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Cretan deep water outflow into the Eastern Mediterranean

M.N. Tsimplis [a,*], A.F. Velegrakis [b], P. Drakopoulos [c], A. Theocharis [d], M.B. Collins [b]

[a] *James Rennell Division for Ocean Circulation, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, UK*
[b] *School of Ocean and Earth Science, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, UK*
[c] *Institute of Marine Biology of Crete, P.O. Box 2214, 71003 Iraklio, Crete, Greece*
[d] *Institute of Oceanography, Natonal Centre for Marine Research, Elliniko 166604, Athens, Greece*

Abstract

A simple hydraulic model is used to estimate the deep water fluxes of Cretan Deep Water (CDW), through the Cretan Arc Straits and into the Eastern Mediterranean Basins. The input to the model consists of the height of the deep water reservoir above sill depth and its density difference from the overlying water masses. Data from four hydrographic cruises, which took place in 1995, 1991 and 1987, are used to estimate the depth of the reservoir above the sill and the density difference. The results show a significant CDW outflow of 0.75×10^6 m^3 s^{-1} in early 1995. The outflow of CDW through Kassos Strait, in the east, is 0.53×10^6 m^3 s^{-1}, while 0.22×10^6 m^3 s^{-1} outflows through the Antikithira Strait in the west. The model results agree with fluxes estimated from current meter observations.

The CDW outflow has been neither steady nor uniform during the period 1987–95. In the Kassos Strait, the outflow commenced in 1987 and increased rapidly until 1991; since then, it appears to have stabilised. In the Antikithira Strait, in contrast, the outflow has increased steadily since 1987. Such modifications in the CDW outflow are associated with changes in its hydrographic characteristics. The salinity of CDW increased constantly, by approximately 0.1, between 1987 and 1995 while its temperature warmed, between 1987 and 1991, and then cooled. © 2000 Elsevier Science Ltd. All rights reserved.

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* Corresponding author. Tel.: +44-1703-596-412; fax: +44-1703-596-204.
E-mail address: mnt@soc.soton.ac.uk (M.N. Tsimplis)

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1. Introduction

The Cretan Sea (Southern Aegean) is a confined peripheral sea of the Eastern Mediterranean (Fig. 1) with water depth which exceeds 2500 m at its eastern margin. Its communication with the northern Aegean basins is confined to shallow (<400 m) waters by the Cyclades Plateau (Fig. 1). To the south, the Cretan Sea communicates with the Ionian Basin through the Elafonisos, Kithira and Antikithira Straits and, with the Levantine Basin, through the Kassos, Karpathos and Rhodos Straits. None of these straits has a maximum water depth greater than around 1050 m (Table 1). Outside the Cretan Arc Straits the seabed plunges towards the deep basins of the Eastern Mediterranean.

The Cretan Sea plays a significant role in the hydrology of the Eastern Mediterranean, as it is a site of formation of both intermediate and deep water masses (Georgopoulos, Theocharis & Zodiatis, 1989; Roether et al., 1996). Deep water masses of the Cretan Sea (Cretan Deep Water: CDW) have been observed to overflow some of the sills of the Cretan Arc and sink into the Levantine and Ionian Basins (Miller, 1963; Ovchinnicov & Plakhin, 1965). These waters were considered to contribute in the creation of the deep waters of the Eastern Mediterranean (Lacombe & Tchernia, 1972). Until recently, the contribution of the CDW to the creation of the East Mediterranean Deep Water (EMDW) was thought to be small, in comparison to that of the deep waters originating from the Adriatic Sea (Roether & Schlitzer, 1991). However, new evidence suggests that, since 1987, there has been a considerable increase in the CDW outflow (Theocharis, Georgopoulos, Karagev-

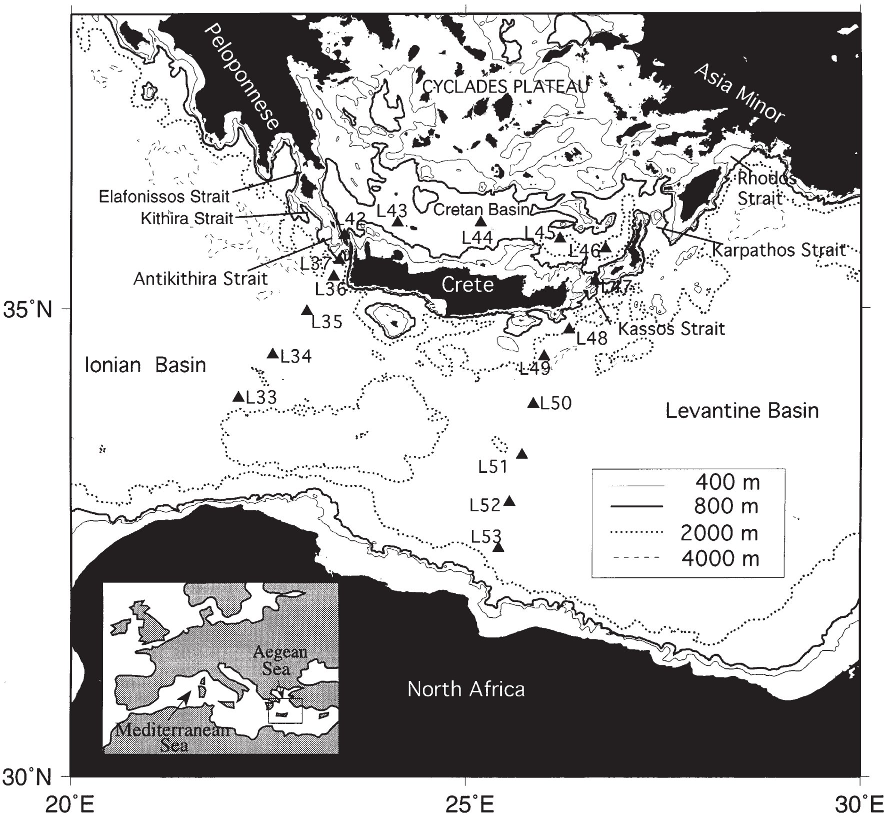

Fig. 1. Bathymetry (in metres) of the Cretan Sea and the adjacent Eastern Mediterranean basins (from IOC et al., 1994). The location of the early 1995 stations, used in the establishment of density anomaly cross-section (Fig. 5), is also shown.

