

## TEMPERATURE-SALINITY STRUCTURE AND MIXED LAYER IN THE WESTERN MEDITERRANEAN SEA

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### البناء الحراري - الملوحة والطبقة المختلطة في غرب البحر المتوسط

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تم تحليل البيانات الهيدروجرافية خلال الفترة من ١٩٣٢ إلى ١٩٨٥ لحساب متوسطات البناء الحراري والملوحة والطبقة المختلطة في الاحواض المختلفة لغرب البحر المتوسط، كما تم حساب معاملات الترابط لكل من درجة الحرارة وعمق الطبقة المختلطة مع الطبقة السطحية والطبقات تحت السطحية في الاحواض المختلفة لغرب البحر المتوسط خلال الشهور الباردة والساخنة، ولقد تم حساب الشذوذ في درجات الحرارة والملوحة والطبقة المختلطة في الاحواض المختلفة لغرب البحر المتوسط، وأخيراً تم حساب الميل السنوي للمحتوي الحراري خلال الاحواض المختلفة لغرب البحر المتوسط. أظهرت النتائج وجود الطبقة المختلطة على مدار السنة في كل الاحواض على عمق يصل الى ٢٥٠ متر تقريباً في خليج الاسود خلال شهر فبراير، بينما يصل العمق الى ٥٠ متر في البحر الابوراني. الاختلافات الحولية لدرجة ملوحة الطبقة المختلطة أظهرت قيم عالية في البحر الكاتيليني وخليج الاسود خلال الشهور الساخنة، لوحظ أن درجة ملوحة الطبقة المختلطة أعلى من درجة ملوحة الطبقة السطحية، ترتبط درجة حرارة الطبقة المختلطة مع قيم درجات الحرارة الى عمق ٢٥٠ متر في شمال غرب المتوسط خلال الشهور الباردة بينما يقل الترابط المعنوي بين عمل الطبقة المختلطة وقيم درجة الحرارة في الاحواض المختلفة خلال الشهور الساخنة، أظهر شذوذ قيم كل من درجات الحرارة والملوحة وعمق الطبقة المختلطة أن درجات الحرارة تتربط عكسياً مع سمك الطبقة المختلطة، ثم رصد قيم عالية للمحتوي الحراري في شمال غرب المتوسط خلال الشهور الباردة وظهرت القيم المنخفضة للمحتوي الحراري في البحر الألبوراني نتيجة لضخلة الطبقة المختلطة في هذا البحر .

*Key ordes* : Temperature - Salinity, Mediterranean.

#### ABSTRACT

The hydrographic data taken during 1932 — 1985 were analyzed to present the mean temperature structure and the mixed layer in the different basins in the Western Mediterranean Sea. The data indicate that a surface mixed layer exists all year round in all basins with maximum depth reach to about 260m in the Gulf of Lions during February. The mixed layer depth (MLD) seemed to be more shallow in the Alboran Sea (average 50 m ) than other basins. The seasonal variation of mixed layer salinity (MLS) was seen as large amplitude of MLS in both Catalan Sea and Gulf of Lions, during the warm months. In Tyrrhenian Sea the MLS has a higher value than the sea surface salinity. Also, the effect of Atlantic water was clearly identified in the Alboran and Algerian Seas. The mixed layer temperature (MLT) is significantly related to temperature values down to 250 m in the northwestern Mediterranean basins during the cold months. The correlation's of MLD with temperature are insignificant in all basins during the warm months. The anomalies of MLT, MLS and MLD showed that the temperature and thickness of the mixed layer have a weak inverse correlation. Finally, the seasonal variations of the heat content of the mixed layer in all basins in the Western Mediterranean are described.

## INTRODUCTION

The surface mixed layer in the Ocean has been subject of intensive research for many years. It is defined as the shallow surface layer that is homogeneous with respect to all of its physical properties (mixed layer temperature (MLT) and salinity (MLS) and is distinguishable from the quasiuniform layer above the principle thermocline. (Rossby and Montgomery,) [1] Dynamical mixing due to wind action, thermal convection caused by heat loss through the sea surface, advection and internal waves are all processes that can affect the depth of the mixed layer, (Maeda, Molinari et al, and Rao et al,) [2,3' 4]. Tabata et al [5] suggested that, in the regions away from Oceanographic boundaries in the absence of turbulent mixing by strong currents, the depth of the surface mixed layer may be related only to wind mixing (forced convection) and convective mixing (free convection). Nihoul et al, [6] and Selman et al [7] have demonstrated the influence of wind duration on deeping of the mixed layer. However, there are difficulties in separating the effects of wind driven entrainment, from advective and convective processes, in natural environment [8-9]. In a given surface buoyancy flux, the variability in the permanent thermocline depends heavily on the coupling between the mixed layer and the thermocline Liu, [10]. Recently, the study of the coupling between the mixed layer and thermocline had concentrated on steady cases. Either the coupling between the mixed layer and thermocline has concentrated on steady cases. Either the mixed layer is essentially passive (i.e. with the density and depth specified) (e.g. Pedlosky et al, [11], Huang, [12], Wang [13] and Pedolsky and Robbins, [14] 11, 12, 13 or the thermocline is somewhat specified (e.g. Marhsall and Nurser, [15]. The analysis of temperature data and the climatological character of the mixed layer has been studied by [16], [17], [18] [19]. Also, the restratification in the sea mixed layer driven by a horizontal density gradient following a storm is examined [20].

In spite of the fact that the mixed layer is important as a region of Biological production, controlled by the mixed layer depth (MLD) and vertical mixing nutrients, only a few works have addressed this subject in the Western Mediterranean, (Fig:1-a and b). Renzt, [21] has been

modeling the mixed layer in the Ligurian Sea to compute the energy loss due to internal waves and to prescribe realistic boundary conditions at the bottom of the mixed layer. In the same area, Colacino, [22] estimated heat and moisture fluxes at the air sea interface in the occasion of the passage of intense atmospheric perturbations to construct a simple mixed layer model to simulate the evolution of sea surface temperature.

In the following paper a discussion of the dataset is followed by a lengthy results where: 1) The monthly variation of temperature structure and the mixed layer temperature (MLT) in the different basins in the Western Mediterranean Sea will be presented. 2) The monthly variation of salinity structure and the mixed layer salinity (MLS) in the different basins in the Western Mediterranean Sea will be considered. 3) The correlation coefficients of the mixed layer temperature MLT and mixed layer depth MLD with surface and subsurface layers in different basins during the cold and warm months has been calculated. 4) The anomalies of the mixed layer temperature, salinity and thickness have been illustrated in the all basins. 5) At last, the annual trend of heat content of the mixed layer in the different basins in the Western Mediterranean has been investigated.

