A REVIEW OF THE DYNAMICAL ASPECTS OF THE BOSPHORUS

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1. INTRODUCTION

The exchange of waters between the Mediterranean and the Black Seas takes place through the Dardanelles - the Sea of Marmara - the Bosphorus (DMB) system (Fig.1). The strait of Dardanelles is 60 km in length and communicates in the south with the Aegean Sea which is considered here as part of the Mediterranean. The extent of the Sea of Marmara from its junction with the Dardanelles to its junction with the Bosphorus is 210 km and covers a surface area of 11000 km^2 (Fig.2). The Bosphorus is 31 km in length and constitutes the smallest component of the DMB system in size.

The fundamental reason for the exchange between the Black and Mediterranean seas through DMB system is well-known. The heavier, highly saline waters of the Mediterranean formed as a result of the excess of evaporation over precipitation and run-off flows north through DMB system as a bottom current to attain its own level. The inverse situation existing in the Black Sea in return leads to a southward surface flow of the lighter and less saline waters. The means and the ways by which the Bosphorus affects the exchange between the Mediterranean and the Black Sea as a component of the DMB system is the main concern of this review.

The Sections 2 and 3 of the present review essentially summarize the available data and the findings that are based on the field observations. In Section 2 the general characteristics and the factors influencing the Bosphorus are considered. The oceanographical features of the strait including the regions near the two ends are summarized in Section 3. The model studies are covered in Section 4.

2. GENERAL FEATURES

2.a. Geometrical Characteristics.

The Bosphorus is not a straight passageway (Fig.3). In addition to its meandering over its length, a series of embayments located along its banks leads to rythmic variations in its width. The width of the strait varies between 0.7-3.5 km with an average of 1.6 km. The width to length ratio is therefore relatively small in comparison to the other straits. A small estuary - the Golden Horn-terminates near the southern tip of the strait, the influence of this estuary on the overall hydrological budget being relatively insignificant.

The depth of the Bosphorus changes in both the transverse and longitudional directions (Fig.3). The mid-cross-sectional depths are larger in the northern parts of the Bosphorus. The average depth is 35.8 m while the maximum depth is 110 m (Gunnerson and Özturgut, 1974). Two sills are well pronounced. One of these sills with 32 m depth is located about 3 km north of the Marmara-Bosphorus junction. The other sill of 50 m depth is actually located at about 4 km from the northern entrance. Both sills play a significant role on the dynamics.

2.b. Atmospheric Factors

The regional wind conditions influencing the DMB system are dominated by northerlies from the Black Sea and occasional southerly to southeasterly winds from the Aegean Sea. The northerly winds pronounced particularly in summer are part of the Etesian winds in the Aegean. It results from a combination of a permanent low pressure center over the Red Sea region with higher pressure over the eastern Europe

The water exchange through the Bosphorus has considerable variation throughout the year. The largest flow toward the Aegean Sea occurs mainly in spring and to a lesser extent in summer corresponding to periods in which the precipitation and river runoff discharged into the Black Sea increase substantially. The average Black Sea outflow and inflow through the Bosphorus have been estimated by Möller (1928) as being 12600 m^3/sec (or 398 km^3/year) and 6100 m^3/sec (or 193 km^3/year), respectively. The values given by Özturgut (1971) are somewhat higher. Assuming 17.5 ‰ average salinity for the upper layer flow in the Bosphorus and using Özturgut's data, Sümer and Bakioğlu (1981) calculated corresponding flow rates as 17400 m^3/sec (or 548 km^3/year) and 7900 m^3/sec (or 249 km^3/year) by simultaneous solution of mass and salt balance equations for the Black Sea. The other estimates shown in Table 1 lie within these two ranges reported respectively by Möller (1928) and Özturgut (1971). United States Navy Hydrographic Office, on the other hand, reported that the flow in either direction varies between 3000 m^3/sec to 30000 m^3/sec. Because of lack of long term current measurements, the more precise inflow and outflow rates and their temporal variations are, however, not known.

