Climate Variability in the Eastern Mediterranean and the Great Aegean Outflow Anomaly

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The Mediterranean region is one of the foremost areas of the world where interannual and longer term climatic variability is predominant (*e.g.* Garrett *et al.*, 1992; Robinson *et al.*, 1993; Rizzoli and Robinson 1994). The Eastern Mediterranean stands out as a region displaying this atmosphere and ocean variability. Both short and long term atmospheric variability is large in the region, displaying many significant local features (Özsoy, 1981), and teleconnections with the long term global atmospheric events (Ward, 1996), via coupling with the Indian Monsoon system. On the other hand, the efficiently ventilated waters of the Mediterranean Sea, with relatively short mean residence time scale on the order of ~ 100 years, are fundamentally very sensitive to climate variability, and possibly to climatic changes. From another point of view, the Mediterranean can have an impact on local and global scale climate, perhaps more significantly than suggested by its size: The Levantine Intermediate Water (LIW) originating from the Levantine Basin is advected westwards, where its cascading outflow from the Gibraltar Strait determines the water mass properties throughout the North Atlantic, preconditioning the climatically important North Atlantic Deep Water (NADW) formation process (*e.g.* Reid it et al., 1994). It is therefore very important to understand climatic variability inherent in the Mediterranean system.

A number of recent studies based on intermediate to long-term observations have shown that the Mediterranean waters are indeed associated with prominent interannual and interdecadal changes. These changes are most directly evident in the main thermocline circulation and Atlantic Water (AW) and LIW water mass properties and volume, but similar changes are also becom'ng evident in the deep waters.

In the Levantine basin, peculiar, abrupt changes in the LIW properties and vertical distribution have first been noticed to take place in 1982, based on the analyses of continuous observations in the eastern part of the basin during the 1979-1984 period (Hecht, 1992). Similar changes have been observed in the Levantine Basin during the POEM programme, 1986-1991, and its continuation into POEM-BC 1991-1996. The properties of the Asia Minor Current and the LIW contained in the cores of coherent Antalya and Shikmona eddies, and the abundance of AW in the basin experienced abrupt changes in 1987 and 1992 (Özsoy *et al.*, 1991, 1993; Brenner *et al.*, 1991; Brenner, 1996). Changes in LIW and AW have also been detected in the Ionian Sea in the same period, but occurring at different times (Manca, 1996).

The evolution of the water mass distribution and circulation are strongly influenced by atmospheric climatic variability. Ocean-atmosphere buoyancy fluxes in winter drive convection leading to the formation and trapping of LIW in the northern Levantine Sea, within anticyclonic eddies and against the Anatolian coast (Brenner *et al.*, 1991; Sur, *et al.*, 1992; Özsoy *et al.*, 1991, 1993), and on some occasions, simultaneously with Deep Water (DW) formation within the core of the Rhodes Gyre, (Lascaratos *et al.*, 1993; Nittis and Lascaratos, 1996; Wu and Haines, 1996), subject to interannual variations. Strong links seem to exist between the changes in the northern Levantine circulation and the recurrence of deep convection events every few years (Özsoy *et al.*, 1991, 1993), analogous to case in the Western Mediterranean (Crepon *et al.*, 1989; Barnier *et al.*, 1989).

Although the changes in intermediate waters were better explored up to the present, studies of the deep waters have only increased in recent years. Evidence for a warming trend and an associated increase in nutrients have been found in the deep waters of the Western Mediterranean (Bethoux, *et al.*, 1989, 1990), possibly linked with annual deep convection events in the northwest (Gascard, 1991) modifying the deep water properties of the basin (Send *et al.*, 1996). Compared to LIW, the origin of the deep waters in the Eastern Mediterranean were less clear for a number of years: While it has been generally accepted that the Bottom Water (BW, deeper than 2000m) is formed by waters cooled in the shallow Adriatic Sea, it was recognised that the more heterogeneous Deep Water (DW) in the 1000 - 2000m depth range could have multiple sources including the Aegean Sea. Evidence for DW formation in the cyclonic Rhodes Gyre region has only been obtained in recent observations (Gertman *et al.*, 1990; Sur *et al.*, 1992). In contrast to the analogous deep convection events in the west (Gascard, 1991), pre-conditioning is not essential for deep convection in the Rhodes Gyre region, a permanent cyclonic region of the Eastern Mediterranean. On the other hand, it seems that the Rhodes Gyre deep convection in an appreciable scale has a recurrence interval of a few years (Sur *et al.*, 1992), unlike the Gulf of Lions case which repeats every year.

The most recent surprise in monitoring the deep water properties came when it was discovered that the entire volume of deep waters of the Eastern Mediterranean (including the previously defined DW and BW volumes) has been replaced and modified by dense (salty, warm) outflow from the Aegean Sea (Roether *et al.*, 1996), lifting the average depth of the shallower features, and among them that of the LIW. The changes first became evident, at least to us, when an unusual warm, saline water mass was observed extending to the bottom fom a depth of about 1000m south of the Island of Crete during the summer of 1993 (Heike *et al.*, 1994, A. Yılmaz, personal communication). Similar, anomalous water masses have been observed in the Rhodes Gyre area since that time, during surveys performed by the IMS-METU.

