Circulation of the Cretan Sea water masses (Eastern Mediterranean Sea)

Cretan Sea
Autumnal circulation
Black Sea water origin
Flows through the straits
POEM

Mer de Crête
Circulation automnale
Eau de la Mer Noire
Flux dans les détroits
POEM

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ABSTRACT

The autumnal circulation of the Cretan Sea is discussed on the basis of CTD data from the *POEM-3* cruise (autumn 1986). Analysis of the thermohaline and dynamic regimes of the basin revealed the existence of a large scale cyclonic gyre. In addition to the data, a numerical model was used to compute the steady-wind driven circulation pattern, taking into consideration the autumnal fields of water density. The resulting dynamic structure of the Cretan Sea waters differs from that of the other seasons. In the surface layer of the western Cretan Sea down to 100 m predominated a relatively brackish water layer of Black Sea origin. In the SE Cretan Sea, this water mass penetrated as far southeast as the Kasos Strait. During this season, the circulation in the adjacent basins consisted of the permanent cyclonic and anticyclonic gyres and was found to be similar to those of the 1986, 1987 winter and summer periods. The Rhodos and Antikithira straits appeared as the flow entrances of the Cretan Sea, while the main outflow of the Cretan Sea takes place through the Kasos and Elafonisos straits.

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RÉSUMÉ

Circulation des masses d'eau en Mer de Crête (Méditerranée orientale)

La circulation des eaux de la Mer de Crête a été étudiée à partir des données hydrologiques obtenues en automne 1986 au cours de la campagne *POEM-3*. Les régimes thermohalin et dynamique du bassin révèlent la présence d'un grand tourbillon cyclonique. De plus, le schéma de la circulation créée par un vent stationnaire a été déterminé à l'aide d'un modèle numérique en considérant les champs de densité obtenus à l'automne. La structure dynamique qui en résulte diffère de celles des autres saisons. Dans la couche superficielle de la Mer de Crête occidentale, jusqu'à 100 m de profondeur, prédomine une eau relativement saumâtre qui provient de la Mer Noire et pénètre vers le Sud-Est jusqu'au détroit de Kasos. En automne, la circulation dans les bassins adjacents est formée de tourbillons permanents cyclonique et anticyclonique, comme cela a été observé en hiver et en été, en 1986 et 1987. Le flux entrant en Mer de Crête arrive par les détroits de Rhodes et Antikithira, tandis que le principal flux sortant traverse les détroits de Kasos et Elafonisos.

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INTRODUCTION

The Cretan Sea, where water masses from Ionian, Levantine and Black seas interact (Fig. 1), is a critical area for the formation and the transformation of the water masses of the Eastern Mediterranean Sea. In order to investigate the autumnal 1986 general circulation of the Cretan Sea, the hydrodynamic regime of the area, the flows through the Cretan Arc straits and the wind-stress driven components are analysed. Previous studies (Lacombe *et al.*, 1958; Bruce and Charnock, 1965; Burman and Oren, 1970; Miller, 1974; Ozturgut, 1976) of the mesoscale thermohaline structure of the Cretan Sea waters were principally directed towards the identification of the water masses and the dynamic characteristics of the region during winter-summer periods. Of particular importance is the interaction between the surface water originating from the Black Sea (BSW), the North Atlantic water mass (NAW), of the Levantine intermediate water mass (LIW) and of the Cretan deep water mass. Ovchinnikov *et al.* (1976) presented a general cyclonic circulation pattern of the Cretan Sea for the autumn period, which maintains features similar to those of the winter and the summer seasons. In the western part of the sea, a cyclonic gyre was reported to extend towards the area of Kasos Strait transferring less saline water, of Black Sea origin. The BSW, entering through the passage between the Andros and Euboea islands (Lacombe *et al.*, 1958), appeared in the NW Cretan Sea. Lacombe *et al.* (1958) reported that the inflow-outflow system through the western and eastern Cretan Arc Straits forms a cyclonic eddy in the western part and an anticyclonic eddy in the eastern part of the Cretan Sea during summer seasons. Roufogalis (1974) argued that the entry-exit system of the straits contributes to the generation of a cyclonic gyre in this basin. Despite the fact that main features of the general circulation pattern of the Cretan Sea have been determined, the interest of further and more detailed research concerning its hydrodynamic regime has increased since 1986. Within the framework of the POEM (Physical Oceanography of Eastern Mediterranean) cruises, the existence of deep convective mixing processes down to a depth of 700 m within the Cretan Sea open areas was demonstrated (Zodiatis, 1991 *b*) during an intensive cooling of the surface water in late winter 1987. The homogenization of the water column formed a water mass with the characteristics of the LIW. The northeastern shelf zone of Crete island has been identified (Georgopoulos *et al.*, 1989; Zodiatis, 1991 *b*) as a secondary region for the LIW formation. An inversion of the main current of the Cretan Sea occurred during winter 1987, as compared to the summer of 1987 (Zodiatis, 1991 *a*; *b*). In winter the geostrophic circulation was from the east to the northwest and was characterized by a set of small horizontal scale alternating cyclonic-anticyclonic eddies. During summer the circulation was defined by two cyclonic and three anticyclonic flow regions of large horizontal scale. Gertman and Popov (1989) and Gertman *et al.* (1990) identified the western part of the sea as an area of the deep Cretan water formation. During winter 1989, waters of high density from the shelf zones of the Kiklades Plateau sank, affecting the deep waters of the Cretan Sea. In this paper we describe the hydrology, the geostrophic flow of the surface and subsurface layers of the Cretan Sea and the adjacent SE Ionian and NW Levantine basins and finally describe the numerical results of a model of the Cretan Sea wind-driven circulation, on the basis of autumnal wind and density fields.