## BACKGROUND

The hydrology and the circulation of the Mediterranean Sea water are strongly affected by the surface energy and mass exchange with the atmosphere; the fresh water budget is negative i.e, the loss by evaporation exceeds the input by precipitation and river run-off. The estimated fresh-water deficit amounts to about 2100 km<sup>3</sup>/year, corresponding to a sea level drop of about 1m/year and to a residence time of about 75-100 year ([23] [24], and [25]. The fresh water deficit (about 5.5% of the total inflowing volume) is mainly replenished by the Atlantic surface waters flowing into the Mediterranean having a salinity of 36.2 psu. The Atlantic surface waters flowing into the Mediterranean are subject to evaporation and mixing with the underlying water, causing a progressive increase of the salinity. Also, the intensive convection movements occur under the influence of cold and dray wind (Mistral, Vendavales and Levante) causing the sinking and mixing of the relatively cold and salty

surface waters to depth of about 1200-1500m. The resulting water mass (12.7°C, 38.4 psu) can enter the Mediterranean outflow at Gibraltar without mixing with the Levantine Intermediate water [26].

According to Millot [27], [28] the surface Atlantic water entering the Mediterranean forms, in the Alboran Sea, two anticyclonic gyres [31], [3456]. The eastern side of the Alboran gyre constitute the Almeria-Oran front and [31], [32], the contact between the inflowing Atlantic water and the resident water of the Mediterranean produce a strong density front deflects the modifies Atlantic water flow toward the African coast and originates the Algerian current flowing along the Algerian coast. The current becomes progressively unstable and generates mesoscale eddies both cyclonic and anticyclonic. Observations [33] showed that only the anticyclonic eddies survive, increase in size, propagate eastward and can leave the coast and drift the modifies Atlantic water into the Balearic Basin to contact with more modified Atlantic water in the northern Balearic Basin, giving rise to the north Balearic front.

## DATA AND ANALYSIS

The hydrographic data set used in this work was a smoothed set of hydrocast of temperature and salinity retrieved from the National Oceanographic Data Center and World Data Center — A (Washington D.C). The data file extends from 1932 to 1985. The stability of each retrieved hydrocast had been taken into consideration. A special treatment was given to those levels showing instabilities. Wherever instability was found at any level, a small correction of the temperature or of the salinity was introduced on the basis of the characters of the surrounding values. An operational objective analysis scheme of the iterative difference-correction type [34] was used to analyse the data points. Input to the analysis scheme was the monthly 1/4 degree grid means of data for whatever period was being analysed. Each 1/4 degree grid value was defined as being representative of the center of that particular grid. This analysis scheme is briefly described in the Climatological Atlas of the World Ocean, professional paper 13 [35].

One way to determine the thickness of the mixed layer is to assume a certain amount of temperature difference between the surface and the bottom of the layer. This isothermal

layer, however, does not always correspond to a vertically uniform layer because salinity can govern the stratification of the water column [35], and density criterion may be preferable in some cases. In this paper, the MLD is defined where the potential density is the sea surface density plus a chosen value, [18]. This value is chosen to be a function of sea surface temperature and sea surface salinity. The increments in density when the surface water is reduced in temperature by 1°C with salinity hold constant.

## RESULTS AND DISCUSSION

### 1-Monthly variation of temperature and mixed layer.

(Fig.2 and 3) show monthly averages of temperature to 250 m depth, MTL and MLD in different basins in the Western Mediterranean. A clear seasonal variation is seen for sea surface temperature (SST) and MLT, with lower temperature between December and April and high temperature from May to November. The maximum values occur in August. During the warm months the average SST and MLT appeared much more variation from month to month than in the cold ones (just about 1-2°C in comparison to about 10°C). The SST and MLT after keeping roughly constant from December to April, rise rapidly to have a maximum temperature (about 24.5-24.2°C respectively) after three months. The minimum values can be detected for the all basins in February (about 14°C).

The monthly temperature behaviour at 20 m closely follows that for the SST and the MLT except for the summer period from May to September. During this period, the MLD is shallower than 20 m, and thus cooler. The 20 m maximum values are shifted to September indicative of the slower warming of the interior water. At 50 and 100 m the rate of temperature changes from month to month is very small and the maximum values occur in October and November. At the subsurface layer (200 and 250 m ) the variation of temperature seemed to be constant for all basins.

The Gulf of lions and the Ligurian sea are specific regions, where direct measurements have shown that mesoscale current display a marked seasonal variability [28]. Also, the Northern Current, which is a major component to the circulation in the Western Mediterranean decrease smoothly in Spring-Summer and then rapidly increases in early Autumn [36]. This may be explain the different

characteristic that detected (minimum observed in September and maximum values appear in November at 100, 150 and 200 m) in the Ligurian sea.

The monthly averaged MLD in the different basins in the Western Mediterranean, (Fig: 3). Indicate that the MLD is deep during the cold months and reaches to its maximum during February. The warm period from June to August appeared a shallow mixed layer in all basins. In the Gulf of Lions and Ligurian Sea the MLD is deep to 260 m and shoals to about 50 m in the Alboran Sea. These phenomena are related to the circulation in the two basins, (In Alboran Sea, almost anticyclonic and shows important fluctuation in shape and strength [29] where the northern basin is characterised by intensive exchange with the atmosphere, by a relatively coast circulation and by the occurrence of deep water formation associated with large mesoscale current.

### **2-Monthly variation of salinity and mixed layer.**

The monthly variation of the MLS has a good agreement with the sea surface salinity in the different basins in the Western Mediterranean, (Fig.4). They are characterised by lowering in the heating months and have a higher value in the cold months. The amplitude is larger in the Catalan Sea and Gulf of Lions than the other basins. (1.3 psu in comparison to 0.3 psu). The low values of salinity appeared in these two basin may be result to local run off. In general, the minimum salinity appears between May and November. The monthly variation of salinity in the subsurface levels along the whole area shows the same character of the sea surface and the MLS, with higher values and lowering in amplitude.