In general terms, slightly saline Black Sea water with 17‰ salinity flowing through the Bosphorus as a surface layer enters to the Marmara with 20‰ - 25‰ salinity. While crossing the Sea of Marmara and Dardanelles its salinity rises to about 27‰ - 30‰ and finally leaves the Dardanelles with 35‰ salinity (Defant, 1961 ; Rojdestvensky , 1971). The flow entering into the Aegean Sea is about 190 km^3/year (Tixeront, 1970) and should have a negligible effect on the total water and salt balance of the eastern Mediterranean.

3. OCEANOGRAPHIC CHARACTERISTICS

3.a Sea Level

Sea level differences between the two ends of the Bosphorus have been studied by Möller (1928), Bogdanova (1965), Gunnerson and Özturgut (1974). Möller estimated an average sea level difference of 6 cm. Based on long term compilations of monthly-averaged sea level data, Bogdanova (1965) has found a mean sea level difference of 42 cm with considerable variation throughout the year. According to Bogdanova (1965), the sea level increases from March to June reaching to a maximum value of 57 cm in accordance with increasing run-off from the Black Sea tributaries. Sea level tends to decrease after June and reaches a minimum of 35cm in October and November. Most rapid variations in the sea level evidently occurs between June and July.

Bogdanova (1965) seemed to have overestimated the sea level differentials. Gunnerson and Özturgut (1974) provides a series of careful measurements carried out at 7,15 and 24 km from the southern tip of the Bosphorus during July 1966 to February 1968. Based on this data, the average surface slope is estimated to be 1.12 cm/km, implying 35 cm sea level difference between the two ends of the Bosphorus.

Utilizing DAMOC (1971) data, Çeçen et al (1981) estimates an average sea level difference of 33 cm with a standard deviation of 13 cm.

Surface slope reversals sustained for a few days during strong southerlies are common. The spectral analyses reveal the existence of semi-diurnal fluctuations of O(2-10 cm) with large diurnal inequality. Lunar fortnightly tides of O(5-20 cm) are also observed. A 63 minute seiche also contributes to the relatively small high frequency variations in the sea level. Further details on surface height variability can be found in DAMOC Report (1971).

3.b. Temporal Variations in Local Salinity and Temperature Values

Salinity and temperature characteristics of the surface water along the Bosphorus are highly variable both in space and time. The amount of outflow and stratification in the Black Sea as well as pronounced short-term southerly or northerly wind episodes affect considerably the upper layer density structure in the Bosphorus. The bottom waters of the Mediterranean origin, on the other hand, flow through the Bosphorus without much change in character and are identified by approximately 35 - 38.5‰ salinity and 14.5 - 15 ^{o}C temperature values.

Surface salinity -temperature variations for the years 1967-1970 at a station 11 km from the southern entrance is given in Figure 4. The average annual salinity is about 17.5‰ and decreases to the values of 16-17‰ during the summer, lasting from June to August, corresponding to a period in which highest level of river discharges occur into the Black Sea. The surface salinities are found to be almost above the average for the rest of the year and take on values of 17.5-19‰. Some short-term peak values as high as 25 ppt (not shown in Fig.4) also appear due to the strong southerly winds in winter.

Typical seasonal variations of temperature and salinity dictating the two-layer stratification in the Bosphorus are given in Figure 5 at a station located about 12km south of the Black Sea entrance. As far as the temperature variations are concerned, the winter season is characterized by almost uniform cold surface waters having temperature values of 9-10 ^{o}C above relatively warmer (15 ^{o}C) Mediterranean waters. Increased radiational heating during late spring and summer months first heats the upper parts of the surface waters and results in a temperature inversion layer, and then affects all of the upper layer waters to form a new two-layer structure in temperature with a sharp thermocline between the layers. The autumn season is a transitional period in which the surface waters start to be cooled.