METHODS

Within the framework of the POEM research program, the *POEM-3* cruise was carried out on board R/V *Aegaio* during autumn 1986. CTD data were collected from 96 stations between November and the first ten days of December 1986 (Fig. 1), using the SBE-9 (Sea Bird Electronics Inc.)

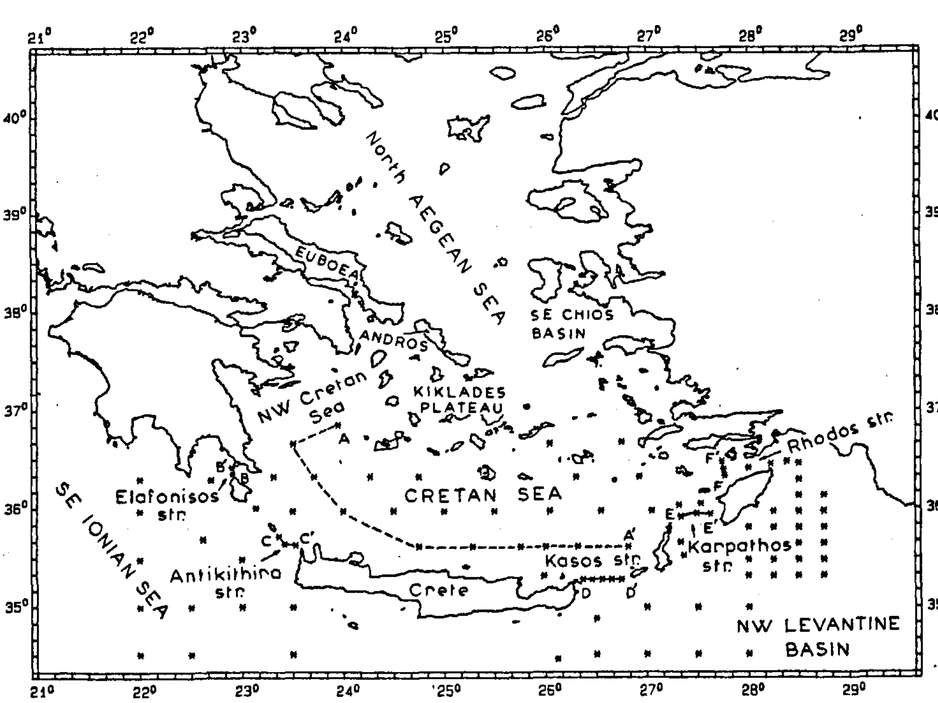

Figure 1

The study area showing the location of the oceanographic stations, autumn 1986. Dashed lines locate the hydrographic sections AA', BB', CC', DD', EE', FF'.

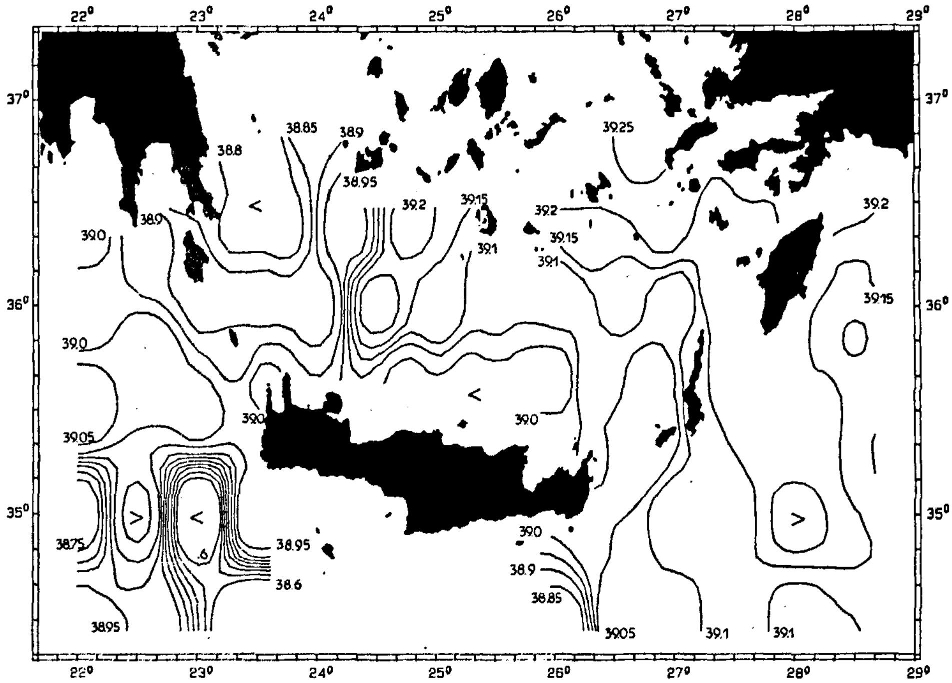

Figure 2 *a*

Horizontal distribution of surface salinity at 2 m in the Cretan Sea and adjacent areas, autumn 1986.