The Tyrrhenian basin act as a reservoir for incoming Livantine Intermediate Water, [37] and thus MLD extended to about 200 m in this basin. From these we can explain the higher values of MLS than the sea surface salinity in the Tyrrhenian basins.

### **3- Correlation coefficients of MLT and MLD with surface and subsurface parameter.**

Table (1-a and b) shows the correlation coefficients for the MLT with SST and subsurface layers during cold and warm months.

During the cold months, the correlation coefficients vary markedly with layers and with different basins in the Western Mediterranean. Higher correlation coefficients with subsurface temperature to 50 m for all basins are seen. The two anticyclonic gyres detected in the Alboran Sea, [30], that eastern side constitute the Almeria-Oran Front [31,32], may be the reason for thig correlation observed in this basin and extended to 100 m depth. In Gulf of Lions, Liguro-provenical Basin and Catalan Sea the higher correlation coefficients are extended to 250 m depth. These phenomena may by due to the strong cooling wind (mistral) and the mixing effect caused by cyclonic pattern of circulation in the North western Mediterranean. The negative correlation coefficients observed in the Algerian Sea from 150 to 250 m indicate the existence of anther water mass (LIW) that occupied the subsurface layer from 150 m or the effect of the big anticyclonic gyre that occupied this basin and could remain almost stationary for several months. As the solar and the mixing effect of wind shape the temperature profile in the warm months, a high correlation coefficient is found to 50 m only in the all basins. During the warm months, the negative correlation coefficients could be detected from 100 m depth in the different basins with one exception related to the basins are located in the North Western Mediterranean.

During the cold months, a high correlation of MLD with subsurface temperature, Table (2-a and b) can be seen to 250 m in the Gulf of Lions as for MLT with subsurface temperature. Also, high correlation to 50 m could be observed in Tyrrhenian and Liguro-Provincial Basin. For all basins, coefficients of MLD with SST are positive in cold months and negative in hot period. This phenomena is expected science Summer heating that inhabit mixed layer formation and winter cooling aids it.

During the warm months, insignificant correlation could be detected at the all levels in the whole area in the Western Mediterranean Sea.

### **4-Anomalies of mixed layer temperature, salinity and thickness**

The monthly mean mixed layer temperature, salinity and thickness are calculated for the period from 1932 to 1985. From these values, the mean monthly mixed layer temperature, salinity and thickness are determined. The

deviation from the mean is computed and considered as the anomalies of mixed layer temperature, salinity and thickness ( $\Delta T = T - T'$  for example). The positive mixed layer temperature anomalies, (Fig 5), can be detected during the cold months while the negative anomalies are seen in the warm period. In all basins, the minimum anomalies, (-6.0°C), are detected during August. In general, the anomalies of the mixed layer salinity revealed the opposite trend has been obtained by mixed layer temperature anomalies. Also, the anomalies of the mixed layer thickness showed the same trend as salinity. The temperature and the thickness of the mixed layer have a weak inverse correlation. This result is reasonable; the decrease of temperature due to active heat release corresponds to the growth of the mixed layer thickness and salinity values. To qualitative clarify the relationship between the evolution of mixed layer of the Western Mediterranean and air-sea heat transfer is a very important subject to is investigated in the future.

**5- Mixed layer depth and heat content**

The heat content plays an essential role in the dynamics of the Oceans. A few works have addressed this subject in the Western Mediterranean Sea. Pico, [38] studied the heat storage in the upper 0-100 and 300 m layers in the Western Mediterranean. He discussed the annual trend of the monthly mean heat storage and the geographic distribution of the amplitude of the annual signal.

The heat content in the mixed layer is estimated at any point by utilizing the following equation.

$$HC = \rho C_p \int_D (T - T_R) dz$$

where

HC heat content Jm<sup>-2</sup>

$\rho$  water density

$C_p$  specific heat J kg<sup>-1</sup> K<sup>-1</sup>

T water temperature °C

D mixed layer depth m

The reference temperature  $T_R$  is chosen as the monthly mean MLT. The annual trend of the monthly mean heat content for different basins in the Western Mediterranean, (Fig. 6), shows that the heat content is higher in cold months than in the warm months. The maximum heat content can be detected between February and April for the all basins except the Alboran Sea. In Alboran Sea, two

maximums can be detected in February and November (about 8.0E+07 and 9.0E + 07 Jm<sup>-2</sup>). The lower values that detected in the Alboran Sea in comparison to the other basins are related to the small thickness of the mixed layer in this basin.

It must be mentioned that the heat sources in the upper layer are mainly solar radiation through the surface and advective from the west by the modified Atlantic water. Also, it is clear that, the annual trend for the heat content at the mixed layer have a strong relationship with the MLD.

**SUMMARY AND CONCLUSIONS**

On the basis of hydrographic observation data for the period extend up to 1985, the monthly variations of temperature, salinity structure and the mixed layer in the Western Mediterranean Sea were presented. The correlation coefficient of the MLT and MLD with surface and subsurface layers in different basins during the cold and warm months has been calculated. The anomalies of the mixed layer temperature, salinity and thickness have been illustrated in the all basins. At last, the annual trend of heat content of the mixed layer in the different basins in the Western mediterranean has been investigated. The main results can be summarised as follows:

- 1) The seasonal variations of SST and MLT showed a lower value between December and May with minimum values appear in the different basins in February (average 14°C). After that, the temperature values of the SST and MLT are rises to reach its maximum in August (average 24.5°C). The behaviour of temperature of water among 50 and 100 m is weekly seasonal with maximum values occur in October and November. In general, the seasonal variations of the subsurface layer (150, 200 and 250 m) are seemed to be constant in the all basins.
- 2) The seasonal variations of the MLS are characterised by lowering in the warm season and higher in the cold months. The amplitude is larger in both Catalan Sea and Gulf of Lions. In Tyrrhenian Sea, the MLS has a higher value than the sea surface salinity. Also, the effect of Atlantic water is clearly identified in both Alboran and Algerian Seas, while the strong mixing in the North Western Mediterranean raises the salinity values in the sea surface layer and the MLS in these basins.
- 3) MLT fields appear to bear sufficient relation to

subsurface structure to 50 m in the whole area during the cold and warm seasons. In Gulf of Lions, Liguro-Provençal Basin and Catalan Sea, a high correlation can be seen to 250 m depth.