Table 1
Physiographic characteristics of the Cretan Arc Straits

	Surface strait width (km)	Deepest sill depth (m)
Western Straits		
Elafonisos	11	210
Kithira	35	170
Antikithira	34	550
Eastern Straits		
Rhodos	17	350
Karpathos	47	850
Kassos	50	1050

rekis, Iona, Perivoliotis & Charalambidis, 1992; Roether et al., 1996). This increased CDW outflow has been accompanied, during the same period, by an increase in the CDW density by about 0.2 kg m^{-3}. The salinity of the CDW increased by about 0.1 (salinity is expressed on the Practical Salinity Scale 1978, UNESCO–IAPSO, 1985) while its temperature decreased by about 0.4°C (Theocharis, Balopoulos, Kioroglou, Kontoyiannis & Iona, 1999). These changes in the water mass characteristics are associated with changes in the thermohaline circulation of the Cretan Sea. For example, the convective mixing depth decreased and a significant inflow of intermediate water masses from the Eastern Mediterranean (Transitional Mediterranean Water or TMW), characterised by low salinity, temperature and dissolved oxygen content (but high nutrient content), was established in the area (Souvermezoglou, Krasakopoulou & Pavlidou, 1996; Theocharis et al., 1999).

The CDW outflow has been estimated from self-recording current meter records to be $(0.52\pm0.3)\times10^6$ m^3 s^{-1} during the period between April and September 1994 (Tsimplis, Velegrakis, Theocharis & Collins, 1997). Most of the outflow (0.36×0^6 m^3 s^{-1}) occurred through the two deep passages of the Kassos Strait, to the east of Crete (eastern and western Kassos passages), whilst the remaining 0.16×10^6 m^3 s^{-1} occurred through the Antikithira Strait, to the northwest of Crete (Fig. 1). In comparison, Roether et al. (1996) estimated that an average flux of 1×10^6 m^3 s^{-1} of CDW out of the Cretan Sea is required to account for the changes, between 1987 and 1995, in the hydrographic and chemical characteristics of the deep waters of the Eastern Mediterranean. Other estimations for the CDW outflow, based on current meter data range from 0.03×10^6 to 0.46×10^6 m^3 s^{-1} for the Antikithira Strait and from 0.14×10^6 to over 1×10^6 m^3 s^{-1} for the Kassos Strait (Papageorgiou & Theocharis, 1997; Kontoyiannis et al., 1999). These values correspond to observations obtained during different years and seasons. Deep water outflow has not been observed through Karpathos Strait, although the water depth at the sill is more than 850 m (Papageorgiou & Theocharis, 1997; Tsimplis et al., 1997; Kontoyiannis et al., 1999).

Although the CDW outflow may have a significant effect on the hydrology of the Eastern Mediterranean (Klein et al., 1999), its monitoring commenced only recently. Detailed observations will be required over a number of years before the outflow time-scales and variability can be established. The present contribution provides an indirect method for CDW flux estimations. The density distribution observed inside and outside the Cretan Arc Straits is used to estimate the height of the deep water reservoir within the Cretan Sea and its average density difference from the overlying TMW. A simple hydraulic model is then used to estimate the CDW outflow from the pressure differences across the straits. The advantage of the method is that it requires only a small number of hydrographic observations.

2. The model

The CDW flow over the sills can be simulated as a flow out of a reservoir over a dam. To model the CDW outflow a hydraulic model (Mercier & Bryden, 1994) is applied. The flow at each strait is modeled as a three-layer system. A level surface of constant pressure (P_0) separates the deeper layers from the shallower flows. This surface is associated with the isopycnal which appears to be approximately level over the Cretan Basin (Fig. 2). Under this surface, a transitional layer (Layer 1, density ρ_1) lies above the deep water masses (Layer 2, density ρ_2) of the Cretan Basin.

If the flow is assumed steady, frictionless and rotationless, the Bernoulli potential along the interface (P_1) between the transitional Layer 1 and the reservoir of deep dense water (Layer 2) may be expressed, for the upstream point A, to the point C on the western sill (Fig. 2) as:

$$\frac{P_0+\rho_1 gH}{\rho_2}+\frac{u_A^2}{2}+gH_1=\frac{P_0+\rho_1 g(H_1+H-h_1)}{\rho_2}+gh_1+\frac{u_C^2}{2} \tag{1}$$

The velocities $u_{A,}$ $u_{B,}$ and u_C are assumed uniform with depth. In the vertical section below A (in the middle between B and C), the velocity u_A is small enough and can be neglected. Thus, Eq. (1) can be re-arranged to derive the velocity u_C at the sill from the height (H_1) of the reservoir above the sill level and the height (h_1) of the flow over the sill:

$$u_C=\sqrt{2\frac{(\rho_2-\rho_1)}{\rho_2}g(H_1-h_1)} \tag{2}$$

If the reservoir is assumed to be filled with dense water, up to a level that allows a steady-state outflow over the sill, then the maximum outflow q_C (per unit width of the sill) is given by:

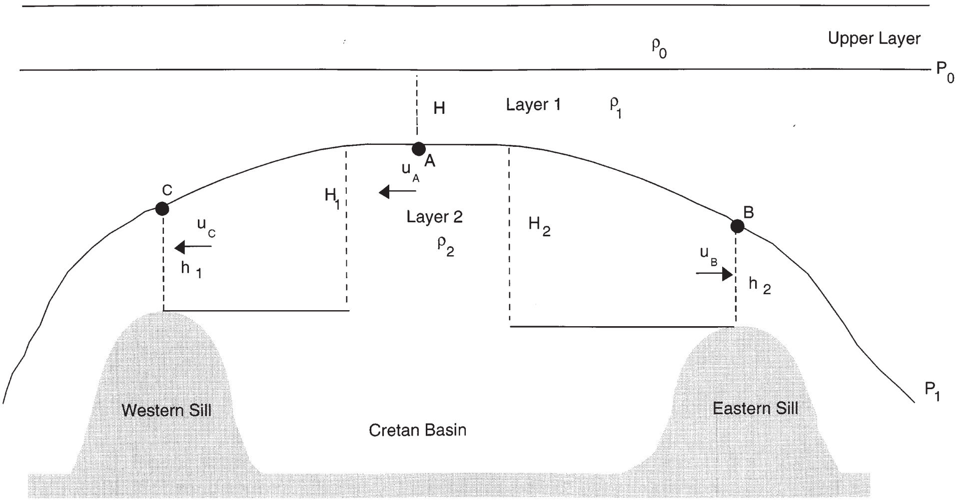

Fig. 2. Schematic representation of the hydraulic model used in the analyses presented here.

$$\frac{\partial q_C}{\partial h_1}=\frac{\partial(u_C h_1)}{\partial h_1}=\sqrt{H_1-h_1}-\frac{h_1}{2\sqrt{H_1-h_1}}=0 \tag{3}$$

This is satisfied when $h_1=2H_1/3$. The corresponding Froude number is then 1 (critical) and the flow is considered to be hydraulically controlled. Therefore, the flux q_C of the dense waters (Layer 2) is:

$$q_C=u_C h_1=\frac{2}{3}H_1\sqrt{\frac{2}{3}g\frac{(\rho_2-\rho_1)}{\rho_2}H_1} \tag{4}$$

Similar equations hold for the Eastern Straits (Point B). Eq. (4) implies that, if the exchange is maximum, the water outflow, per unit width of the sill, is a function of: (i) the density difference between the deep water reservoir (Layer 2) and the overlying transitional waters (Layer 1); and (ii) the height of the deep water reservoir above the sill level H_1. Finally, in order to derive the total water flux Q from the water outflow per unit width (q), q must be multiplied by the width of the sill. However, as the physiography of the deep ‘channel-like’ passages of the Cretan Straits can be approximated better by ‘up-side down’ triangles, than by rectangles, the multiplication of q by the sill width (L) would clearly overestimate the fluxes by a factor of 2. Thus, the total flux may be given by:

$$Q=q\times\frac{L}{2} \tag{5}$$

where L is the sill width, at the depth of the reference surface P_1.