It seems that relatively large changes leading to the Great Aegean Outflow Anomaly have taken place before 1993. An atmospheric anomaly of global scale may have played an important role. Globally, 1992 was the coolest year since 1986 in the north hemisphere, in the period following the June 1991 eruption of the Mt. Pinatubo volcano, which resulted in a significant decrease in solar energy input especially in the northern hemisphere, lasting for more than a year (Halpert *et al.*, 1993; Boden *et al.*, 1994). The surface air temperature anomaly pattern for the first three months of 1992 showed a significant deviation from climatic means, of up to -4°C in the Eastern Mediterranean and the Middle East, and +5°C in northern part of Europe (Figure 1). In the remaining nine months of the year, the anomaly in the Middle East receded to less than -2°C, and dissipated over Europe (Halpert *et al.*, 1993). The atmospheric solar transmission (Figure 2) measured at Mauna Loa (Dutton, 1994) reveals that three notable events took place, all resulting from volcanic eruptions (Agung in 1963, El Chichón in 1982 and Pinatubo in June 1991) which had long term effects on solar transmission, each lasting for a number of years. The average air temperature for the year 1992 obtained from all weather stations in Turkey was cooler by 1-2°C in comparison to the averages of the previous years, making this year the coldest since 1932 (Türkeş *et al.*, 1995). In Israel, the winter of 1992 was the coldest in the 46-year record of air temperature in Eilat (Genin *et al.*, 1996).

Extreme oceanic effects of the anomalous winter atmospheric conditions in 1992 are evident from recent observations in the entire region. In Eilat (Gulf of Aqaba) the anomalous situation resulted in uniform mixing to depths in excess of 850m and produced a massive algal bloom, covering the coral reefs and leading to their destruction (Genin *et al.*, 1996). In the Rhodes Gyre and the northern Levantine region, the formation of DW and LIW resulted in massive plankton blooms (Yılmaz *et al.*, 1996). In the neighboring Black Sea, the Cold Intermediate formation (Ivanov *et al.*, 1996a), and the erosion of the pycnocline (Ivanov *et al.*, 1996b) were intense during the same winter.

The most permanent effect of the 1992 winter conditions could be the Great Aegean Outflow, which has been evidenced by the intrusion of saline, warm and well oxygenated waters into the Levantine Sea from the Aegean Straits at depths below 1000m observed since 1993 (IMS-METU), and demonstrated to occupy the entire Eastern Mediterranean deep waters in 1995 (Roether *et al.*, 1996), and causing an uplift of nutrient rich waters near the surface. Corresponding to this event, large differences in the deep zooplankton populations, including great increase in numbers of some species, and invasion of previously absent new species have been observed in the deep waters of the Levantine Sea (Weikert, 1996). Heat flow observations deep basins of the Ionian Sea during 1993 and 1994 have shown anomalous heat flow conditions in the sediments, resulting from the variation in the properties of the new DW (Della Vedova *et al.*, 1995b), and estimates based on heat diffusion have shown that the transient event could have started in about 1992 (Della Vedova, 1995b).

The scale of importance of the anomalous event can be established by investigating if a similar event has been observed in the past. In the preceding years of intensive surveys during POEM, no evidence of a similar event is found. However, it is evident that the salinity in the Aegean Sea deep waters below 500m have been increasing since 1987 (Roether *et al.*, 1996), which could be associated with the diversion of the Asia Minor Current towards the Aegean Sea in recent years (Theocharis *et al.*, 1996).

To analyse the evolution of the Eastern Mediterranean deep waters, and in particular to address the role of Aegean outflow in the changes, we have joined the MODB historical data base (Brasseur *et al.*, 1996) with the last 10 years of POEM data for a combined analysis. The data was then subsampled within three separate geographical regions as shown in Figure 3: (*i*) the deep Cretan Sea part of Aegean Sea, (*ii*) the Western Levantine Sea adjacent to the Aegean, and the (*iii*) the Eastern Ionian Sea adjacent to the Aegean.

The collective historical deep profiles in these regions are shown in Figures 4a-c to display the variability and to give an indication of data quality issues. The large deviations in deep water mark renewals or deep intrusions. However, some of the data appear to be untrustworthy, despite selection from the historical data base with specified quality flags. For example, the bottle data have large scatter, and the salinity values, especially in the Ionian sea appear to have large drifts. The potential temperature profiles appear to be less problematic and the deep water profiles appear to be bundled into a few groups, which represent renewal events. In fact most of the anomalous profiles in the Ionian and Levantine basins belong to the recent survey of 1995 which showed the DW and BW renewals. Howevere, there are other events at mid water column, which represent more frequent DW intrusions at other times as well as in 1995.

The data grouped under regions (i)-(iii) were then studied further to display temporal changes. Two averages, one for depths of 1000-2000m and the other 2000-4000m were constructed for each data set, grouping all data within the corresponding depth interval and within one year periods and forming the average and statistics for each set of profiles. The average values of salinity and temperature and the number of samples found for each average are shown in Figures 5, 6 and 7 for the three regions. The vertical error bars are the 95 % confidence intervals for the average.

In the Cretan Sea (Figure 5), both the potential temperature and salinity of the deep waters (maximum depth about 2000m) have fluctuated at least twice between minimum and maximum values in the last 60 years, starting a last increasing period in the 1980's, after about 1983. The salinity has reached its last ascent in the 1990's, and reaching a peak in 1995, while the temperature first increased until 1991, and between 1991 and 1995 dropped sharply (last two data points), resulting in a rapid and steady increase in density during the 1980's and 1990's with a maximum in 1995 (Figure 8).

Note that the densities (and most probably salinities) before the 1970's are suspect in terms of accuracy because of the comparatively lower quality of instruments and techniques in those days, before the rapid developments in instruments took place in the 1980's when the last group of measurements were taken, mostly in the POEM era. We can further argue for this change in measurement sensitivity as follows: Firstly note that in addition to the accuracy problem, there is also a resolution problem with the older instruments, since the error bars are larger for the older measurements. Secondly, there are large changes in density during the same periods of measurements, even within the same year, between the older data sets, while this is not the case for the modern period.