3.c. Flow and Stratification characteristics

The well known feature of the Bosphorus is the two-layer current system associated with the two-layer stratification (Fig.6). The basic mechanism leading to the two-layer current system within the strait is well documented and understood. The flow from the Black Sea to the Sea of Marmara is driven by the pressure gradient induced by the higher surface elevation existing at the northern entrance. The pressure gradient at the lower levels changes sign because of the density difference between the Black Sea and the Sea of Marmara, leading to a bottom current and an interface that slopes down towards the Black Sea. This mechanism was first suggested by Merz (1918, 1921) and Möller (1928) following the earlier studies of Spratt (1870), Makarov (1885), Wharton (1886), Gueydon (1886) and Magnaghi (1894).

The magnitudes of the velocities of the two-layer system vary seasonally and with distance along the strait. Under calm weather conditions, the upper layer velocity tends to be largest at the surface, with values 40-50 cm/s near the northern entrance. In the vicinity of the Bosphorus-Marmara junction, currents in excess of 50 cm/s exist. Values of upto 250 cm/s are reported in the DAMOC Report (1971). The surface currents are greatly influenced by the northerly and the southerly winds. The winds from the south evidently causes strong mixing in the upper layer and considerably weaken the surface flow. Depending on the flow rate, occasional reversals are observed (Pektaş, 1953). On the other hand, during strong northerlies the surface currents increase in magnitude, reaching values of up to 100 cm/s near the northern entrance and 350 cm/s near the southern entrance (the Black Sea Pilot, 1955). Changes in the currents induced by the strong winds are however transient, lasting only a few days.

The lower layer current has been reported to have magnitudes of upto 100-150 cm/s (Möller, 1928). Carruthers's (1963) measurements imply smaller velocities of 0(4 cm/s) near the Bosphorus-Marmara junction and of 0(75 cm/s) near the northern end. Needless to say, the meanders of the strait largely influence the velocity field. In the embayments, counter currents of 0(30 cm/s) and the associated small scale gyres are the persistent features of the system at large.

Möller's (1928) studies as well as those carried out by Bogdanova (1965), Gunnerson and Özturgut (1974), Çeçen et.al., (1981) reveal the existence of a sharp density transition between the surface and the bottom waters of the Bosphorus.The respective average densities of the upper and lower layers are 1.013 and 1.028 gm/cm^3, implying a relative density difference of 0.014 gm/cm^3. The typical interface slope estimated by Möller (1928) is 1.13 m/km which is higher than 0.97 m/km estimated by Çeçen et.al.,(1981) and smaller than the DAMOC (1971) estimate of 1.6 m/km. The measured slope of the interface is essentially linear along most of the strait, with rapid variations in the interfacial height occuring at the two ends. This is in accord with most of the theories (Sec.4). The variation of the interfacial slope with seasons will be discussed shortly (Sec.3.d).

The sharpness of the interface as well as the salinity/temperature difference between the two layers varies along the strait (Gunnerson and Özturgut, 1974) (see also DAMOC Report, 1971 for a more detailed coverage). Considerable mixing across the interface evidently occurs along the strait as it is reflected by a typical 0(2 ppt) difference in the upper layer salinities of the two extreme ends (Gunnerson and Özturgut, 1974). The lack of reliable current data prevents the computation of Richardson numbers. Consequently, it is not possible to ascertain in detail the spatial-temporal mixing characteristics experimentally. It is worth pointing out also that lateral mixing resulting from meandering features of the strait is well evident in the existing data.

Another feature of the two-layer system in the Bosphorus is the separation of the current and the density interfaces (Defant, 1961, p.523). The latter, having a greater slope, raises southward and intersects the current boundary at the narrowest part of the strait. Tolmazin (1981) attributes the separation of the two interfaces to the entrainment at two ends of the strait. Because of this feature, the water masses should be partially advected back to the seas of their origin. As a result, the wedges of the waters emanating from the Bosphorus should become thinner. Tolmazin (1981) regards this as an inhibiting factor for the Black Sea whose salt balance critically depends on the exchange through the Bosphorus. It is worth pointing out that in the absence of reliable current data, the separation of the current and the density interfaces is mostly based on the theoretical model of Tolmazin (1981) (see also Sec.4).