3. Estimation of fluxes

Hydrographic stations occupied during the early 1995, PELAGOS and LIWEX cruises (Table 2), are used to estimate the deep water outflow over the sills of the Antikithira and Kassos Straits, where such an outflow was previously observed (Tsimplis et al., 1997; Kontoyiannis et al., 1999). These results are compared to those obtained during previous hydrographic cruises (1991 and 1987), in order to gain an insight into the evolution of the deep water outflow during the period 1987–

Table 2
Summary of the hydrographic cruises referred to in the text

Vessel	Period of observations	Project	Station prefix
R/V *Aegaio*	January–February 1995	PELAGOS	P
F/S *Meteor*	January 1995	LIWEX	L
R/V *Aegaio*	October–November 1991	POEM	O
F/S *Meteor*	August–September 1987	POEM	M

95, i.e. when the water circulation in the area appears to have changed (Roether et al., 1996). The locations of all the hydrographic stations in the vicinity of the sills are shown in Figs. 3 and 4. The physiographic characteristics (width and depth) of the sills are based upon the GEBCO digital topography (IOC, IHO & BODC, 1994). The depth of the density anomalies σ_0 and σ_1 that correspond to the reference pressures P_0 and P_1 are extracted from the hydrographic observations together with the maximum density anomaly σ_2 outside the strait. The densities ρ_1=1+0.5(σ_0+σ_1) and ρ_2=1+0.5(σ_1+σ_2) are used to calculate the average density difference between the two layers.

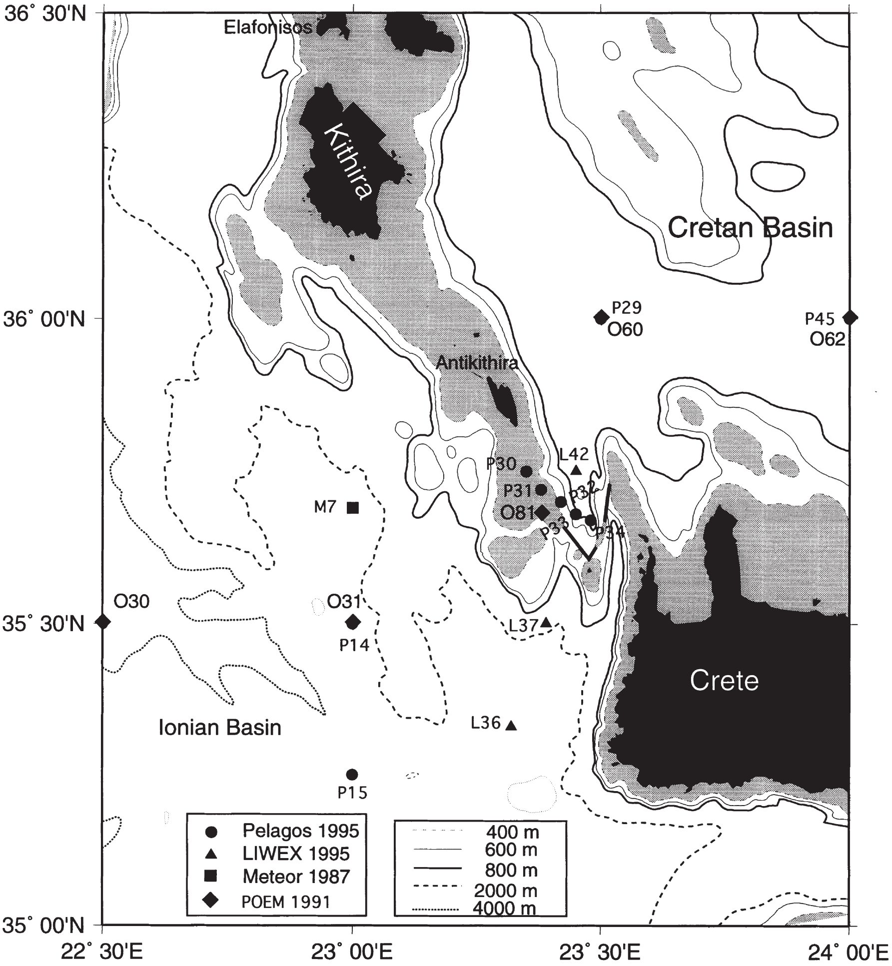

Fig. 3. Bathymetry and location of stations within the Antikithira Strait. Areas shallower than 400 m are shown shaded.