In the Western Levantine Sea, as well as the Ionian Sea, the salinity and potential temperature display fluctuations in the DW between 0-1000m depth (upper part of Figure 6). Part of these fluctuations are real and a result of the ventilation of the 'mid-waters' by dynamical processes, and possibly intrusions from the Aegean Sea as evidenced in Figure 2.

These observations caution us to be more careful with the measurements. In this, we are encouraged to suspect the salinity measurements more than the temperature measurements, because especially near the deeper part of the adjacent Ionian and Levantine basins (lower part of Figures 6 and 7), *i.e.* averages between 0-2000m, the temperature fluctuates much less than the salinity values, except in the last part of the record when temperature was also influenced by the extreme event of Aegean Outflow. In fact, there is very little possibility for the salinity of a bottom water mass to change without a concurrent change in temperature, since this would imply identical temperature of the source water; hence such changes are most likely to be artefacts of measurement technique. Such increases in salinity, without change in temperature are evident in the bottom waters about 1970.

The average density at depths of 1000-2000m for the Cretan Sea, and at 2000-4000m for the W. Levantine and E. Ionian Seas (Figure 8) is more revealing. In the Levantine basin there is only a slight net increase in density even in the recent times, indicating that the Aegean Outflow in the 1995 survey did not influence the BW density to a great extent, in spite of the fact that the sharp increase in density of the water outflowing from the Cretan Sea. This result gives reason to suspect the density fluctuations rising above the noise level around the 1970's. In the Ionian Sea, there are larger fluctuations in BW density, and perhaps this is expected as a result of the continuous source in the Adriatic.

If the measurements of the last decade are to be trusted, there has been a well defined, steady increase in Cretan deep density starting with 1983 and continuing until the present, which is quite different than the relatively constant values of the previous three decades. The same can be argued for the adjacent basins, extending the period back about a century, because if we take the temperature as a more stable indicator of BW renewals (lower part of Figures 6 and 7), we observe that the recent evolution contrasts strongly with relatively stable state within the last century before the changes.

Comparing the observation of a steady increase in Cretan deep density within the last decade, with our earlier comments concerning a singular event in 1992, one is left uncertain, as to which of these processes would be more significant in determining the new state of the Eastern Mediterranean. It seems that both of these factors are important, and should be further investigated. There was already a change in the system, when a atmospheric pulse in 1992 most likely reversed the rate of change of temperature in the deep Cretan basin, still producing waters with higher density than implied by the decadal trend.

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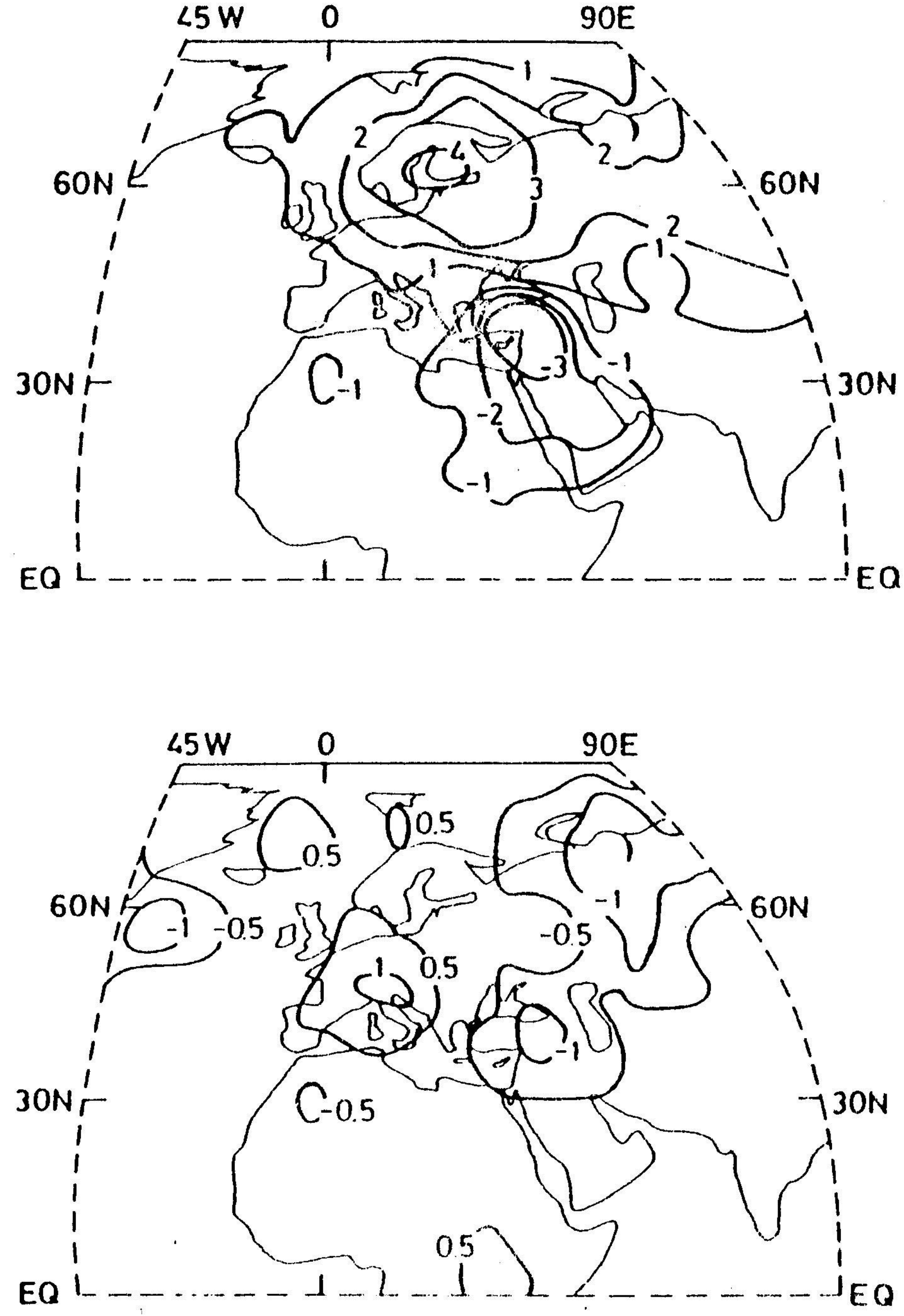