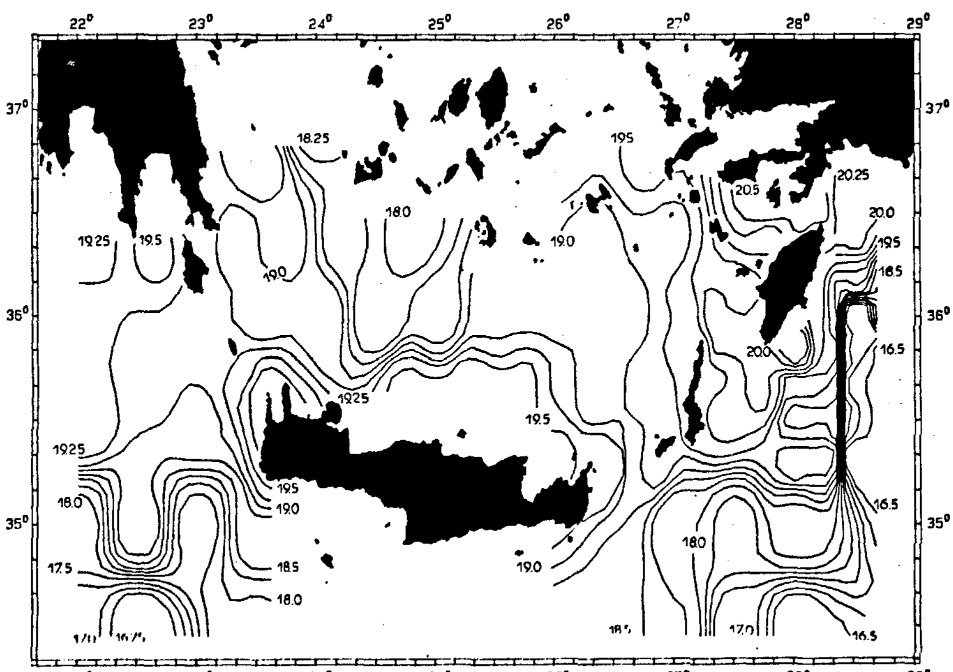

Figure 2 *b*

Horizontal distribution of surface temperature (°C) at 2 m in the Cretan Sea and adjacent areas, autumn 1986.

profiler. The data were processed with programs developed at the National Centre for Marine Research (Athens). The maps of the dynamic height topography were constructed using the depth of 500 m as the reference velocity level, which is reasonable for this area considering: a) the determination of this depth (Ovchinnikov *et al.*, 1976) with the Defant method; and b) the depth distribution of the data. Geostrophic velocities of the Cretan Arc straits were estimated taking into account the values of the specific volume anomaly for the deep and shallow stations for each strait with the Helland-Hansen, Somov method (Bourkov and Moroshkin, 1965). Previous estimates of the Cretan Arc straits flows (Zodiatis, 1992), using this method, showed a good agreement of the geostrophic velocity values with the available current meter measurements.

RESULTS AND DISCUSSION

Hydrology

During autumn 1986, the thermohaline structure of the Cretan Sea was defined by the interacting warm and saline waters from the NW Levantine (T = 19-20.8°C; S = 39.1-39.2), SE Ionian waters (T = 19.5°C; S = 39.1) and the less saline water (38.76) of Black Sea origin (Fig. 2 *a*; *b*). Hydrographic characteristics of the surface layer indicate that the central part of the Cretan Sea was occupied by saline (39.1-39.2) and relatively cool (18-19°C) waters. In the eastern part of the sea, warmer (19.2-20.8°C) and saline (39.26) NW Levantine water appears to have entered the area through the eastern Cretan Arc straits. In the western