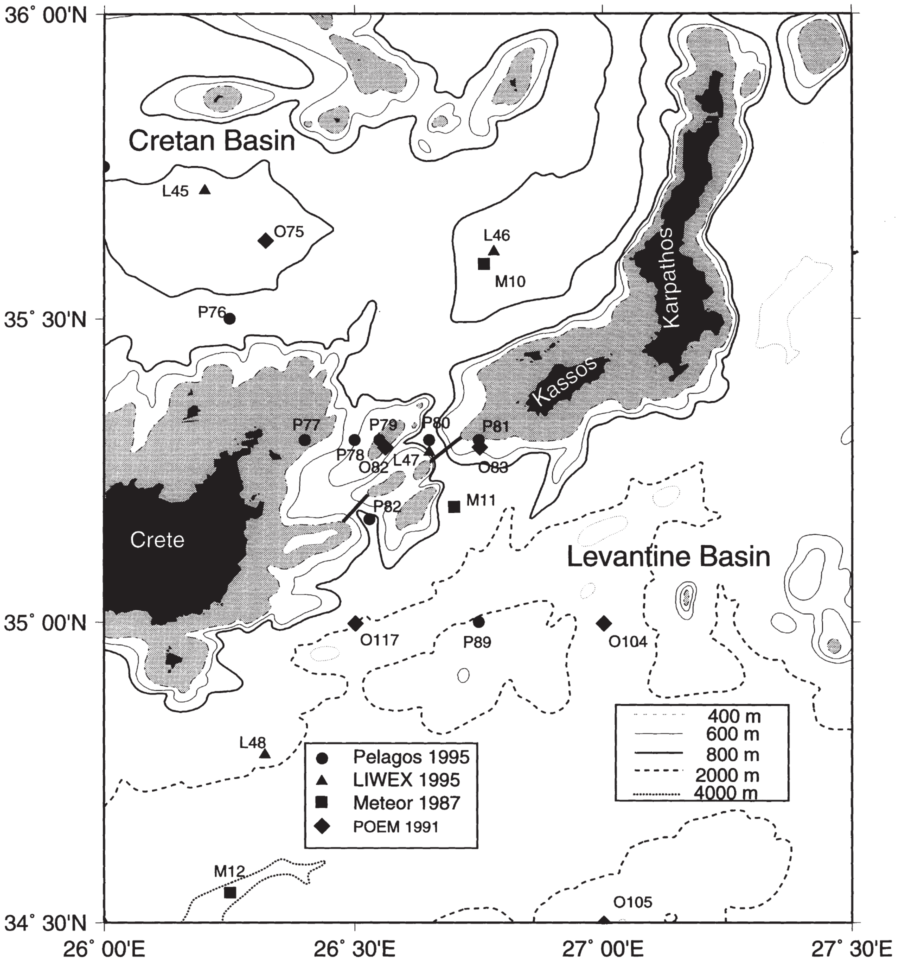

Fig. 4. Bathymetry and location of stations within the Kassos Strait. Areas shallower than 400 m are shown shaded.

3.1. Fluxes during early (January/February) 1995

A density anomaly cross-section, based upon the data collected during the LIWEX 1995 cruise, is plotted as Fig. 5. The isopycnal σ_0=33.51 kg m^{-3} ($\sigma_\theta\approx$29.17), referenced at 1000 m, which is almost horizontal along the Cretan Sea it has been selected as the upper boundary of Layer 1 (surface P_0, in Fig. 2). The isopycnal σ_1=33.53 kg m^{-3} ($\sigma_\theta\approx$29.18), the shallowest isopycnal which appears to cascade over the sills, has been selected as the upper boundary of Layer 2 (surface P_1). The height of the selected isopycnals σ_0 and σ_1, above the sill level, has been estimated on the basis of the hydrographic data collected from hydrographic stations located closest to the sill.

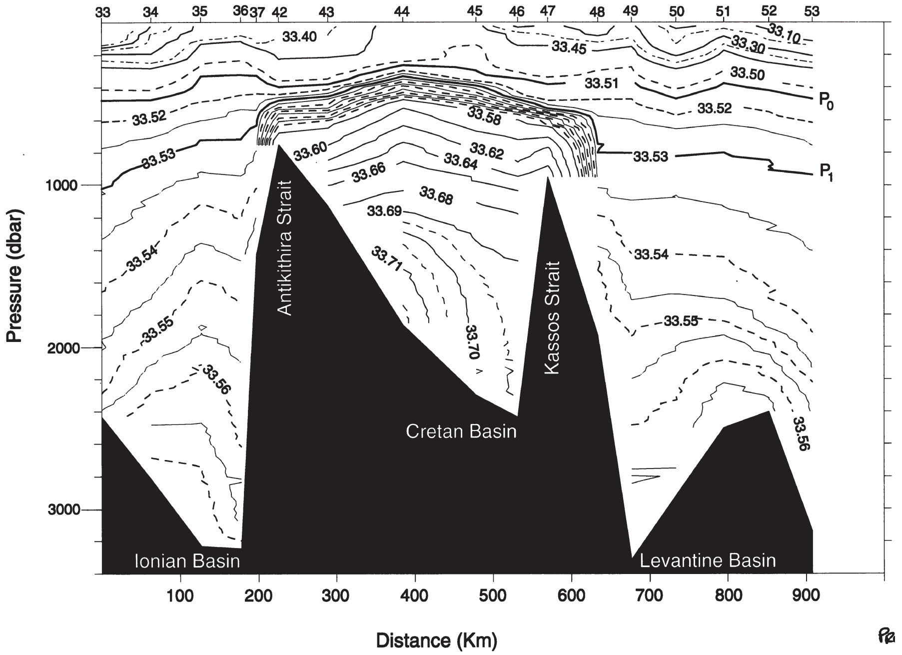

Fig. 5. Density anomaly distribution (referenced to 1000 m) in the Cretan Sea, in early 1995. Station reference numbers relating to the LIWEX 1995 (F/S Meteor) Cruise are also shown. For location of the cross-section, see Fig. 1.

In the Antikithira Strait, Stations L42, P33 and P34 (Fig. 3) were located inside the sill; Station L37 was outside (Fig. 3). The depths of the isopycnals σ_0 and σ_1 together with the water depths and densities close to the seabed for these stations, are listed in Table 3. The maximum (bottom) densities at Stations P33 and P34 (Cretan Basin) were higher than those at Station L37. If the deep Cretan waters had cascaded over the Antikithira sill for a considerable time before the observation period, then it is reasonable to assume that the bottom waters at downstream Station L37 (located close to the sill) were of Cretan Sea origin. Therefore, the bottom density anomaly at Station L37 may be used as the deepest isopycnal (σ_2) cascading over the sill. The average density of the layer included between σ_1 and σ_2 is then calculated. The depth of the reference isopycnal σ_1 has been taken as the average of the depths of σ_1 at Stations P33 and P34.

In the Kassos Strait, there are two deep passages (Fig. 4). Stations P78 and P82 were located within the southwestern passage, whereas Station P80 was located within the deeper northeastern passage. In order to verify that the Station P82 occupied the downstream flank of the sill (as the available bathymetric information is not of sufficient resolution), the density anomaly distributions at the bottom layers of Stations P78 and P82 were examined. The maximum (bottom) density anomaly observed at Station P78 was higher than the bottom density anomaly at Station P82, indicating that Station P78 was located inside the sill. Moreover, at Station P82, the

Table 3
Depths of the isopycnals σ_0 (33.51 kg m^{-3}) and σ_1 (33.53 kg m^{-3}), water density close to the bed and water depths at the selected stations in the Antikithira and Kassos Straits, in early 1995 (see Figs. 3 and 4)

Station	Depth of σ_0 (m)	Depth of σ_1 (m)	Bottom density (kg m^{-3})	Bottom depth (m)
Antikithira Strait				
L42	393	480	1033.598	767
P33	228	281	1033.617	753
P34	225	360	1033.645	880
P37	322	633	1033.548	1434
Kassos Strait (eastern passage)				
P80	337	420	1033.675	1084
P89	272	560	1033.542	961
Kassos Strait (western passage)				
P78	367	505	1033.595	694
P82	435	615	1033.568	842

reference isopycnal σ_1 had descended over 100 m from its depth inside the sill (Station P78); this indicated that Station P82 was located on the downstream flank of the sill (see Fig. 2). If the same assumptions (as for the Antikithira Strait) are used here, then the bottom density anomaly at Station P82 may be considered as the density anomaly of the densest isopycnal (σ_2) that flowed over the sill. At the northeastern Kassos passage, Station P80 had a bottom density anomaly higher than that of Station P82 or Station P89. As Station P89 was located at a considerable distance from the sill, the maximum (bottom) density anomaly at Station P82 is, once again, taken as that of the densest isopycnal (σ_2) which originated from inside the sill.