- 4) Highest correlation of MLD temperature layer to 250 m depth can be detected in the Gulf of Lions during the cold season. However, insignificant relation between the MLD and the subsurface layer is observed during the warm months. The positive anomalies of MLT are detected during the cold months, while the negative ones are noticed in the warm season with minimum negative values (about  $-6.0^{\circ}\text{C}$ ) occurred in August in all basins. The anomaly of MLS appears to reveal the opposite trend obtained by anomalies of MLT. Also, the anomalies of MLD showed the same trend of salinity. So, the temperature and thickness of the mixed layer have a weak inverse correlation.
- 5) The annual trend of the heat content revealed a high value in the cold season. The maximum heat content ( $2.9\text{E}+08 \text{ j m}^2$ ) can be detected in the North Western Mediterranean basins between January and April. The lower value of the heat content that detected in the Alboran Sea is related to the small thickness of the mixed layer in this basin.

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**Table 1**  
**Correlation coefficients of mixed layer temperature with sea surface and subsurface temperatures., a) cold months, b) warm months.**

a	0	20	50	100	150	200	250
Alboran Sea	0.98	0.98	0.79	0.71	0.59	0.39	0.04
Catalan Sea	0.89	0.92	0.92	0.81	0.84	0.71	0.96
Algerian Sea	0.97	0.97	0.86	0.22	-0.44	-0.74	-0.63
Gulf of Lions	0.99	0.99	0.98	0.75	0.82	0.08	0.94
Ligurian Sea	0.97	0.97	0.84	0.51	0.43	0.48	0.67
Liguro-Provencial Basin	0.97	0.98	0.97	0.94	0.92	0.81	0.73
Tyrrhenian Sea	0.98	0.97	0.92	0.77	0.68	0.79	0.81
b	0	20	50	100	150	200	250
Alboran Sea	1	0.75	0.94	0.17	-0.08	-0.38	-0.28
Catalan Sea	0.99	0.79	0.86	0.74	0.57	0.53	0.35
Algerian Sea	1	0.91	0.63	-0.93	-0.91	-0.97	-0.23
Gulf of Lions	0.95	0.27	0.83	0.59			
Ligurian Sea	1	0.82	0.97	-0.17	-0.82	-0.43	-0.71
Liguro-Provencial Basin	1	0.82	0.66	0.54	0.09	0.13	0.54
Tyrrhenian Sea	1	0.83	0.62	-0.82	0.07	0.77	0.9

**Table 2**  
**Correlation coefficients of mixed layer temperature with sea surface and subsurface temperatures., a) cold months, b) warm months.**

a	0	20	50	100	150	200	250
Alboran Sea	0.57	0.46	0.16	0.14	0.04	0.01	0.01
Catalan Sea	0.55	0.5	0.43	0.46	0.5	0.76	0.57
Algerian Sea	0.74	0.7	0.53	-0.38	-0.67	-0.94	-0.63
Gulf of Lions	0.88	0.87	0.88	0.68	0.87	0.89	0.85
Ligurian Sea	0.66	0.61	0.48	0.29	0.21	0.25	0.36
Liguro-Provencial Basin	0.72	0.71	0.65	0.55	0.49	0.29	0.27
Tyrrhenian Sea	0.73	0.68	0.64	0.57	0.54	0.51	0.69
b	0	20	50	100	150	200	250
Alboran Sea	0.57	-0.13	0.25	0.49	0.62	0.06	0.32
Catalan Sea	-0.41	-0.82	-0.74	-0.86	-0.32	-0.05	-0.66
Algerian Sea	-0.11	-0.52	0.51	-0.13	-0.05	0.21	-0.01
Gulf of Lions	0.5	0.85	0.24	0.1	-----	-----	-----
Ligurian Sea	0.74	0.34	0.82	0.4	-0.24	-0.65	-0.79
Liguro-Provencial Basin	-0.49	-0.92	-0.98	-1	-0.85	-0.82	-0.95
Tyrrhenian Sea	-0.22	-0.74	-0.87	-0.25	-0.66	-0.66	-0.39