3.d. Interaction with the Black Sea.

The northern sill extending in a semi-circular fashion from the Thracian to the Anatolian coast, having an apex 4 km north of the Bosphorus-Black Sea junction and a depth of 50 m evidently plays a crucial role on the fate of the Mediterranean waters. After the initial studies of Merz and Möller, objections with regard to the extent and the nature of the Mediterranean waters issuing from the Bosphorus have been raised by Ullyott and Ilgaz (1943a, 1943b, 1946a, 1946b), Ilgaz (1944) and Ullyott (1953). Ullyott and Ilgaz claimed that 75 percent of the mediterranean flow is returned back to the Sea of Marmara as a result of the blocking by the northern sill. It was also asserted by Ullyott and Ilgaz that only during the cases of strong southerlies (inducing small surface level differences), substantial amounts of waters of the Sea of Marmara reaches the Black Sea.

Pektaş (1953, 1956) claimed that the Ullyott- Ilgaz hypothesis should be valid during March - August coinciding with the times of increasing outflows from the Black Sea. The essential idea behind this claim is that increasing sea level elevation at the Black Sea entrance should lead to the further downward tilting of the interface. As a result, the slope of the interface may increase to a value of 39 m/30 km in the spring and the interface may even intersect the bottom and a salt-wedge type salinity structure may form in the Bosphorus. The interfacial slope is smaller in late Autumn and winter with an average value of 20 m/30 km (Çeçen et.al., 1981). Measurements made by Pektaş (1953) at a station 16 km from the southern end of the Bosphorus during January 1953 revealed a two - layer normal state of stratification, while a single water mass of Black Sea origin having salinity 17.5 ppt at all depths was observed during March 1953. Even though the possibility of a salt wedge formation with increasing outflows from the Black Sea can be anticipated, the fact that it was observed in early March at a mid-point in the

Bosphorus raises doubts with regard to what has actually been observed. Maximum surface discharges at the Bosphorus occur in July to August, indicating a travel time of 2 months from the Danube where peak dicharges were recorded in May during the period 1928-1959 (Gunnerson and Özturgut, 1974 and Özturgut, 1966). It is indeed diffucult to envision flows in March pushing the Mediterranean waters to the mid-point of the Bosphorus. It is quite possible that what was actually observed by Pektas is due to the meandering of the bottom flow (see DAMOC data, 1971 and Gunnerson Özturgut, 1974)

Bagdonova (1961,1967, 1969a,b, 1974) has raised strong objections to the Ullyott - Ilgaz hypothesis and the Pektaş' version of it. Utilizing all the available data obtained to the north of Bosphorus-Black Sea junction, Bagdonova claims that the Mediterranean water enters the Black Sea as a well-defined plume along the bottom and is in fact not blocked persistently by the northern sill. Bagdonova (1969a) maintains that the physical mechanism responsible for the raise of the Mediterranean flow over the northern sill is the horizontal divergence caused by the bifurcation of the flow impinging onto the northern end of the Bosphorus (Fig.1). After flowing over the sill, the Mediterranean waters flow towards northwest and is eventually entrained into the large scale circulation towards northeast. However, considerable mixing is induced over the shelf because of the presence of the northern sill. As a result, the Mediterranean waters become higly diluted within 25-50 km from the Bosphorus. This water can then be characterized by temperatures (9.92^{o} to 10.14^{o}C), salinities (22.12 to 22.30 ppt) and 0.11 to 0.37 ml/l oxygen content, joining the depths of 500 m to form the abyssal water mass (Bagdonova, et al, 1967; Rojdestvensky, 1971; see also Tolmazin, 1974 and the references cited therein).

Bagdonova has supplemented her assertion on the blockage over the northern sill by a one-dimensional analytical model which is essentially a salt-wedge analysis giving the critical conditions for the formation of the wedge (Bagdonova, 1974). It is found that the blockage can occur only when the upper layer velocity in the vicinity of the northern entrance exceeds a value of 60 cm/s, occuring under most favourable conditions three to four days a year during intense storms.

