						13.55						38.72			
2 - Cool season												38.66			
Eastern Straits					5-10			60-85			13.35	1			
												38.68		10	
	13.55	38.72	50	40		13.40	38.70		20	<10	1		60		5-10
	1	1	1	1		1			1				1		
	13.60	38.75	60	50		13.45	38.75		40		13.40		80	<40	
Western Straits					<5			50-70				38.70			
												38.75			

N.B.
* Ad. = Adratic water type percentage
** D.C. = Deep Cretan Sea water percentage
*** Lev. = Levantine water type percentage

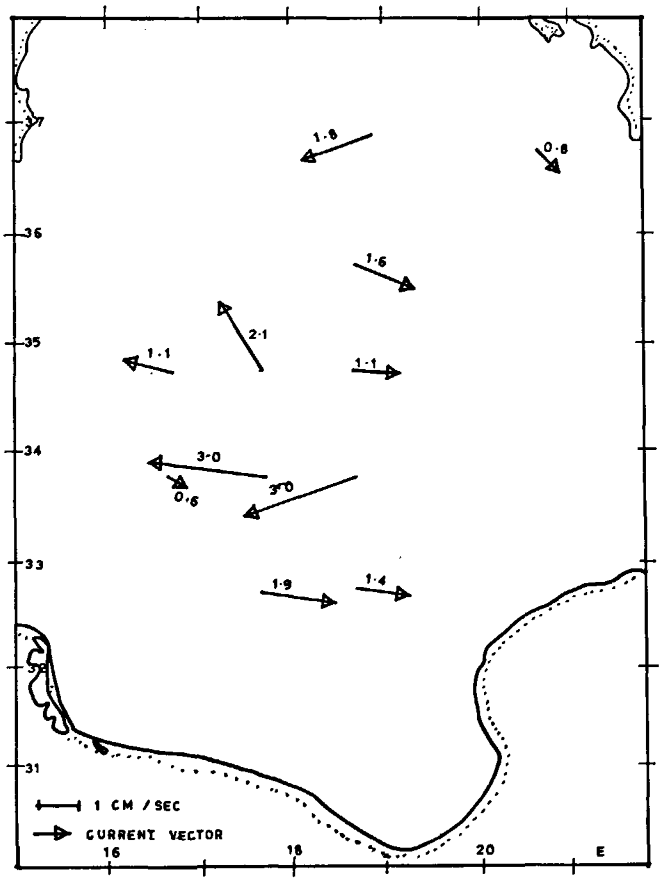


Figure 14
Absolute geostrophic current in the Ionian Sea, in May, at a depth of 1000 m, from the data of Origny (1969), and using Stommel and Schott method, 1977.

Acknowledgement

The authors are indebted to Professor Henri Lacombe at the *Laboratoire d'Océanographie Physique du Muséum d'Histoire Naturelle*, Paris, for his cooperation and constructive suggestions during the analysis of this work.

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