Figure 1. Surface temperature anomaly (°C) (a) January-March 1992, and (b) April-December 1992. Analysis based on station data relative to the 1961-1990 base period, and sea surface temperature measurements relative to the COADS/ICE climatology. (After Halpert *et al.*, 1993).

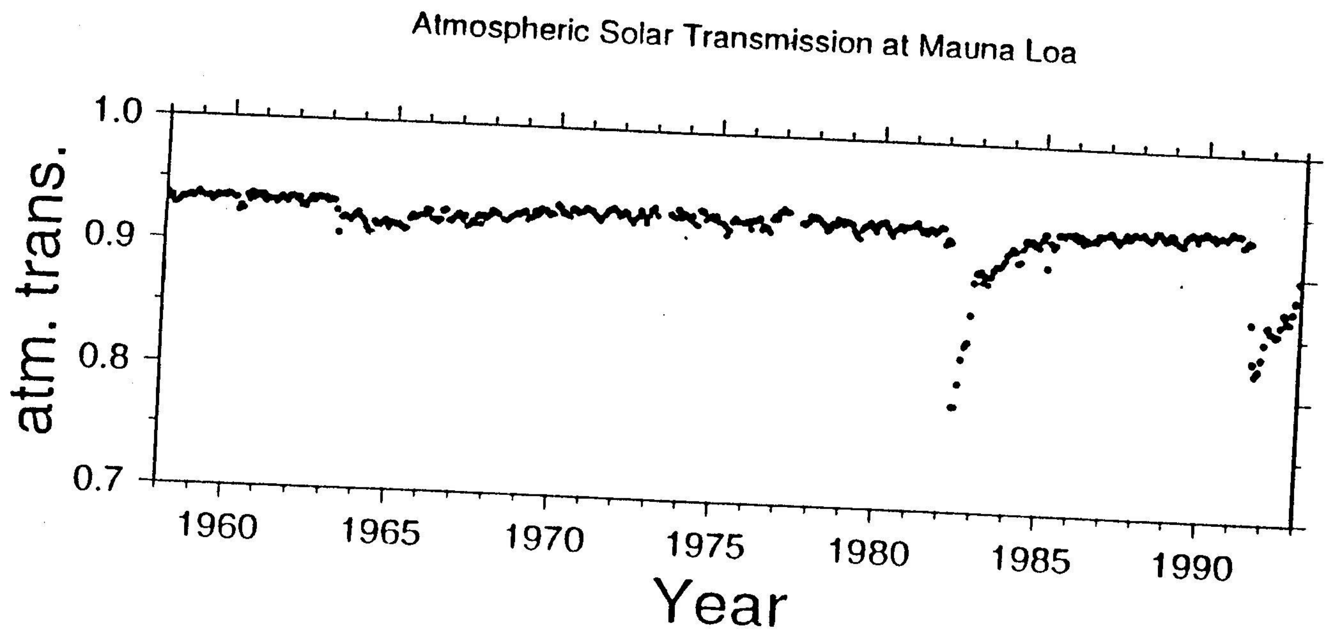

Figure 2. Atmospheric solar transmission measured at Mauna Loa. (After Dutton *et al.*, 1994).