The average densities of Layers 1 and 2 (Fig. 2) can be estimated from the density anomaly distributions between the isopycnals σ_0 and σ_1, and σ_1 and σ_2. If a constant elevation of the relevant isopycnals (σ_0, σ_1 and σ_2) is assumed along the sill, then the maximum outflow through the straits can be estimated (using Eqs. (4) and (5)). The results of this estimation are listed in Table 4. The estimated fluxes are 0.22×10^6

Table 4
Estimated maximum outflow during early (January/February) 1995. Note: the σ_1 depth at Antikithira Strait is the average of Stations P33 and P34

Strait	ρ_1 (kg m^{-3})	ρ_2 (kg m^{-3})	$(\rho_2-\rho_1)/\rho_2$ ($\times10^{-5}$)	Depth of σ_1 (m)	Sill width L at depth of σ_1 (km)	Deepest sill depth (m)	Outflow ($\times10^6$ m^3 s^{-1})
Antikithira	1033.52	1033.539	1.863	320	17.5	550	0.22
East Kassos	1033.52	1033.549	2.810	420	6.5	1050	0.46
West Kassos	1033.52	1033.549	2.810	505	5.5	700	0.07

$m^3\ s^{-1}$ for the Antikithira Strait and 0.07 and $0.46\times10^6\ m^3\ s^{-1}$ for the western and eastern Kassos passages, respectively. These estimations relate to the total outflows, below the reference isopycnal σ_1 ($\sigma_\theta\approx29.18$).

Over the same period, CDW flux estimations (based upon near-bed current meter measurements at 50 m above the bed and assuming that this water mass with a density anomaly $\sigma_\theta>29.2$ is found below (average) depths of 420 m in the Antikithira Strait and 550 m in the Kassos Strait) yielded values of $0.26\times10^6\ m^3\ s^{-1}$ for the Antikithira and $0.24\times10^6\ m^3\ s^{-1}$ for the Kassos Strait (Kontoyiannis et al., 1999). Consequently, the fluxes derived from the hydraulic model (Table 4) are consistent with these results for the Antikithira Strait. For the Kassos Strait, however, the model fluxes appear to be higher than those estimated on the basis of the current meter data. This difference may result from: (i) the different cross-sections used in the model and current meter estimations; (ii) the fact that the model estimates the water outflow under the reference isopycnal $\sigma_1=33.53$ ($\sigma_\theta\approx29.18$) and not that associated with waters having a density anomaly (σ_θ) higher than 29.2; and (iii) that the model predictions are associated with maximum flows.

3.2. Fluxes during October–November 1991 and August–September 1987

The spatial distribution of the water density anomaly structure across the Cretan Sea and the adjacent Mediterranean basins, during late (October–November) 1991, shows that the isopycnals $\sigma=33.51$ ($\sigma_\theta\approx29.16$) and $\sigma=33.53\ kg\ m^{-3}$ ($\sigma_\theta\approx29.18$) can be taken, once again, as the reference isopycnals σ_0 and σ_1. The positions of the stations used in the analysis are shown in Figs. 3 and 4; their relevant hydrographic characteristics are listed in Table 5. The results of the model for this period (Table 6) indicate that a significant outflow ($0.56\times10^6\ m^3\ s^{-1}$) of deep water masses was already present, in 1991. Most of this outflow was associated with the eastern Kassos deep passage ($0.38\times10^6\ m^3\ s^{-1}$).

The spacing of the hydrographic data, obtained during the 1987 F/S Meteor cruise, is sparse; hence, the structure revealed for the hydrographic fields near the straits is, somewhat, incomplete. Nevertheless, an attempt has been made to estimate the outflow. The hydrographic data show that the deep Cretan waters were less dense in 1987 than those found in later years. They also show that the reference isopycnal $\sigma_1=33.53\ kg\ m^{-3}$ (used in the model for the 1991 and 1995 observations) did not extend out of the Cretan Arc Straits. Consequently, in this case, the isopycnal $\sigma=33.51\ kg\ m^{-3}$ (the lightest isopycnal appearing to cascade over the Cretan Arc sills) has been selected as the reference isopycnal (σ_1). This density anomaly was found at depths of 945, 566, 810, 944 and 736 m at Stations M7, M8, M10, M11 and M12, respectively (Table 7). If the average depth of this isopycnal was around 800 m inside the sills of the Cretan Straits (Case A), outflow of waters of higher density anomaly could not take place through the Antikithira Strait and the western Kassos passage as the water depth over these sills is much shallower (see Table 4). Alternatively, if the average depth of the reference isopycnal (σ_1) is assumed to have been 566 m, then deep water outflow was possible through both the eastern and western Kassos passages (Case B).

Table 5
Depth of the isopycnals σ_0 (33.51 kg m^{-3}) and σ_1 (33.53 kg m^{-3}), water density close to the bed and water depths at selected stations in the Cretan Sea and the adjacent Mediterranean basins, in late 1991

Station	Depth of σ_0 (m)	Depth of σ_1 (m)	Bottom density (kg m^{-3})	Bottom depth (m)
Ionian Sea				
O30	480	690	1033.550	1825
O31	420	560	1033.552	1925
Antikithira Strait (not on the sill)				
O81	333	498	1033.533	525
Western Cretan Basin				
O60	320	408	1033.591	1225
062	575	642	1033.587	1175
Central Cretan Basin				
O59	360	448	1033.610	1475
Eastern Cretan Basin				
O58	336	486	1033.592	1000
O75	320	411	1033.604	1925
Eastern Kassos passage (not on the sill)				
083	460	Deeper than sill depth	1033.512	475
Levantine Basin				
O104	508	720	1033.548	1175
O117	378	580	1033.556	1575

Table 6
Estimated maximum outflow during October/November 1991

Strait	ρ_1 (kg m^{-3})	ρ_2 (kg m^{-3})	$(\rho_2-\rho_1)/\rho_2$ ($\times10^{-5}$)	Depth of σ_1 (m)	Sill width L at depth of σ_1 (km)	Deepest sill depth (m)	Outflow ($\times10^6$ m^3 s^{-1})
Antikithira	1033.52	1033.541	2.037	408	12	550	0.08
East Kassos	1033.52	1033.539	1.829	411	6.5	1050	0.38
West Kassos	1033.52	1033.539	1.829	411	6	700	0.10

The bottom density anomaly at Station M8 (Table 7, western Cretan Sea) was 33.540 kg m^{-3}, at 1825 m. At Station M10 (eastern Cretan Sea), the maximum density anomaly was 33.532 kg m^{-3} at a depth of 2250 m. However, higher density anomalies (33.578 kg m^{-3}) were found near the bottom of the water column at a depth of 575 m in another part of the Cretan Sea (Station M9). If this latter density anomaly value was neither the result of pre-conditioning nor erroneous, it may indicate that although the formation of the dense water had commenced already in 1987, this water had not yet filled the deepest basins of the Cretan Sea.