Recent measurements carried out by the Hydrographic Office of the Turkish Navy and reported in Çecen et al (1981) and Beyazıt and Sümer (1982) have revived the blockage controversy. Çecen et al (1981) noted that in the measurements made during April, 1980, the saltier waters of the Sea of Marmara were absent at stations north of Büyükdere, located 7 km north of the Pektaş (1953) station at Kanlıca (Fig.3). Reservations were made by Çeçen et al (1981) with regard to what the measurements dictated. This is because, only one station was occupied at each cross-section with the station depth not necassarily being the maximum depth of that cross-section. Consequently, a new series of measurements were made during May 1981. Four stations located along the cross-section X in Fig.3 which is situated 2.5 km south of the Bosphorus - Black Sea junction were occupied. The result of these measurements are displayed in Fig.7. It is seen that even in the deepest station salinity does not exceed 18 ppt and a two-layer structure is definetely absent.

It is only unfortunate that the measurements reported in Beyazıt and Sümer (1982) do not encompass regions to the south as well to the north of the stations occupied during May, 1981. However, there is little doubt that these measurements definitely establish a complete blockage of the Mediterranean waters during specific times of the year at the upper reaches of the Bosphorus. Evidently, the concepts initially proposed by Pektaş (1953) are valid even though his measurements may not be considered as supporting evidence.

The determination of the periods during which the blockage occurs still awaits reporting of data taken in a systematic manner. Nevertheless, as Pektaş has suggested, the mechanisms for its occurance should be intimately related to the raising stages at the northern entrance during the times of excess run-off from the tributaries of the Black Sea. Moving on this premise, Sümer has developed an analytical model that in particular produces the discharges in the two layers and the interfacial height (h_1) as a function of the surface elevation difference (h) between the two ends of the strait (Sümer and Bakioğlu , 1981, Çeçen et al, 1981, Beyazıt and Sümer, 1982). The pertinent results of this model are displayed in Fig.8. It is seen that with increasing h, the discharge in the lower layer decreases while the interfacial height h_1 (measured from the water surface) increases. When the surface level difference h exceeds a critical value of 45cm, the discharge in the lower layer diminishes, leading to the formation of a salt wedge. The corresponding discharge in the upper layer is $Q_1 \simeq 31x10^3$ m^3/s and this value is very close to the maximum discharges that have been reported (sec.2c). In order to have an idea of the corresponding critical velocities at blockage, we consider the cross-section X where the observations reveals the existence of a salt-wedge during May 1981. The area of the cross-section X is ~$56x10^3$ m^2 (DAMOC, 1971). The critical velocity is thus 55 cm/s. This value is quite close to the Bagdonova's(1974)critical velocity of 60 cm/s. It appears, therefore, that what has been thought as exceptional by Bagdonova (1974) may not after all be very exceptional. This is especially true in view of the observations indicating O(50 cm/s) velocities at the northern entrance even during calm weather conditions. In any event, detailed long-term field observations are much desired, especially in view of the impending problems associatied with the utilization plans such as the diversion of the Black Sea run-off (Tolmazin, personal communication), and sewer discharge into the lower Bosphorus current (Beyazıt and Sümer, 1982).

3.e. Interaction with the Sea of Marmara

Relative to the exit-entry conditions near the northern entrance, lesser attention has been paid to the prevailing state of affairs in the region to the south of the Bosphorus-Marmara junction (hereafter referred to as the BMJ region). It appears that the DAMOC Report (1971) and a study by Artüz (1977) are the only systematic investigations of the physical oceanography of this region that have been published, containing a judicious blend of data and interpretations. In the DAMOC Report the relation of the BMJ region to the Sea of Marmara at large is also considered. The pertinent findings in these studies as well as that has been recently carried out by Ünlüata et.al.(1983) are reviewed in this section.