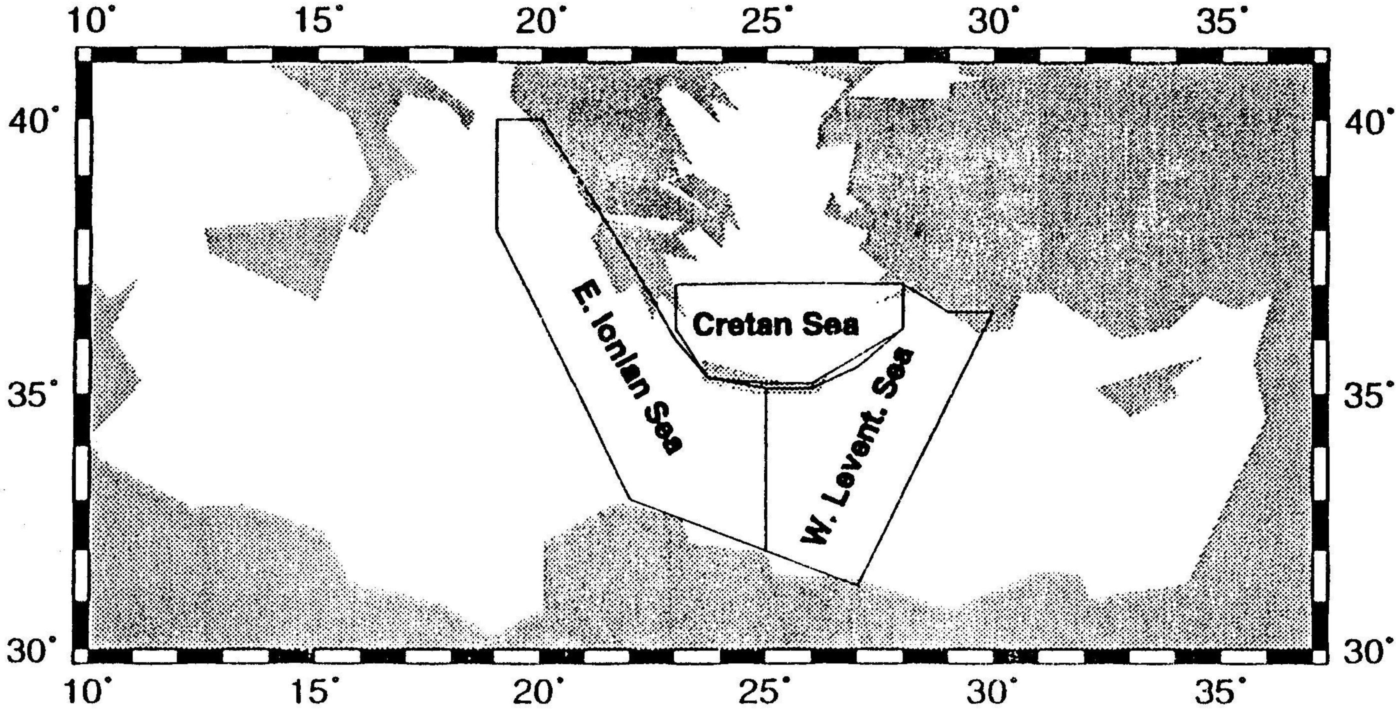

Figure 3. The three subregions for analysis of deep water properties associated with Aegean Outflow.

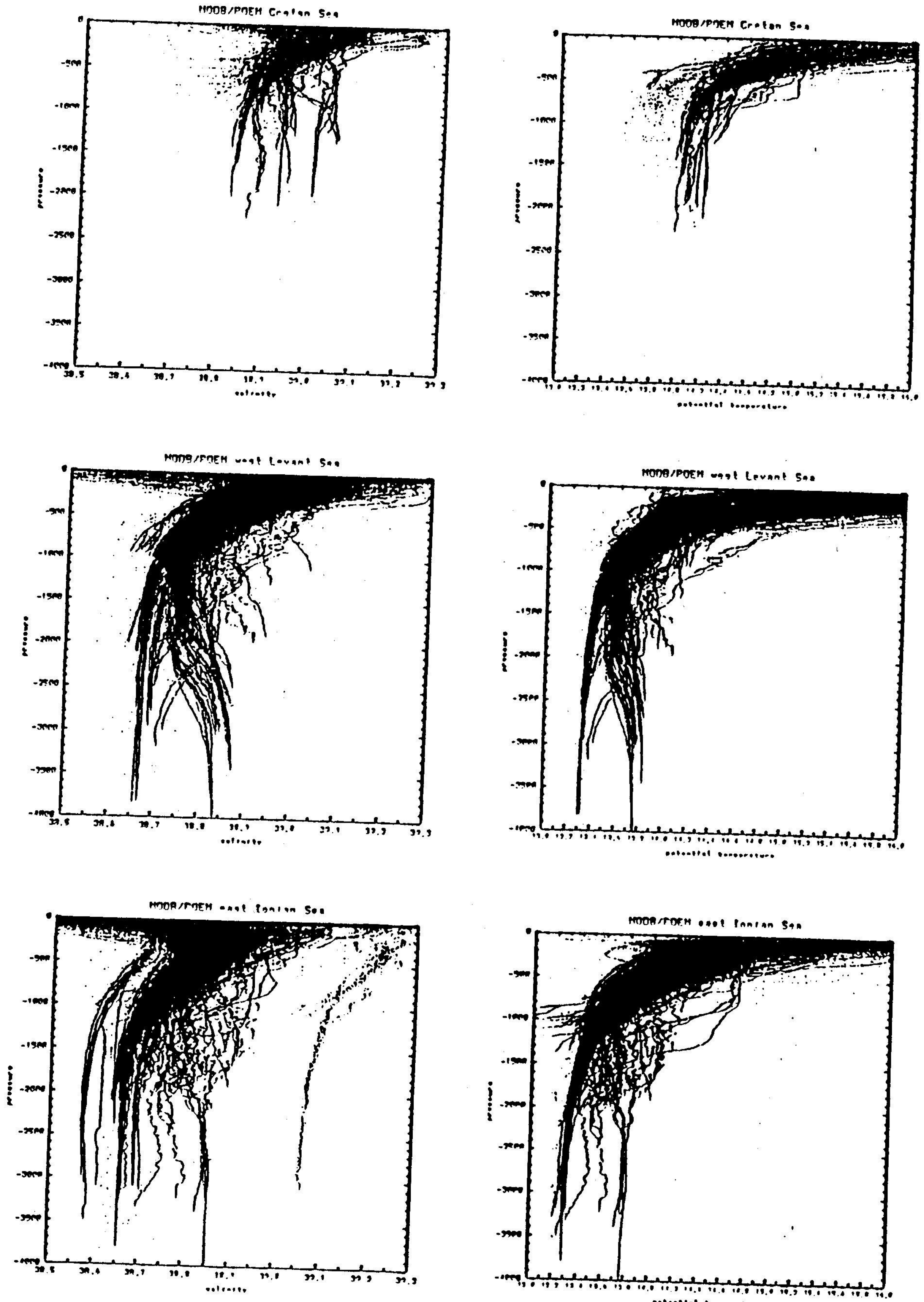

Figure 4. Collective profiles of potential temperature ($°C$) and salinity versus depth in (a) the Cretan, (b) Western Levantine and (c) Eastern Ionian regions marked in Figure 3, based on the combined analysis of the MODB (bottles, bathythermograph and CTD) and POEM (CTD) data.