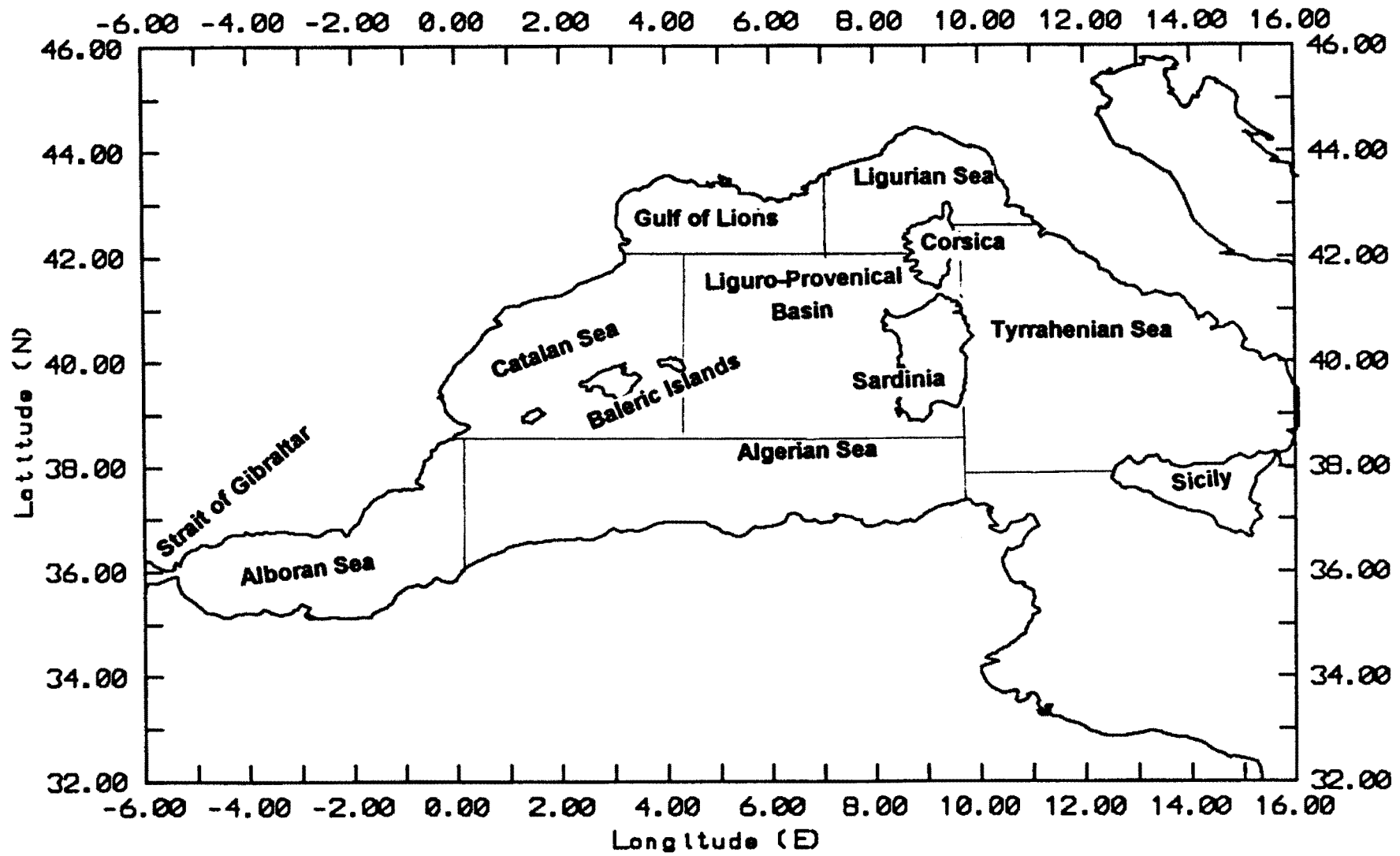
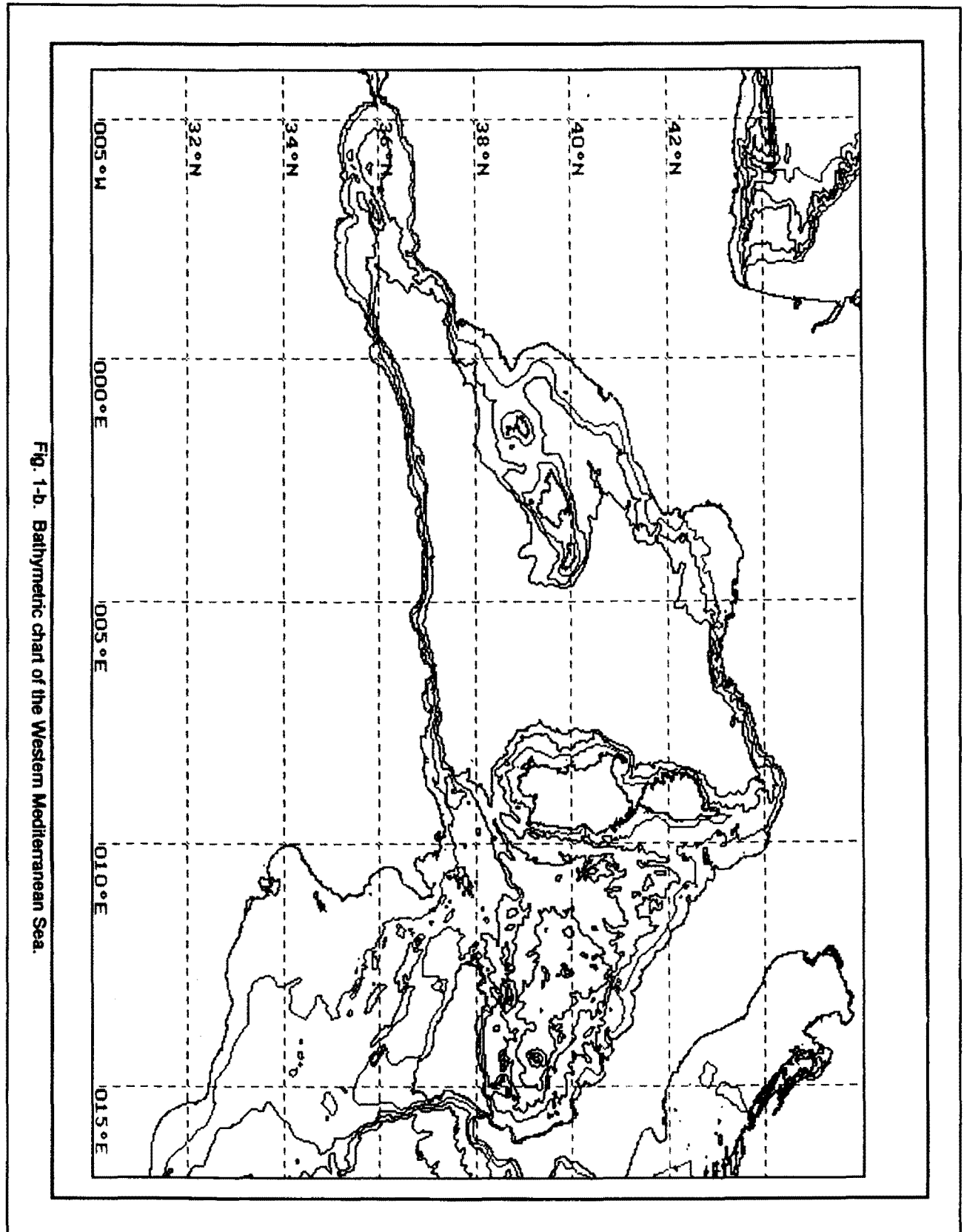


Fig. 1-a. The Western Mediterranean Sea.