The bottom water had a density anomaly of 33.532 kg m^{-3} at 2218 m outside the Antikithira Strait (Station M7) in the Ionian Basin (Fig. 3). In comparison, the

Table 7
Depths of the isopycnals σ=33.51 and 33.53 kg m^{-3}, water density close to the bed and water depths at selected stations in the Cretan Sea and the adjacent Mediterranean basins, in late 1991

Station	Depth of σ=33.51 kg m^{-3} (m)	Depth of σ=33.53 kg m^{-3} (m)	Bottom density (kg m^{-3})	Bottom depth (m)
Ionian Sea				
M7	945	1812	1033.532	2218
Cretan Basin				
M8	566	740	1033.540	1825
M9	280	340	1033.578	575
M10	810	1615	1033.532	2250
Levantine Basin				
M11	944	N/A	1033.522	1170
M12	736	2125	1033.532	3825

bottom water density anomaly was lower (33.522 kg m^{-3}), at the relatively shallow Station M11 (depth of 1170 m) outside the Kassos Strait; it was higher (33.533 kg m^{-3}) farther out in the Levantine Sea (Station M12). As Station M12 was located far from the sill (Fig. 4), the bottom density anomaly at Station M11 (σ=33.522 kg m^{-3}) is used as the density anomaly along the densest isopycnal (σ_2) flowing into the Levantine Basin. However, in relation to the low sampling resolution during the 1987 cruise, it is not clear whether Station M11 is representative of the outflow; it may, for some reason, lie outside the core of the outflowing dense water. Both estimations (Cases A and B) of the water fluxes are given in Table 8 and Fig. 6. The outflow estimates vary from 0.08×10^6 (Case A) to 0.42×10^6 m^3 s^{-1} (Case B).

Table 8
Estimated maximum outflow, during August/September 1987

Strait	ρ_1 (kg m^{-3})	ρ_2 (kg m^{-3})	$(\rho_2-\rho_1)/\rho_2$ ($\times10^{-5}$)	Depth of σ_1 (m)	Sill width L at depth of σ_1 (km)	Deepest sill depth (m)	Outflow ($\times10^6$ m^3 s^{-1})
Case A							
Antikithira	1033.48	1033.521	3.948	800	–	550	0.00
East Kassos	1033.48	1033.501	2.008	800	3	1050	0.05
West Kassos	1033.48	1033.501	2.008	800	–	700	0.00
Case B							
Antikithira	1033.48	1033.521	3.948	566	–	550	0.00
East Kassos	1033.48	1033.501	2.008	566	5	1050	0.21
West Kassos	1033.48	1033.501	2.008	566	4.5	700	0.03

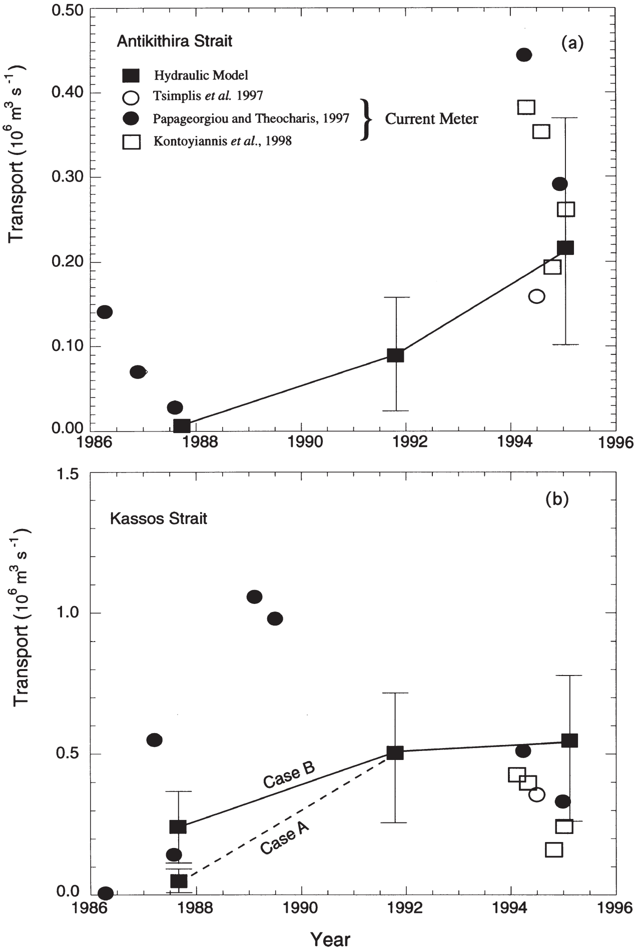

Fig. 6. Comparison of model outflow calculations with those estimated on the basis of the current meter observations for: (a) Antikithira Strait; and (b) Kassos Strait. The Kassos Strait estimations include the fluxes for both passages (see Fig. 4). In Case A, the reference isopycnal σ_1 is considered to be at a depth of 800 m; in Case B, at 570 m.

4. Estimation of errors

Several errors are present in the estimation of the outflow. There are errors associated with uncertainties related to the physiography of the straits and the cross-strait variation of the height H_1 of the reference isopycnal σ_1. Moreover, neglecting the Earth's rotation introduces another error. As the average tilting of the reference isopycnal observed across the relevant straits is of the order of 50 m, it may be suggested that the geostrophic effects are not significant. Nevertheless note that the observed height differences along the Kassos Strait for the 33.548 ($\sigma_\theta \approx 29.2$) isopycnal vary between 0 and 95 m, while along the Antikithira Strait the same isopycnal has a slope between 9 and 165 m. In the present study, it is assumed that the error of the estimated sill width is 500 m while the uncertainty in H_1, which includes the error in bathymetry and the variation of the height of σ_1 across the strait (because of geostrophic effects) is 50 m.

The approximation of the complex configuration of the cross-sectional area of the strait by an equivalent (half) rectangular, although a common practice in Oceanography (see for example Canizo, 1984, pp. 447–456; Dalziel, 1988), may introduce a significant error. To estimate this error, the hydraulic expression for the outflow through a triangular notch ($q=\frac{8}{15}H\sqrt{2gH}\,\tan(\theta/2)$, where θ is the angle of the notch) must be considered. This expression produces lower values (20%) than the equivalent (half) rectangular approximation. Bormans and Garrett (1989) did a more detailed calculation of the hydraulic exchange for the two-layer system of the Strait of Gibraltar. They considered the complex cross-sectional area of the strait and concluded that there was a 20% reduction in the exchange. Therefore, the errors in the transports are assumed to include a 20% overestimation.

The deviation from the basic assumptions of the model may also introduce errors. One reviewer suggested that the deviation from the hydrostatic pressure distribution over the sill would probably introduce a 10% underestimation of the true maximum flows, while the fact that the maximum outflow is not reached would probably give an overestimation of the same magnitude. An error of 20% is assumed for the above mechanisms.