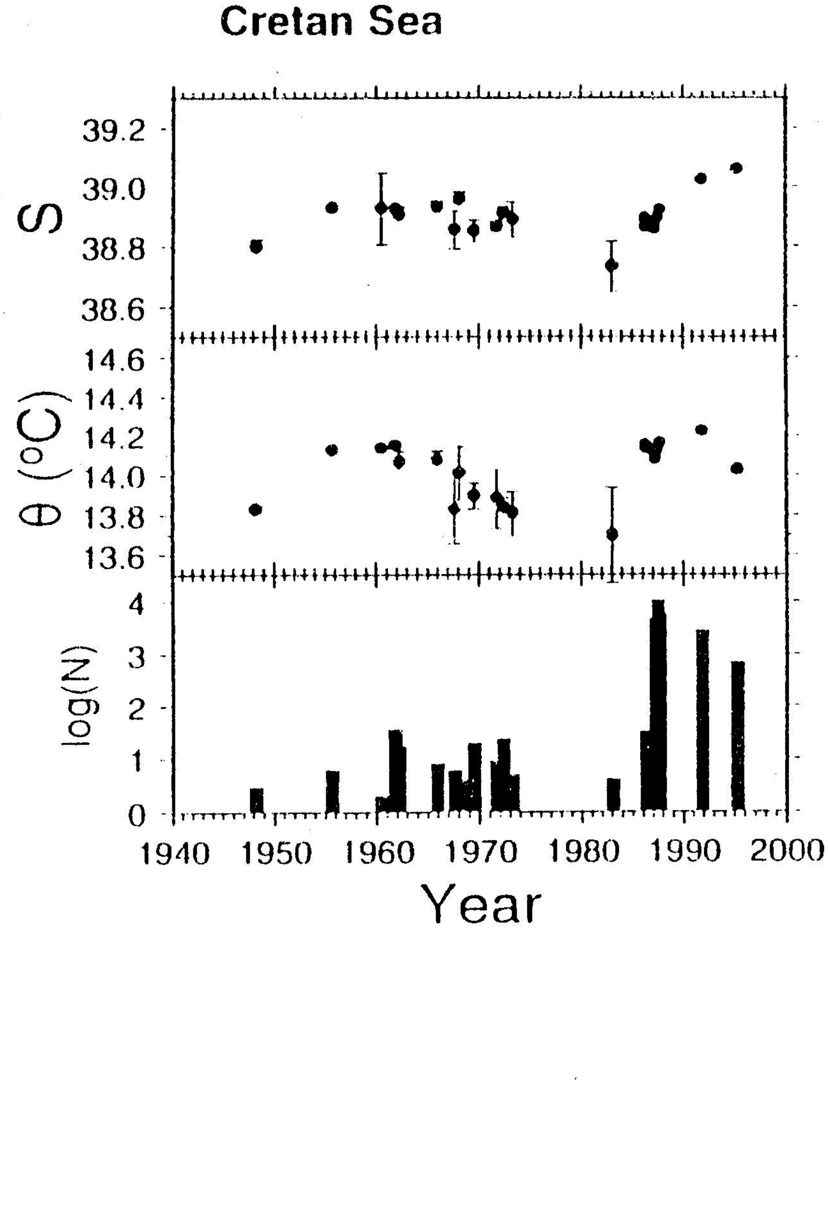

Figure 5. Average values of salinity, potential temperature (°C), and number of data points, in the depth range of 1000-2000m, in the Cretan Sea region of Figure 3. The averages are obtained from individual data sets contained within the combined MODB / POEM data and grouped into 1 year intervals falling within the specified depth range.