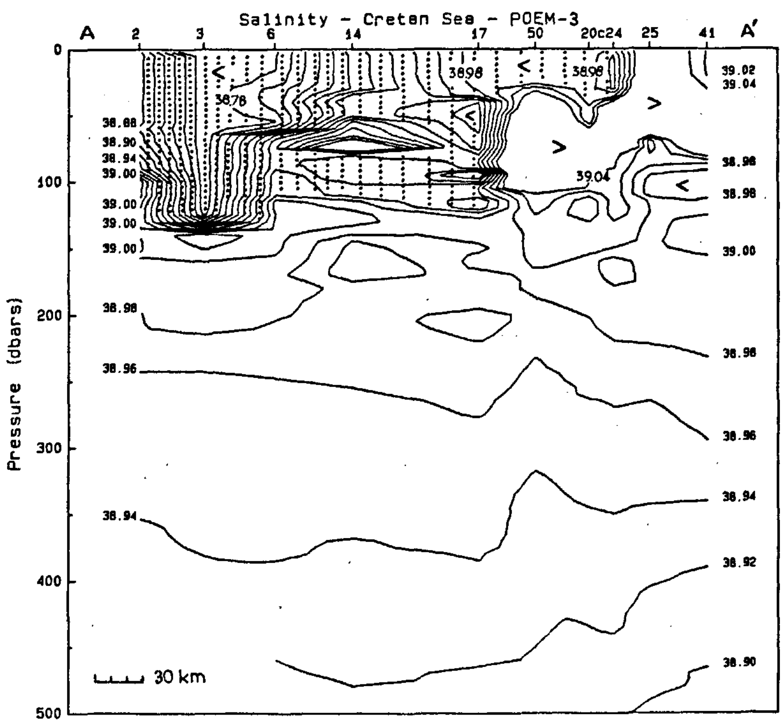

Figure 3

Vertical distribution of salinity along the section AA' in the Cretan Sea, autumn 1986. The stipped area shows water of Black Sea origin.

and southern parts of the sea, BSW (38.76-38.99) overlies the more saline water of the Cretan Sea (Fig. 2 *a*; 3). During this season, the BSW in the NW Cretan Sea was encountered at larger depth than in the other seasons, from the surface down to 120 m. Surface salinity shows that the BSW penetrated as far as the Kasos Strait and the SE Ionian Sea near the western Cretan Arc straits. Therefore, this water mass predominated in the surface layers of the NW and southern Cretan Sea. The homogenization of the surface layer down to 100 m in the area of the Cretan Sea resulted from the mixing processes during the autumnal 1986 cooling of the surface water. In comparison to the summer seasons this surface water was about 6-7°C cooler. Therefore, the vertical thermohaline gradients were smaller. This also explains the disappearance of the subsurface NAW from the Cretan basin. However, small portions of the NAW were observed to flow into the Cretan Sea near the areas of the eastern Cretan Arc Straits (Fig. 3). Moreover, within the upper layer of the Cretan Sea a well developed horizontal thermohaline gradient was due to the BSW intrusion over a large part of the area. The hydrological characteristics of the water masses acted in clockwise fashion on the autumnal potential temperature/salinity relationship (Fig. 4), *i. e.*, the BSW from the NW Cretan Sea became saltier during its southeastward advection. The gradual decrease of the halocline obviously led to the reduction of the water column stability, and indeed convective mixing processes were developed only in areas far from the BSW influence.

Circulation pattern and flows through the Cretan Arc straits

A novel accurate image of the geostrophic circulation of the area under study is presented for autumn 1986. As main features of the circulation pattern in the Cretan Sea we identify: a) the large cyclonic flow region in the central part; b) the northward flow region in the eastern part; c) the anticyclonic eddy in the area of the Karpathos Strait and d) two small scale anticyclonic flow regions in the western part (Fig. 5 *a*). The permanent flow features of the adjacent regions are worthy of note: the large-scale anticyclonic gyre south of the Greek mainland; the cyclonic flow region southwest of Crete island; the Rhodos cyclonic gyre south of the eastern Cretan Arc straits and the Asia Minor current along the periphery of the Rhodos gyre. These cyclonic and anticyclonic gyres contribute to the modification of the Cretan Sea surface and subsurface circulation patterns by their influences through the Cretan Arc Straits. A similar dynamic regime for the NW Levantine Basin (Rhodos gyre) was found (Ozsoy *et al.*, 1989) during October-November 1985. Numerical results of the wind-driven circulation in the Eastern Mediterranean

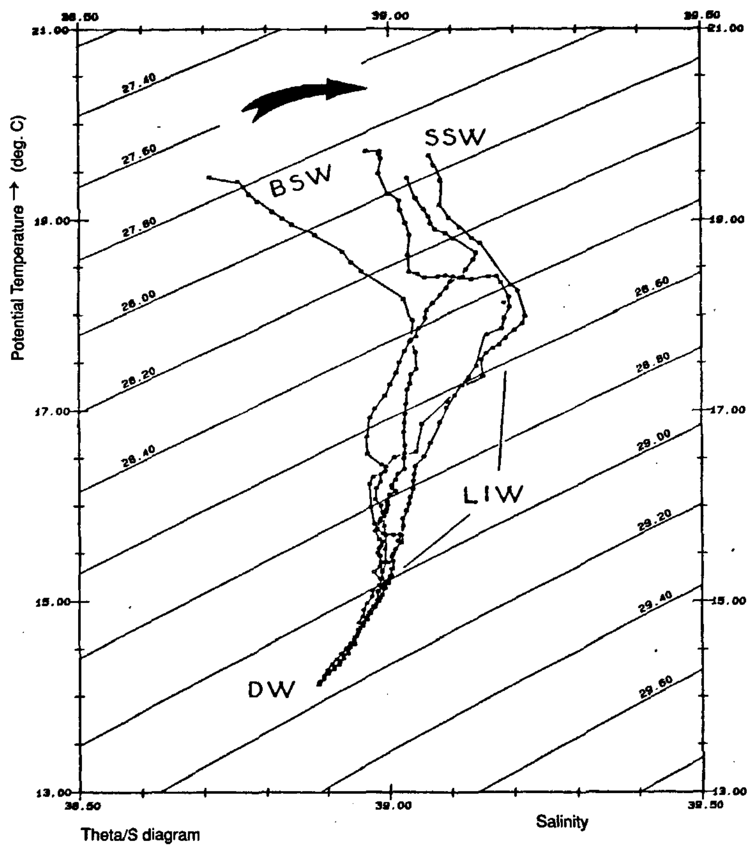

Figure 4

Potential temperature and salinity relationship showing the Black Sea water advection in the Cretan Sea, autumn 1986.