The error for the outflow estimates is calculated as follows. First, the errors associated with uncertainties related to the sill width and the cross-strait variation of the height H_1 are used to estimate the range of possible values. Then, the lower value is decreased by 20% to account for the use of the equivalent half rectangular cross-section. Finally, the range limits are increased by 20% to account for the deviation of hydrostatic pressure. Comparison of the errors indicates that the error assumed in the estimation of H_1 (50 m) is the most significant.

5. Comparison with current meter estimates

The model estimates of the CDW and the estimates from current meter measurements (Tsimplis et al., 1997; Papageorgiou & Theocharis, 1997; Kontoyiannis et al., 1999) are shown in Fig. 6. The agreement between the direct estimates of the outflow and the model is good within the error bars. There is a better agreement between the different data sets for the Antikithira Strait while larger differences exist in the outflow estimations for the Kassos Strait, for 1995. In this case, the model tends to overestimate the outflow. A large part of this difference can be attributed to the different reference isopycnals used to distinguish CDW in the model and in the direct estimates. The current meter estimations are related only to outflows of water with a density anomaly (σ_θ) higher than 29.2, whilst the model estimates the deep water fluxes beneath the 33.53 isopycnal ($\sigma_\theta \approx 29.18$). If the isopycnal 33.548 ($\sigma_\theta \approx 29.2$) is used as reference ($\sigma_1$) in the model, then the estimated CDW flux for the Kassos Strait is approximately 0.32×10^6 m^3 s^{-1}, which is very close to that derived on the basis of the current meter data (0.24×10^6 m^3 s^{-1}), for the same period (Kontoyiannis et al., 1999). As the density anomaly distribution (Fig. 5) shows that the 33.548 isopycnal cascades into the Levantine Basin, it is likely that the current meter estimates, which are based on only one current meter in the CDW, may underestimate the outflow.

The model is sensitive to the depth of the reference isopycnal selected. This depth does not only exercise control on the flux per unit width (q) (see Eq. (4)) but, in the case of deeply incised 'channel-like' passages, can also alter significantly L (the sill width at the depth of the reference isopycnal). Finally, it should be noted that significant errors may be present also in the computations based upon the current meter data.

6. Discussion

The model describes the CDW outflow in a manner consistent with the available direct estimates. Nevertheless, the model can undoubtedly provide only an approximation of the water fluxes. As the model requires only a small number of hydrographic stations, which can be repeated at regular intervals, it may prove to be a useful tool in the estimation of the fluxes by providing insight and constraining the results of more elaborate models and extensive current meter observations. As the model relies on the hydrographic structure, it is probably more reliable than any short-term direct current observations. It has to be noted that the model accuracy would be significantly improved if detailed bathymetric maps of the straits become available and the model is extended to account for the real cross-sections of the straits.

6.1. Interannual variability and controls of the CDW fluxes

Because in the present study the temporal resolution of the hydrographic information used is low (with only three observation periods at different seasons between 1987 and 1995), a detailed study of temporal variability in CDW outflow during the recent energetic period can not be undertaken. Nevertheless, some characteristics of the development of the outflow throughout these years can still be identified.

The results derived from the present model suggest that, between 1987 and 1991, the CDW outflow increased rapidly (by at least a factor of 2) in the Kassos Strait. After 1991, the outflow appears to have reached a steady state. In contrast, the CDW outflow through the Antikithira Strait appears to have increased steadily between 1987 and 1995. Generally, the eastern and western Cretan Arc Straits appear to be characterised by different outflow patterns.

Reliable flux estimations are not available before 1986. Therefore, it is difficult to trace when the CDW outflow from the Cretan Sea started. However, current meter observations confirm that the deep water outflow had already started in the spring of 1986. In 1986, the Kassos Strait was not an outlet for the deep waters of the Cretan Sea; whereas, a significant outflow (up to 0.14×10^6 m^3 s^{-1}) was observed within the Antikithira Strait (Zodiatis, 1992; Papageorgiou & Theocharis, 1997). After 1987 this pattern changed and the largest part of the outflow was through the Kassos Strait during 1987–95 (Fig. 6).

The CDW outflow is controlled by: (a) the density difference between the deep and transitional waters; and (b) the upstream height of the deep water reservoir, above the sill level. Even if there was a uniform rate of deep water formation over the Cretan Sea, the basin physiography would exercise a significant control on the outflow patterns through the different straits. Transient/recurrent water circulation features (i.e. cyclonic and anticyclonic gyres and related currents and jets), which are present in the Cretan Sea and the adjacent basins (Zodiatis 1992, 1993; Theocharis, Georgopoulos, Lascaratos & Nittis, 1993; Theocharis et al., 1999), may also have a significant effect on the outflow patterns. These features influence the rate of dense water formation and its spreading at a sub-basin scale. These controls are reflected in the seasonal variability of the CDW fluxes (Kontoyiannis et al., 1999; Theocharis et al., 1999).

Theoretical considerations suggest that a gradual reduction in the water density difference between the upstream and downstream flanks of the sills will take place in response to the progressive infilling of the Ionian and Levantine Basins, with denser water from the Cretan Sea. Such a reduction will have an effect on the deep water outflow: water fluxes will decrease, unless the head at the sill increases accordingly. Alternatively, if the rate of formation of dense water in the Cretan Basin declines, then the head of water over the sill will also decrease until the pressure difference is diminished. Under such conditions, the Cretan Basin below sill depth will become isolated (and unventilated) from the Eastern Mediterranean Basins until a new episode of dense water formation takes place.

6.2. Mechanisms of CDW formation and regional significance

The potential temperature–salinity (T–S) diagrams for the water masses lying beneath 500 m, for selected stations in the Cretan Sea are shown in Fig. 7(a); their location is shown in Fig. 7(b). The evolution of the hydrographic characteristics of the deep water masses is evident in the data presented. The salinity of the dense water increased by more than 0.1, between 1987 and 1995 (see also Theocharis et al., 1999). The water temperature also increased (generally) between 1987 and 1991. However, the 1995 measurements (P and L stations) indicate that the deep waters were cooler and slightly saltier than those present during the 1991 measurements (O stations) (Fig. 7).