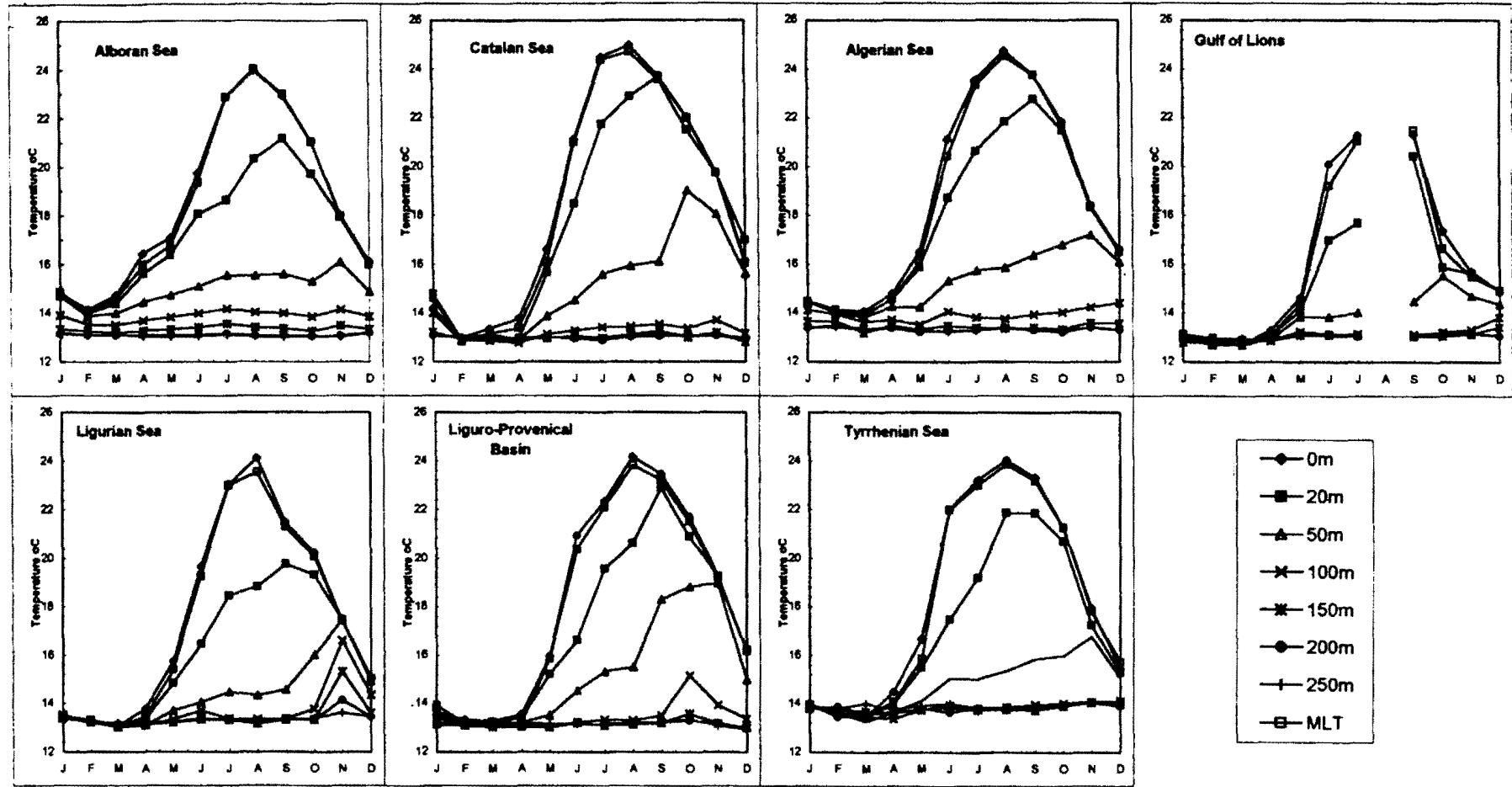


Fig. 2. Average monthly temperature at selected depths to 250 m and average monthly mixed layer temperature in different basins in the Western Mediterranean Sea.

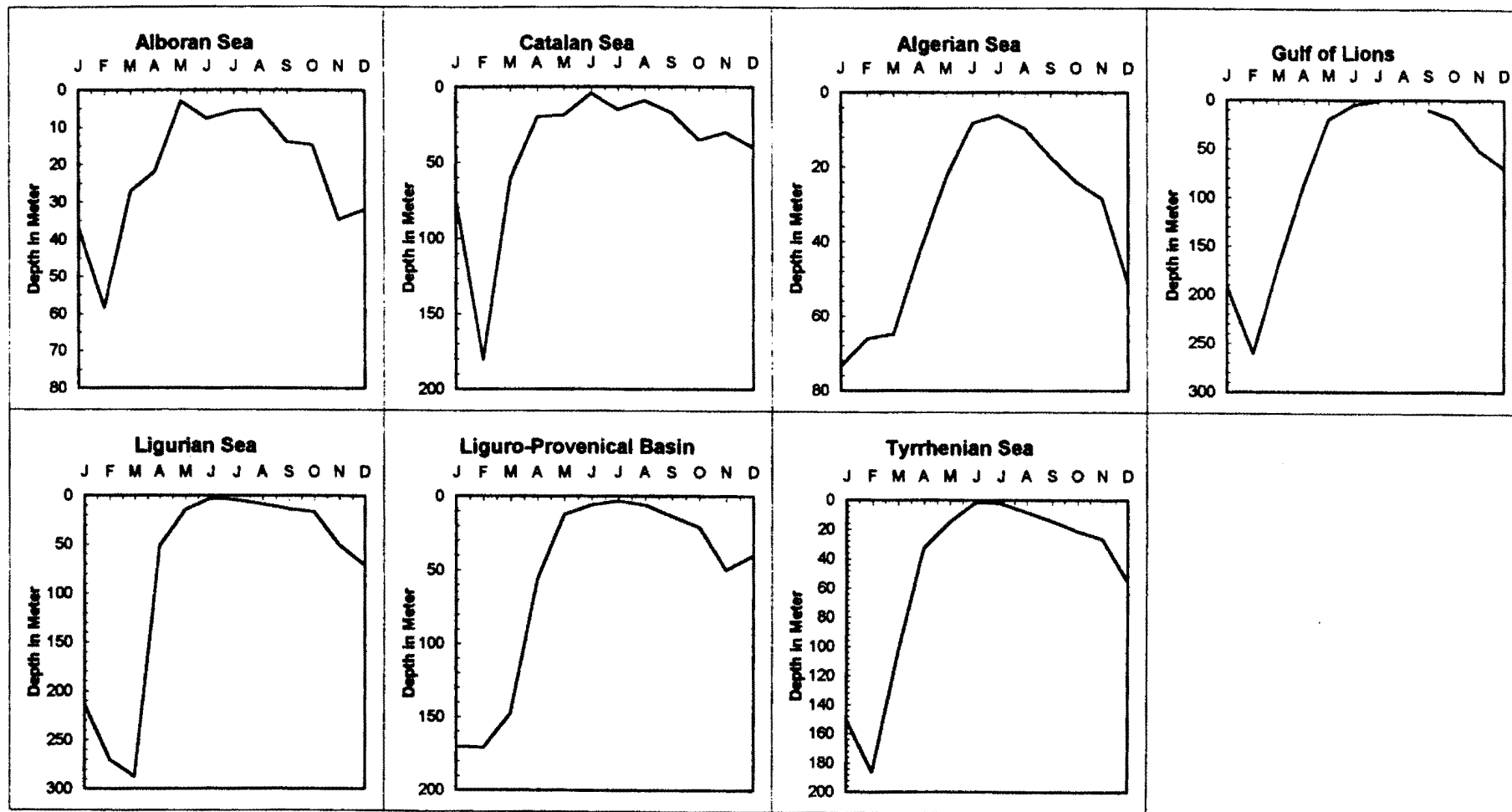


Fig.3. Average monthly mixed layer depth in different basins in the Western Mediterranean Sea