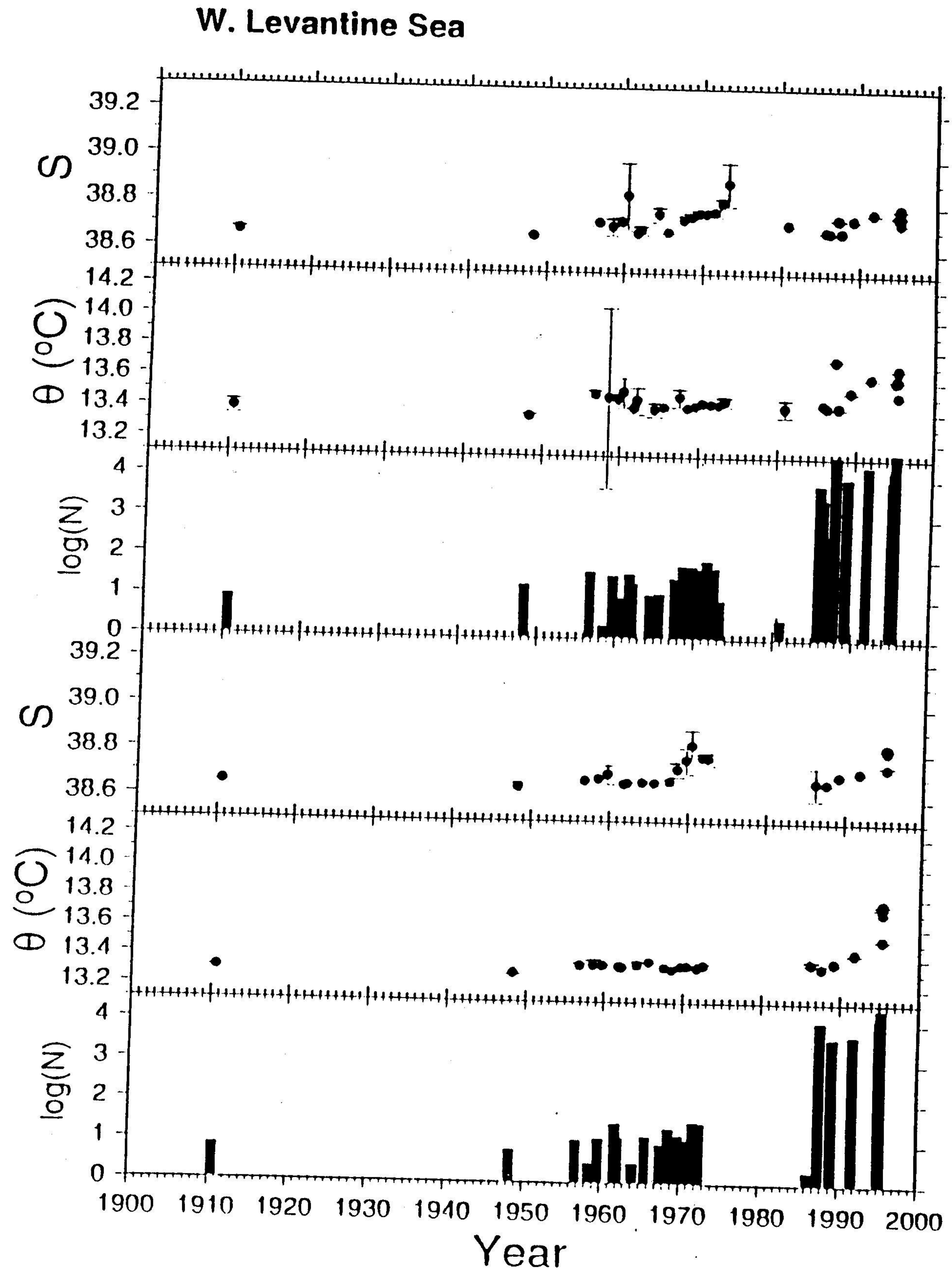

Figure 6. Average values of salinity, potential temperature (°C), and number of data points, in the depth ranges of (a) 1000-2000m (upper part of Figure), and (b) 2000-4000m (lower part of Figure) in the Western Levantine Sea region of Figure 3. The averages are obtained from individual data sets contained within the combined MODB / POEM data and grouped into 1 year intervals falling within the specified depth range.