The mechanism for CDW formation can be described as follows: (i) as the surface water salinity increases as a result of evaporation, there will be a point at which its density exceeds that of the underlying waters (although its temperature remains relatively high); (ii) convection would involve waters of higher salinity and slightly higher temperature, than previously; (iii) as the deeper waters become progressively denser, the surface waters must become colder, in order to sink. Evidence for this process is provided by the decrease in CDW temperature observed between 1991 and 1995. Recent observations (not shown) during September 1998 by one of the

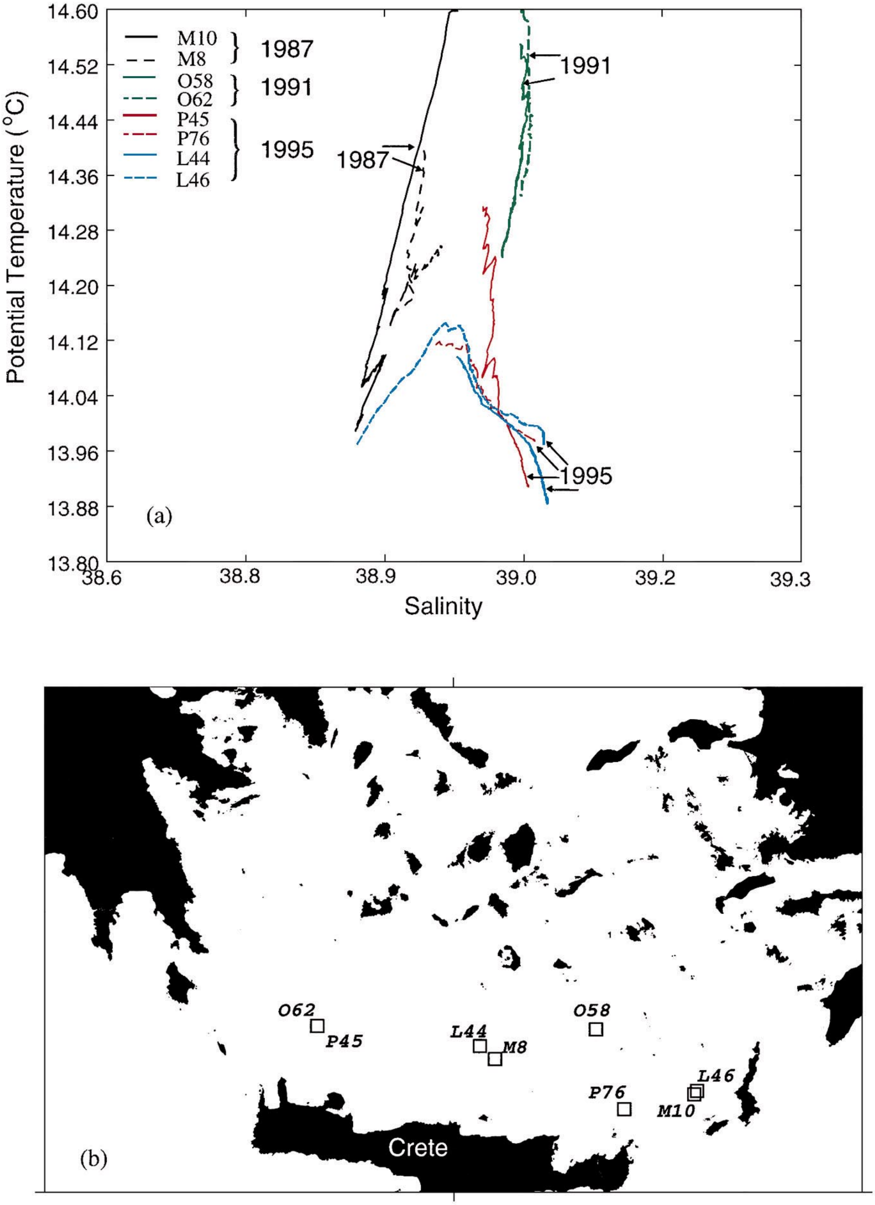

Fig. 7. Potential temperature–salinity diagram, under 500 m (a), for selected stations in the Cretan Sea. Station locations are shown in (b).

authors (P. Drakopoulos, on board R/V Philia, Institute of Marine Biology of Crete) suggest that the salinity of the deep waters inside the Cretan Basin appears to have remained at the 1995 levels, whereas the temperature has increased back to 1991 levels. These observations imply that: (i) the outflow of dense waters may have ceased; and (ii) in the near future light cooling of the surface waters may result in significant CDW formation.

The recent changes in the CDW formation and outflow may relate to larger-scale changes in the thermohaline circulation of the Mediterranean Sea. In the adjacent Ionian and Levantine Basins, the increased CDW outflow has already resulted in changes in the hydrography of the EMDW; in the past the homogeneity of this water mass presented one of the most prominent features of the Eastern Mediterranean (Roether et al., 1996). Other recent and important changes in the general thermohaline circulation over the area have also begun to emerge. Most of these changes are associated with the formation and spreading of the Levantine Intermediate Water (LIW) (Hecht, 1992; Sur, Ozsoy & Unlüata, 1992; Klein et al., 1999). This particular water mass plays a very significant role in controlling the hydrography of the entire Mediterranean Basin (Roether & Schlitzer, 1991; Leaman & Schot, 1991).

Elsewhere, Rohling and Bryden (1992) have shown that both the salinity and temperature of the Western Mediterranean Deep Water (WMDW) have been increasing (since 1909) at rates of 6.9×10^{-4} yr^{-1} and 8.3×10^{-4}°C/yr, respectively. These authors have also suggested there has been a consistent increase in the salinity of the Levantine Intermediate Water (LIW) in the Levantine and Ionian Seas, of between 20 and 45×10^{-4} yr^{-1} after 1955. It has been argued that this increase in salinity might explain some of the observed changes in the hydrology of the WMDW. Applying similar reasoning to the Cretan basins, the salinity of the intermediate waters in the Cretan Basin would become gradually higher as saltier LIW is involved in this process (see also Theocharis et al., 1999). Consequently, the contribution of the LIW water to the creation of the deep water masses of the Cretan Sea (CDW) would also increase. Therefore, a larger portion of the LIW generated in the Eastern Mediterranean basins (Malanotte-Rizzoli & Hecht, 1988) would be used in the formation of the CDW (and, consequently, the EMDW). Then, less LIW would be available for mixing within the other Mediterranean basins, farther to the west: some evidence of such a process has already started to emerge (Klein et al., 1999). If the above interpretation is correct, then a decrease in the density of the Western Mediterranean Deep Water is to be expected, as less LIW of high salinity would be involved in its formation.

Continuous monitoring of the CDW outflow is of considerable significance to developing an understanding of the thermohaline processes of the Eastern Mediterranean. Moreover, as the forcing factor for the observed changes is not yet clear (Rohling & Bryden, 1992; Roether et al., 1996), information related to changes in the hydrographic characteristics and circulation patterns of the deep Cretan waters may provide an insight into the large-scale meteorological and/or human-induced changes over the Mediterranean region.

Direct measurements of spatial and temporal variability in the CDW outflow, together with its hydrographic characteristics, is the most reliable method for the investigation of the formation of the deeper waters of the Eastern Mediterranean. Outflow information could be obtained through the deployment of bottom-mounted ADCPs; these could monitor the deep water flow at the Cretan Arc sills, at high spatial and temporal resolution. Consequent and regular sampling of the water column is also required, in order to estimate the heat and salt outflows from the Cretan Basin. The method described here does not provide an alternative to direct flow measurements; rather, it permits the evaluation of flow measurements within a synoptic pattern of observations.

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