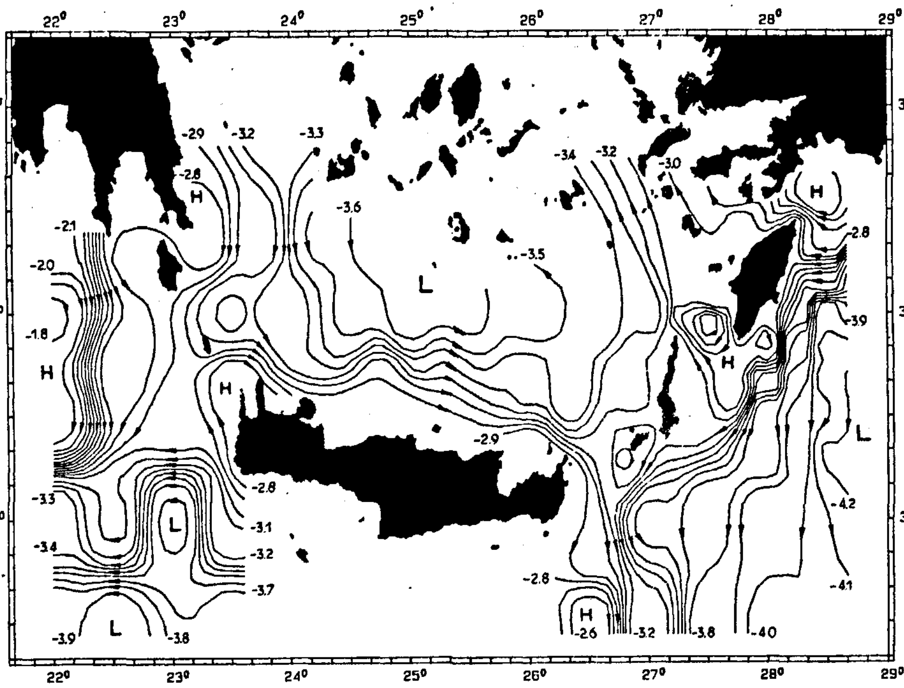

Figure 5 *a*

Surface dynamic height topography at 2 m relative to 500 m (m^2/s^2), autumn 1986.

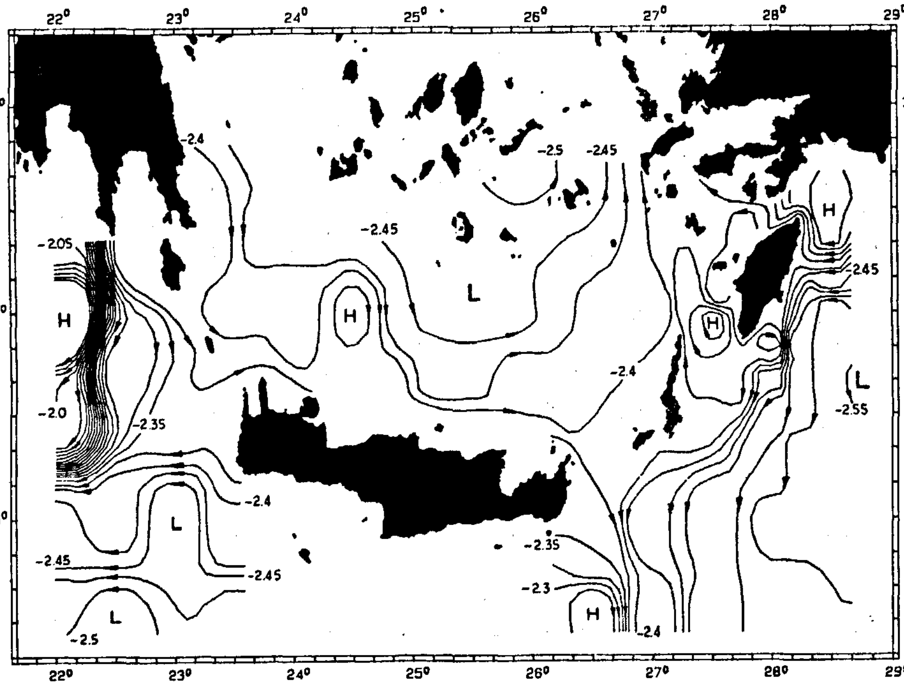

Figure 5 *b*

Dynamic height topography at the surface 200 m relative to 500 m (m^2/s^2), autumn 1986.