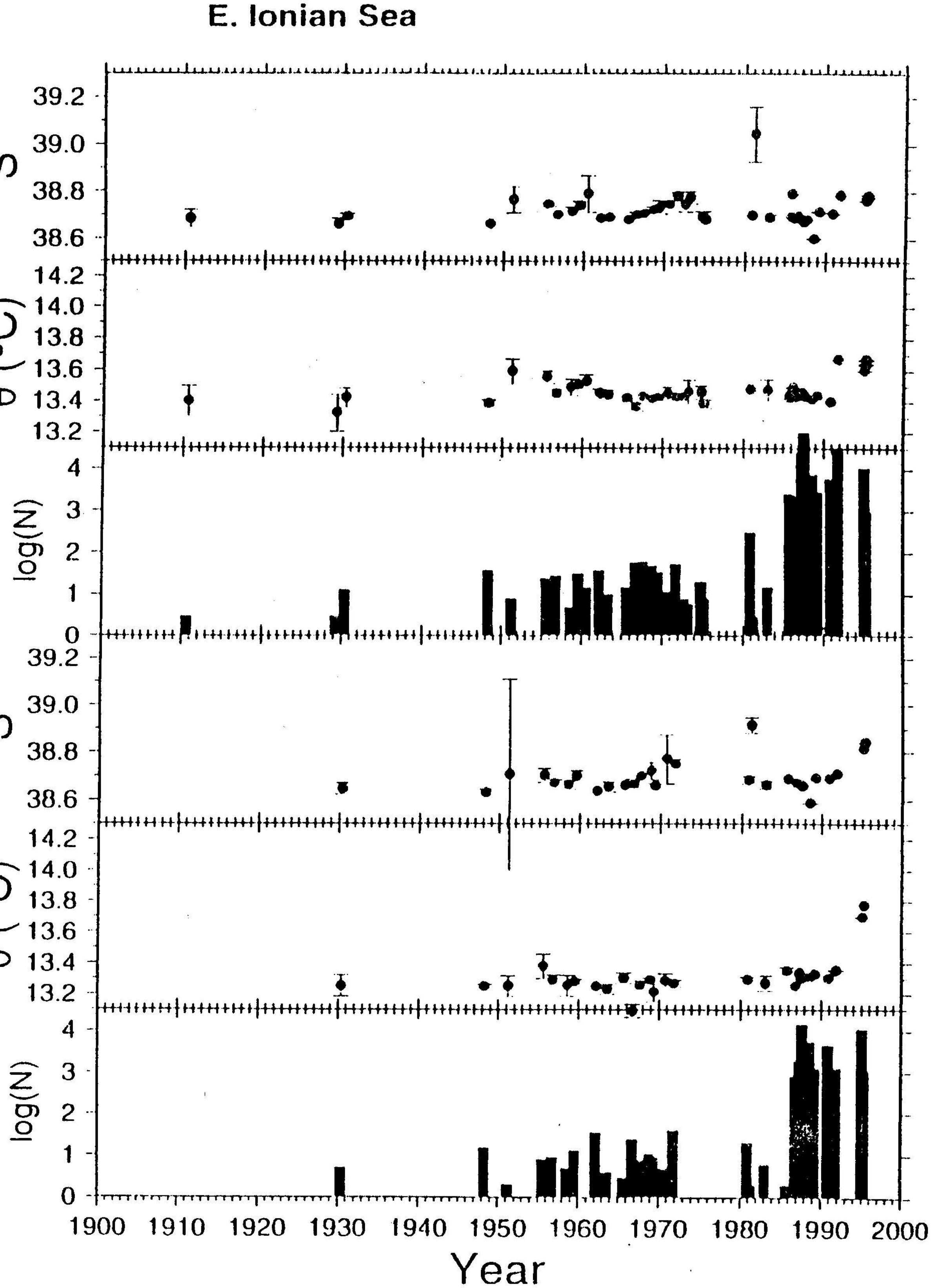

Figure 7. Average values of salinity, potential temperature (°C), and number of data points, in the depth ranges of (a) 1000-2000m (upper part of Figure), and (b) 2000-4000m (lower part of Figure) in the Eastern Ionian Sea region of Figure 3. The averages are obtained from individual data sets contained within the combined MODB / POEM data and grouped into 1 year intervals falling within the specified depth range.

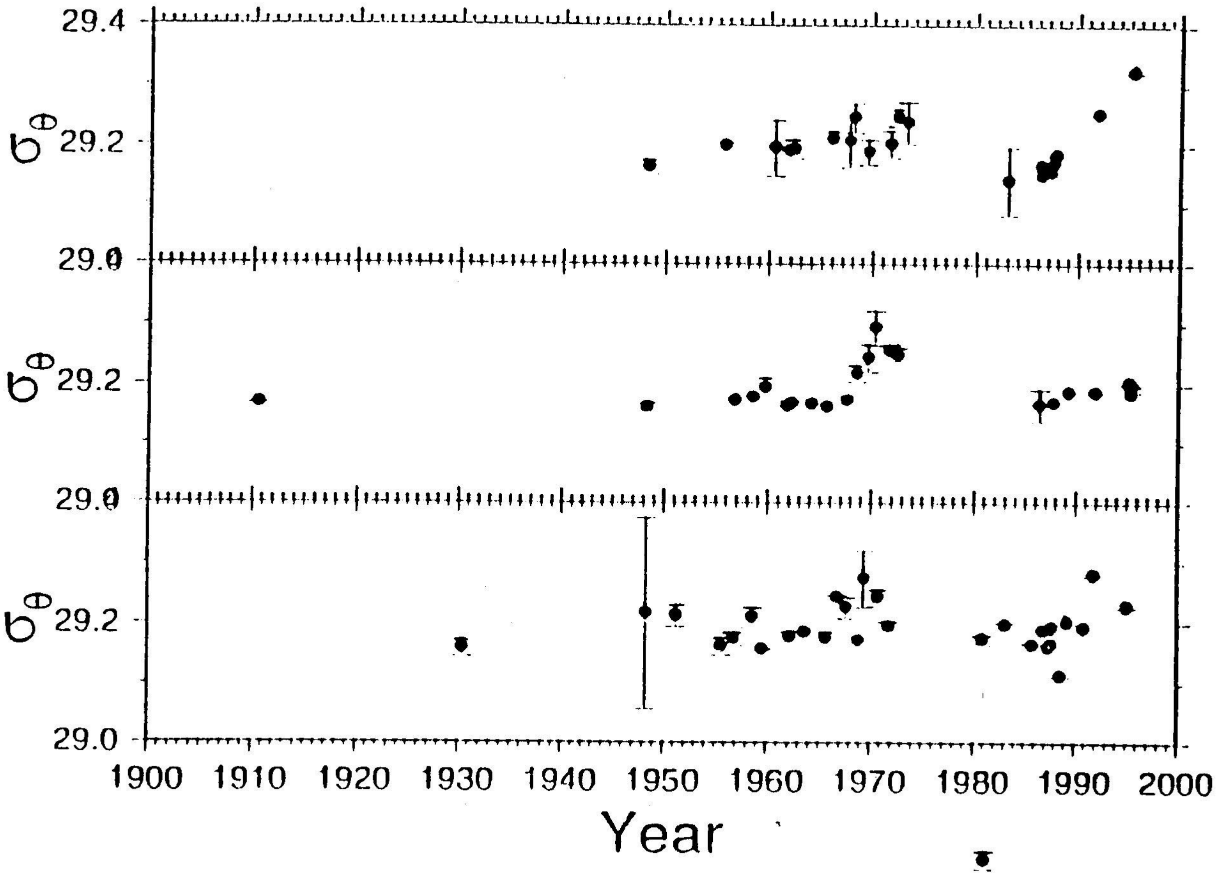

Figure 8. Average values of σ_theta density (kgm^{-3}), in the depth range of 2000-4000m (lower part of Figure) in the Cretan, Western Levantine and Eastern Ionian Sea regions of Figure 3. The averages are obtained from individual data sets contained within the combined MODB / POEM data and grouped into 1 year intervals falling within the specified depth range.

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