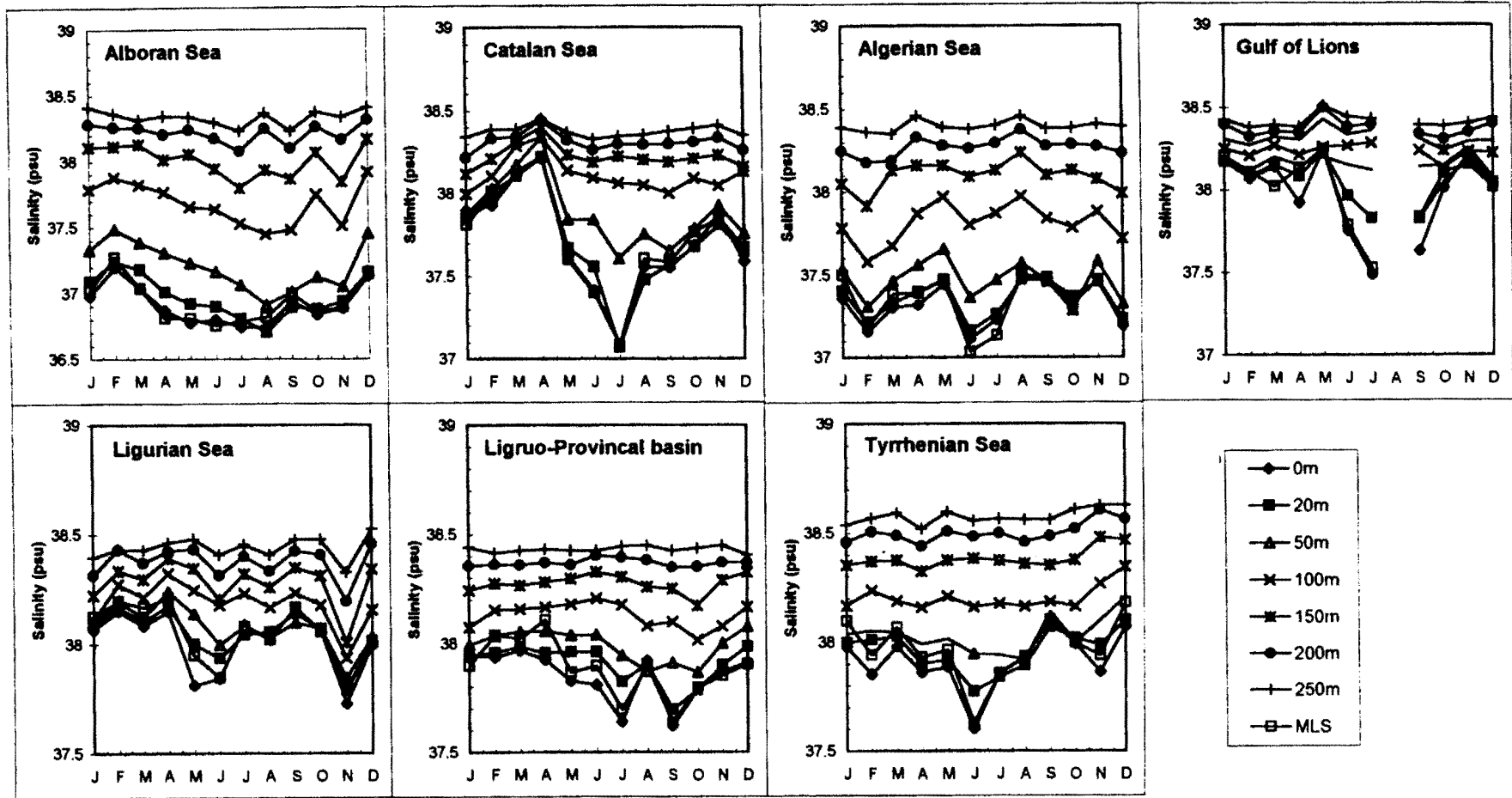


Fig. 4. Average monthly salinity at selected depths to 250 m and average monthly mixed layer salinity in different basins in the Western Mediterranean Sea.