The principal bathymetric features of the BMJ region involve a shallow coastal area extending up to 5 km from the coast to a depth of 20-30 m, followed by a deeper shelf area which terminates at a 100 m depth from a distance varying up to 10 km from the coast (Fig.9). The deeper waters (~ 1000 m) of the eastern sea of Marmara is then rapidly joined. All these regions are concave northward. A submarine canyon extending from BMJ to a depth of 70 m is also an integral part of these topographical features.

The region is triangular in shape on the horizontal plane, with the southern tip of the Bosphorus defining its apex.

The results of the DAMOC Report (1971) together with the recent studies carried out by Ünlüata et al (1983) lead to the following conclusions on the regional flow structure.

In the absence of the strong local southerlies, it appears that the Black Sea waters emanating from the Bosphorus tend to spread assymmetrically into the BMJ region, with more intense currents tending to concentrate initially towards the Anatolian coast. The surface flow, initially attached to the Anotolian coast, curls around in the neighbourhood of the Prince Islands to proceed westward along the northern coast of the Sea of Marmara. The principal feature of this surface current in the BMJ region is an anti-cyclonic gyre inshore of the westward curling main Bosphorus flow. This circulatory pattern is sketched in Fig.10.

The surface flow structure decribed above is constructed by putting together the following pieces of information.

(i) Using the salinity - temperature meridional section near E28° 40′ obtained by the Turkish Meat and Fish Cooperation as well as the data reported by U.S. Navy Oceanographic Office, it is shown in the DAMOC Report (1971) that after leaving the BMJ region the Black Sea waters in general flow along the northern coast of the Sea of Marmara. By way of example, we produce in Fig.11 the salinity - temperature measurements made along the meridional section near E28°40′ during March 21,1960. The attachment of the low salinity, colder Black Sea waters to the northern Marmara coastline is clearly demonstrated in the Fig.11. It is also pointed out in the DAMOC Report that in summer the Sea of Marmara sigma-t sections indicate the presence of a large scale cyclonic circulation which may strengthen the coastally attached Bosphorus outflow.

(ii) The preferential intensification of the Black Sea waters issuing from the Bosphorus on the left hand side (looking out onto the sea of Marmara) Anatolian coast can be inferred from the temperature sections and the current data reported in DAMOC study as well as the recent observations by Ünlüata et al (1983)

Considering the DAMOC study first, we reproduce in Fig.12 the temperature sections taken during 5-7 February, 1968 along the transects (1-4) also shown in the same figure. In the DAMOC Report it is stated that the surface layer of the 0(15 m) indicates a greater thickness along the shore west of the Bosphorus, implying surface flows to the west. It is diffucult to agree with this statement, because the series of castings along the transects actualy shows the preferential spreading towards the left hand Anotolian coast of the colder (8°C) Black Sea waters. The splitting of the 8°C waters along transect No.4 actually imply recirculation towards BMJ and hence the presence of an eddy along the coast to the west of the Bosphorus. Indeed, the Current Meter measurements conducted by the Turkish Navy Hydrographic Office supports this conclusion (DAMOC Report, 1971).

During 16-18 May 1968, a series of current measurements were made at the current meter mooring stations 1-3 shown in Fig.9. The measurements at the sta.3 just to the south of BMJ showed high intensity surface currents of 100-250 cm/s with an average of 125 cm/s flowing south. Northerly currents 15-25 cm/s was observed at depth of 25 m. Currents at Sta.1. flowed westerly for only 5 hours with very small velocities and turned towards northeast for the next 18 hours with velocities 5-30 cm/s . At sta.2, the surface flow was towards east all the time at about 15 cm/s. Winds were generally light throughout the measurements.

The existence of an eddy is also pointed out in the DAMOC Report. In fact, it was observed that "floating materials discharged offshore would consequently tend to be carried toward the shoreline".

It appears, therefore, that the Black Sea flow after leaving the Bosphorus tends to first intensify along the Anatolian coast, subsequently curling towards west and in parts recirculating via a clockwise gyre.