Sea (Malanotte-Rizzoli and Bergamasco, 1989) showed a flow pattern for the NW Levantine and SE Ionian basins similar to the autumnal 1986 circulation. The BSW from the NW Cretan Sea was transferred (with geostrophic velocity of about .14 m/s) by the western and southern (.17 m/s) peripheries of the large cyclonic flow region of the Cretan

Levantine basin through the western part of the strait. The other continued to move cyclonically in a northerly direction, towards the SE Chios basin. The weak anticyclonic flow region along the western coast of Crete island transferred warmer and more saline water, of Levantine origin, through the SE part of the Antikithira Strait. Water of the

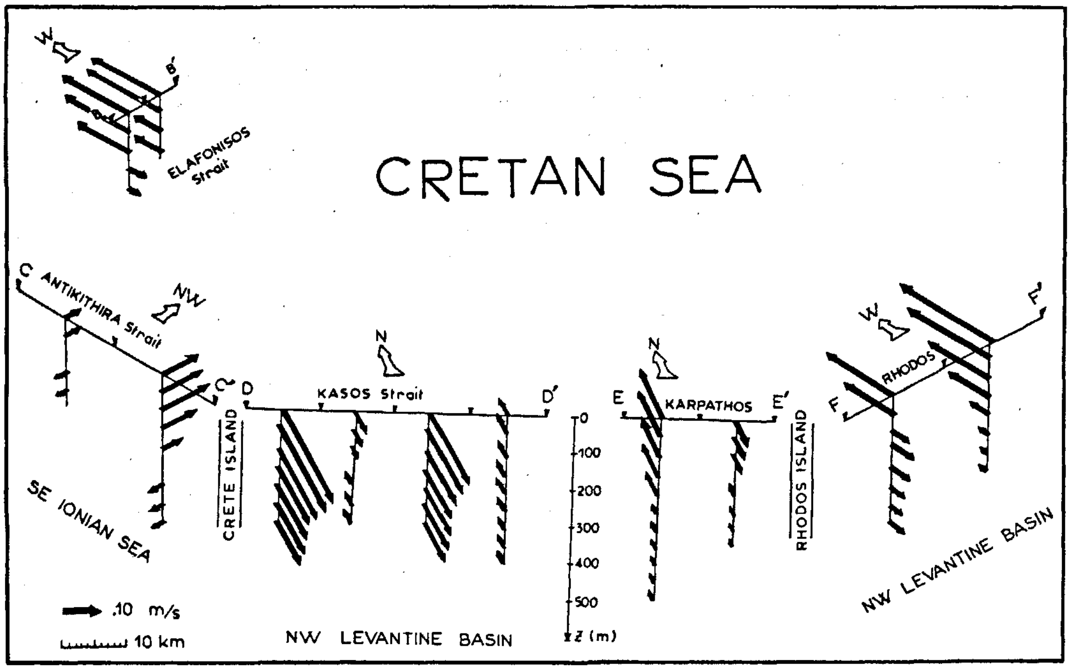

Figure 6

Sketch of the geostrophic velocities along the Cretan Arc straits, autumn 1986.

other seasonal flows. The influence of this gyre on the autumnal circulation of the Cretan Sea was negligible. The main reason which prevented this gyre from playing a crucial role in the formation of Cretan Sea flow was the outflow of the BSW through the western Cretan Arc straits. The subsurface circulation pattern at 50 m repeats the dynamic features of the surface. The currents had the same direction, which became attenuated with depth. However, the geostrophic velocity values remained significant (.15-.20 m/s). The main currents at intermediate depths of 200 and 300 m followed the basic schemes of the upper-layer circulation. The anticyclonic eddy in the central part of the western Cretan Sea (Fig. 5 *b*) would become one of the dominant features of the winter 1987 flow (Zodiatis, 1991 *b*). However, the above changes did not alter the structure of the total dynamic regime, which remained cyclonic. During autumn, it is interesting to note that the smallest of the straits - the Elafonisos Strait - played an important role in the water exchanges between Cretan-Ionian seas as compared to the winter-summer seasons. The intense (.25-.30 m/s) outflow of the BSW from the surface down to 125 m (Fig. 6) was induced by the anticyclonic flow region in the western Cretan Sea. A less significant inflow between 150-200 m was the result of the weakness of the above anticyclonic flow. Through the Antikithira Strait, BSW and Levantine water masses entered simultaneously (Fig. 5, 6). The latter saline water entered (.1 m/s) the Cretan Sea from the surface down to 200 m, while the BSW flowed through the NW part of the strait from the surface down to 50 m. Below 250 m weak outflow existed, influenced by the SW periphery of the Cretan Sea cyclonic activity. Strong outflow (.3 m/s) prevailed from the surface down to 300 m through the Kasos Strait, while insignificant inflow was encountered in the most eastern part. During this period, a flow reversal was observed in comparison with the summer velocity structure (Zodiatis, 1992) at the Karpathos Strait as a result of the anticyclonic eddy activity (Fig. 5, 6) in the strait. A significant inflow (.16 m/s) was found through the western part of the strait, while a weak outflow (.06 m/s) existed in the eastern part. The Levantine water continued to flow (.3 m/s) as usual through the strait of Rhodos. However, the migration of the Rhodos gyre boundaries and the existence of the northward flow north of the Karpathos Strait caused the outflow (.07 m/s) through the southern part of this strait from 50 m down to the bottom.