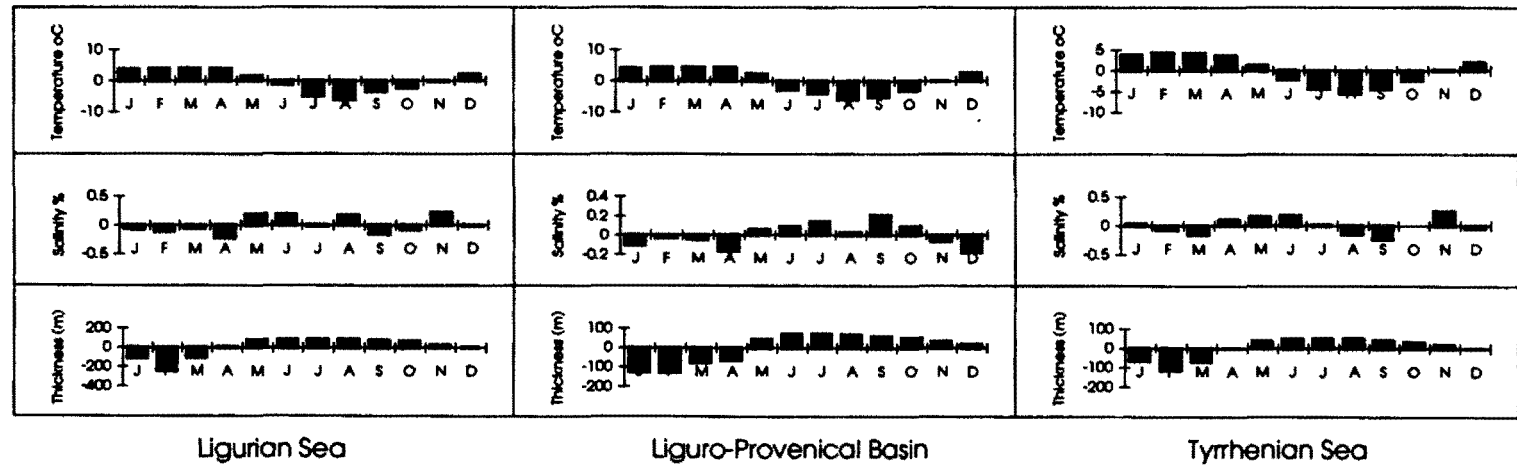
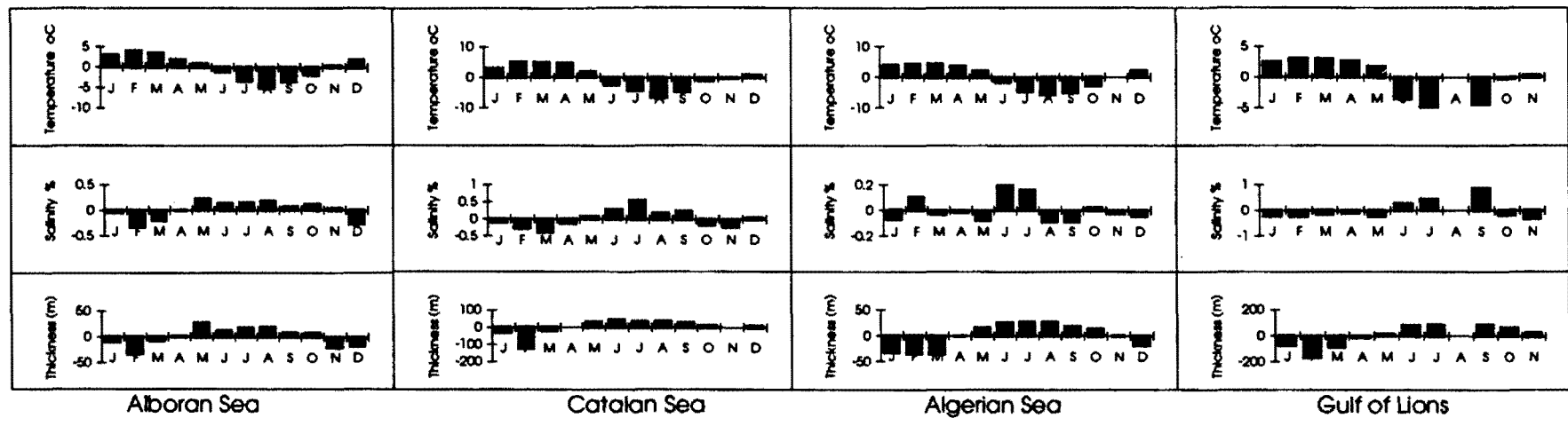


Fig. 5. The monthly variations of anomalies at the mixed layer temperature, salinity and thickness in different basins in the Western Mediterranean Sea.

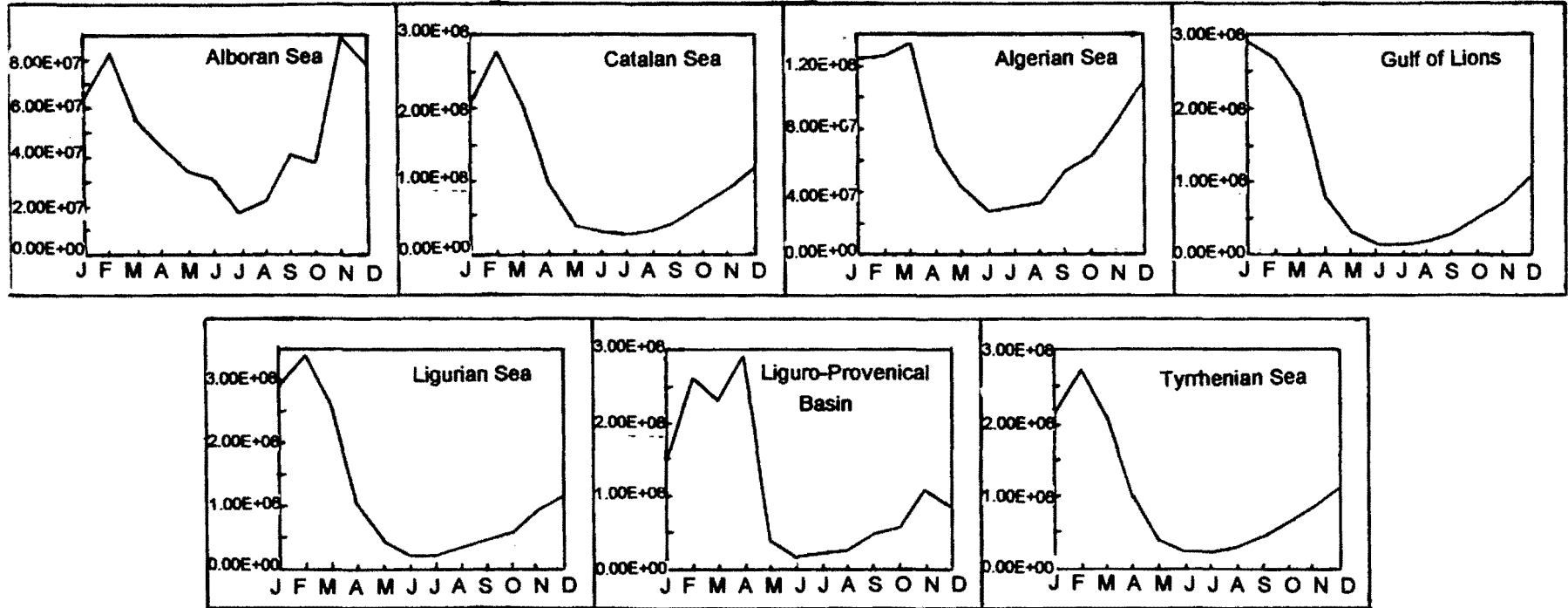


Fig. 6. The monthly variations of the heat content at the mixed layer in different basins in the Western Mediterranean Sea. ( $\text{J m}^{-2}$ )