Further evidence of the circulation described above is provided by Ünlüata et al, (1983). A series of CTD castings were carried out on board the R/V BİLİM of the Erdemli Marine Science Institute in the BMJ region during June, 1983. The salinity transect displayed in Fig.13 as an example show the preferential attachment of the outflow to the Anatolian coast and intense mixing in the region of flow concentration. The study was carried out under very calm weather conditions, and the drifting of the ship and other visual observations also indicated the presence of a clockwise gyre near the European coast.

The observed circulatory features of the BMJ region is in harmony with the predictions of Beardsley's (1978) two-layer model for the flow issuing from estuaries. Beardsley and Hart (1978) has shown that, in the northern hemisphere, the flow in the upper layer generally tends to be concentrated toward the left hand coast (corresponding to the Anotolian coast in the present situation) because of the steering due to the interfacial height and the drag exerted by the lower layer. The eventual curling towards the right hand coast and the formation of an anticyclonic vortex to the right (looking onto the open sea) of the estuary mouth is also predicted. The application of this model to the BMJ region is considered by Unlüata et al (1983).

The persistency of the BMJ flow structure warrants further observations. It is very likely that the anticyclonic vortex intermittently gets destroyed with local instabilities.

It is also worth to note in passing that the DAMOC data (Fig.12) clearly shows the mixing in the exit area. The thickness of the transition layer is about 10m at BMJ and decreases to 3-5 m off-shore.

It is diffucult to assess via an analysis of the S-T distributions the lower layer Mediterranean inflow features in the BMJ. It appears that the main underflow is topographically controlled and flows in through the deeper mid-section. The current data presented in the DAMOC Report suggest a secondary cyclonic circulation below the surface gyre (Fig.10). The circulation suggested for the inflow may have very serious ramifications for the fate of the materials discharged into the lower layer, for the local recirculation coupled with seasonal blockage upstream near the northern entrance may accumulate the disposals at their very origin.

4. MODELLING EFFORTS

Classical theory of the dynamics of sea-straits are given by Defant (1961) who describes a steady-state two-layer model of water flow. As shown by Defant (1961) and also by Filippov (1968), this model was quite sufficient to describe the vertical structure of current and the interfacial profile along the Bosphorus. Laboratory models of sea-straits and qualitative description of current patterns in straits are studied by Anati et al, (1977). The works of Assaf and Hecht (1974) and Tolmazin (1981), however, appear to be the first relevant hydrodynamical model studies describing the dynamical structure of sea-straits. Assaf and Hecht (1974) considered a frictional, two-layer, steady-state model which includes the momentum and continuity equations as well as a simple salt balance equation for a closed basin (which is the Black Sea in the case of Bosphorus). They were able to reduce these equations into a single equation, an iterative solution of which together with critical flow conditions at the end sections then resulted in the depth of interface and the "strait salinity ratio", $(S_2-S_1)S_1^{-1}$, in terms of the strait geometrical parameters. The model was, in fact, an extension of the work given by Stommel and Farmer (1953) on estuaries and assumes that the closed basins adjacent to the straits are in a state of "overmixing" relative to the straits communicating with the basins. The model predicts a semi-linear profile for the interface such that it is almost linear for most part of the strait but is curved strongly near the end section where the outflow of saline, lower layer flow occurs. The computed strait salinity ratio, depth and characteristic shape of interface are reported to agree reasonably well with observations performed in the Bosphorus and some other straits.

Tolmazin (1981) developed a two-dimensional, continuously stratified model for straits having constant width and variable depth to describe longitudional gravitational circulation and density distribution along the straits. The model considers the balance between vertical diffusion and longitudional advection of mass, and between the vertical shear flux of momentum and longitudinal convective transport similar to those found in estuaries (Pritchard, 1956). The roles of density differences at two ends of straits, surface slope and tangential wind stress on the density and flow structure in straits are examined by the model. The mass and momentum equations are coupled with an auxilary function for which a nonlinear equation of fifth order, in terms of the vertical coordinate, is obtained by means of a similarity method of solution similar to that described by Rattray and Hansen (1962). A self-similar solution for the auxilary function is then obtained based on a characteristic specification of longitudinal changes of bottom topography, wind and sea level at entrances of the straits. The model further encompasses entrainment process and predicts a seperation between the level of no-horizontal motion and the interface between the water masses, which is a characteristic feature of straits such as the Bosphorus (Defant 1961). The calculated horizontal and vertical velocity profiles are reported to be in fair agreement with measurements in the Bosphorus (see Figure 14).