Integral water circulation of the Cretan Sea

To evaluate the dominant driving force mechanisms of the circulation in the Cretan Sea, the integral transport streamfunction ψ was computed. The theoretical assumption of the model relates the transport streamfunction ψ, which describes the trajectories of the flow around the basin, with the wind stress field taking into account the autumnal 1986 inhomogenity of the Cretan Sea waters. Boundary conditions are:

$\psi = 0$ at solid boundaries

$\partial\psi/\partial n = 0$ at open boundaries

The transport streamfunction equation (Ramming and Kowalik, 1980) is:

$$r\Delta\Psi + \frac{f}{H}J(H,\Psi) + \beta\frac{\partial\Psi}{\partial x} - \frac{r}{H}\left(\frac{\partial H}{\partial x}\frac{\partial\Psi}{\partial x} + \frac{\partial H}{\partial y}\frac{\partial\Psi}{\partial y}\right) = \frac{1}{\rho_o}\mathrm{rot}_z\tau$$

$$-\frac{1}{\rho_o H}\left(\frac{\partial H}{\partial x}\tau_y - \frac{\partial H}{\partial y}\tau_x\right) + \frac{g}{\rho_o H}\frac{\partial H}{\partial y}\int_o^H \frac{\partial\rho}{\partial x}\,z\,dz$$

$$-\frac{g}{\rho_o H}\frac{\partial H}{\partial x}\int_o^H \frac{\partial\rho}{\partial y}\,z\,dz$$

where f is the Coriolis parameter, τ_x, τ_y are the (x, y) components of the wind stress, ρ_o is the mean water den-

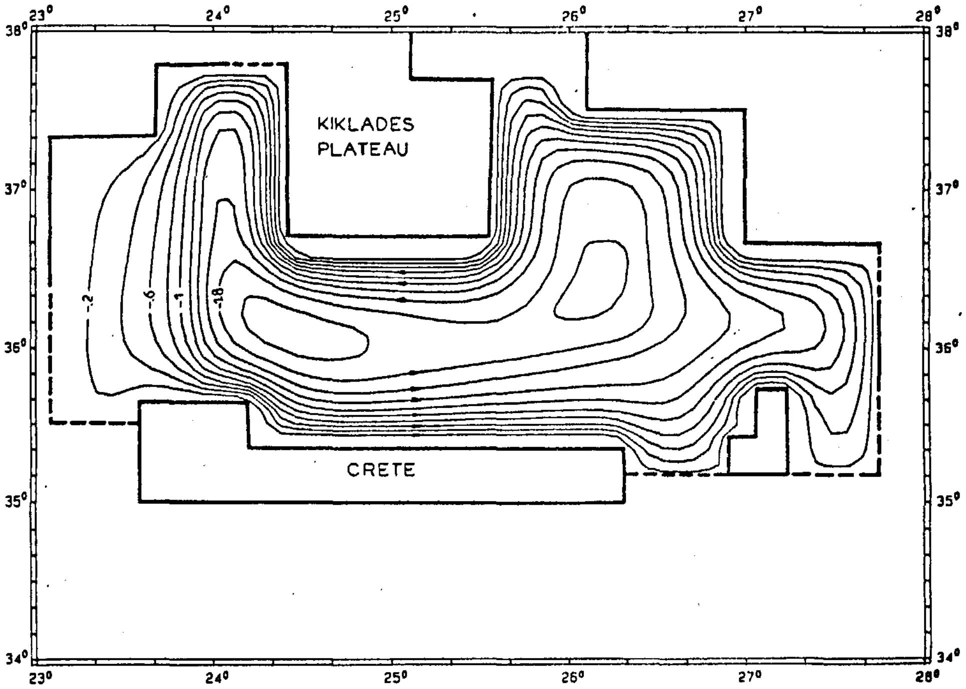

Figure 7 *a*

Streamlines of the vertically integrated horizontal mass transport (in Sv) of the wind driven circulation in the Cretan Sea for homogeneous water and constant depth, autumn 1986. A NW wind is blowing (7-12 m/s).

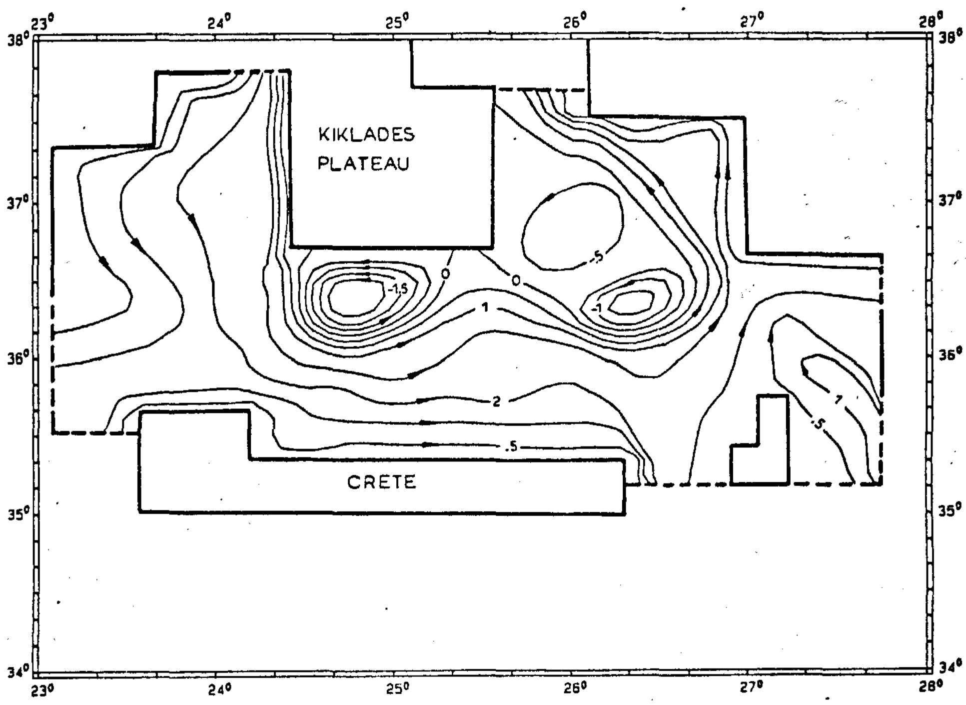

Figure 7 *b*

Streamlines of the vertically integrated horizontal total mass transport (in Sv) in the Cretan Sea for baroclinic water with bottom relief, autumn 1986. A variable, from NE to NW, wind is blowing (7-12 m/s).

sity, ρ (x, y, z) is the variable density of water, r is the horizontal viscosity coefficient, H (x, y) is the bottom depth, β is the latitudinal variation of the Coriolis parameter, g is the acceleration of gravity.

The data base for this numerical experiment comprised: a) the monthly averages values of the atmospheric pressure data (October and November 1986), collected from nine meteorological stations around the Cretan Sea (Hellenic Meteorological Service); and b) the density data set of the water column, obtained from the examined cruise. The wind-stress driven components were computed from the atmospheric pressure field. The differential scheme of the total stream-function equation was constructed with the aid of the method of directed differences. The differential problem was solved by means of Gauss-Seidel method (Ramming and Kowalik, 1980). The results of our numerical experiment showed that the steady wind stress field was the main driving force of the Cretan Sea circulation during the autumn period. Initially the equation was used in its simplest form, namely the Stommel solution (Ramming and Kowalik, 1980) was employed. The values of the stream-function were estimated for homogeneous waters of constant depth with the predominance of weak northern wind in the western part of the sea and NW wind (7-12 m/s) in the other area. Previous studies on the wind-driven circulation of the Aegean Sea (Krestenitis *et al.*, 1987) indicated the same large scale cyclonic activity for the Cretan Sea, including also the two small scale cyclonic eddies south of the Kiklades Plateau (Fig. 7 *a*). The total transport streamfunction was computed for the baroclinic

mode with the application of the equation, taking into consideration a more variable wind stress field. From a comparison of these computations - of the total transport stream-function (Fig. 7 *b*) with the current for the Cretan Sea, as calculated by the dynamic method, indicated that the eddies noted above also appeared quite clearly on the dynamic maps. The derived circulation from the numerical experiment identified a large cyclonic flow region in the central region including two cyclonic eddies, while in the other part of the Cretan Sea anticyclonic flow activities were generated.

CONCLUSIONS

On the basis of thermohaline data, the autumnal Cretan Sea geostrophic circulation pattern, as well as the distribution of the Cretan Sea water masses, are more accurately defined. The dominant surface-subsurface water mass appeared to be the less saline water of Black Sea origin, which covered the NW and southern part of the sea. The general circulation pattern of the Cretan Sea and adjacent basins consisted of cyclonic and anticyclonic eddies and gyres with different horizontal scales. During this season, the flow image of the Cretan Sea was governed mainly by the large cyclonic gyre, which caused the southeastward current in the west and central part and the northward current in the eastern part of the Cretan Sea. The importance of the wind-stress driven components on the circulation of the Cretan Sea was documented through the computation of a numerical model, considering the water density distribution and mean monthly field of wind stress. The computed integral stream-function indicated flow activities similar to those obtained by using the dynamic method. The permanent anticyclonic gyre south of the Greek mainland, the Rhodos gyre and the Asia Minor current appeared to be well developed. However, some variabilities of these features, such as their deformation and the shift of their centres and boundaries influenced to a lesser degree the circulation of the Cretan Sea. The straits of Rhodos, in the eastern, and the Antikithira, in the western part of the basin, were the inflow passages of the Cretan Sea during autumn 1986, whilst the straits of the Kasos, in the eastern, and the Elafonisos, in the western part, were the outflow gates.

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