Beyazıt (see Çeçen et al., 1981) developed a two-layer, steady-state numerical model that, in addition to the momentum and continuity equations, considers the salt balance in the upper and the lower layers. The model takes into account the vertical mixing between the layers as well as the interfacial and bottom friction. Critical flow conditions are assumed to exist at the two ends of the strait. The predicted profile of the interface is essentialy linear, with rapid variations occuring at the two entrence boundaries. This result agrees with Assaf and Hecht (1974). It is found that the model is sensitive to the choice of the frictional coefficients. Mixing, on the other hand, is found to have negligible influence on the interfacial profile. The salinity changes of the 0(2 ppt) along the strait are predicted. This and the other results of the model agree reasonably well with the observations of the Turkish Navy Hydrographic Office.

Sümer and Bakioğlu (1981) (see also Çeçen et al, 1981; Beyazıt and Sümer, 1982) have developed a longitudinally integrated two-layer model assuming a linear interfacial profile at the outset. The losses at the embayments are taken into account and the changes in the cross-sectional areas are accounted in an approximate way. Some of the salient results of this model have already been discussed. The model in addition predicts that within the strait the combined densimetric Froude number of the flow remains less than unity, implying stable conditions with regard to vertical mixing. This simple model, clearly demonstrating the sensitivity of the system to the surface elavation difference and the blockage of the underflow, agrees well with the field data as it can be seen in Fig. 15. In the same figure the solution due to Assaf and Hecht (1974) is also given for comparison. The differences in the two models appear to be essentially due to the assumed input conditions. Finally, for an average surface elevation difference of 33 cm based on the DAMOC Report the model produces, respectively, discharges $Q_1 = 19700\ m^3/s$, $Q_2 = 7300\ m^3/s$ for the upper and the lower layers. These values are found to be close to those obtained through an overall salt balance equation for the Black Sea when Özturgut's (1971) values for runoff, precipitation and evaporation are utilized together with the salinities 17.5 and 38.5 ppt for the upper and the lower layers, respectively (See Sec. 2.c.)

5. Conclusions

It appears that the rudiments of the overall physics of the Bosphorus away from the two ends of the strait have been reasonably well established. However, the understanding of the entire system extending from the neighborhood of the Black Sea entrance to the Bosphorus-Marmara junction region requires further field studies.

The times, the duration and the extent of the blockage of the Mediterranean underflow, the reasons for its establishment and its influence on the Black Sea salt balance still awaits long term measurements well integrated into the relevant area. In return, an assesment of the detrimental effects that may emerge as a result of the future diversions of the Black Sea tributaries should be made.

In the south, the near-field interactions of the Bosphorus with the sea of Marmara is another topic requiring a series of systematic investigations.

Finally the various components of the Bosphorus-Marmara-Dardanalles system should be brought together by extended oceanographic studies to understand this system as a whole. Otherwise, both the ancient and the modern legends about the Bosphorus will continue to remain unclarified, the latter increasing in number.

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TABLE 1

Estimates of Black Sea Water balance components (km^3/year).

	Precipation	River run off	Evaporation	Black Sea inflow	Black Sea outflow	Black Sea net outflow
Möller (1928)	231	328	354	193	398	205
Casper (1957)	234	320	354	—	—	200
Leonov (1960)[x]	—	—	—	193	392	199
Solyakin (1966)[xx]	119	346	332	176	340	164
Tixeront (1970)	181	400	392	211	400	189
Özturgut (1971)	300	352	353	249	548	299

x cited in Scholten, 1974

xx cited in Shimkus and Trimonis, 1974

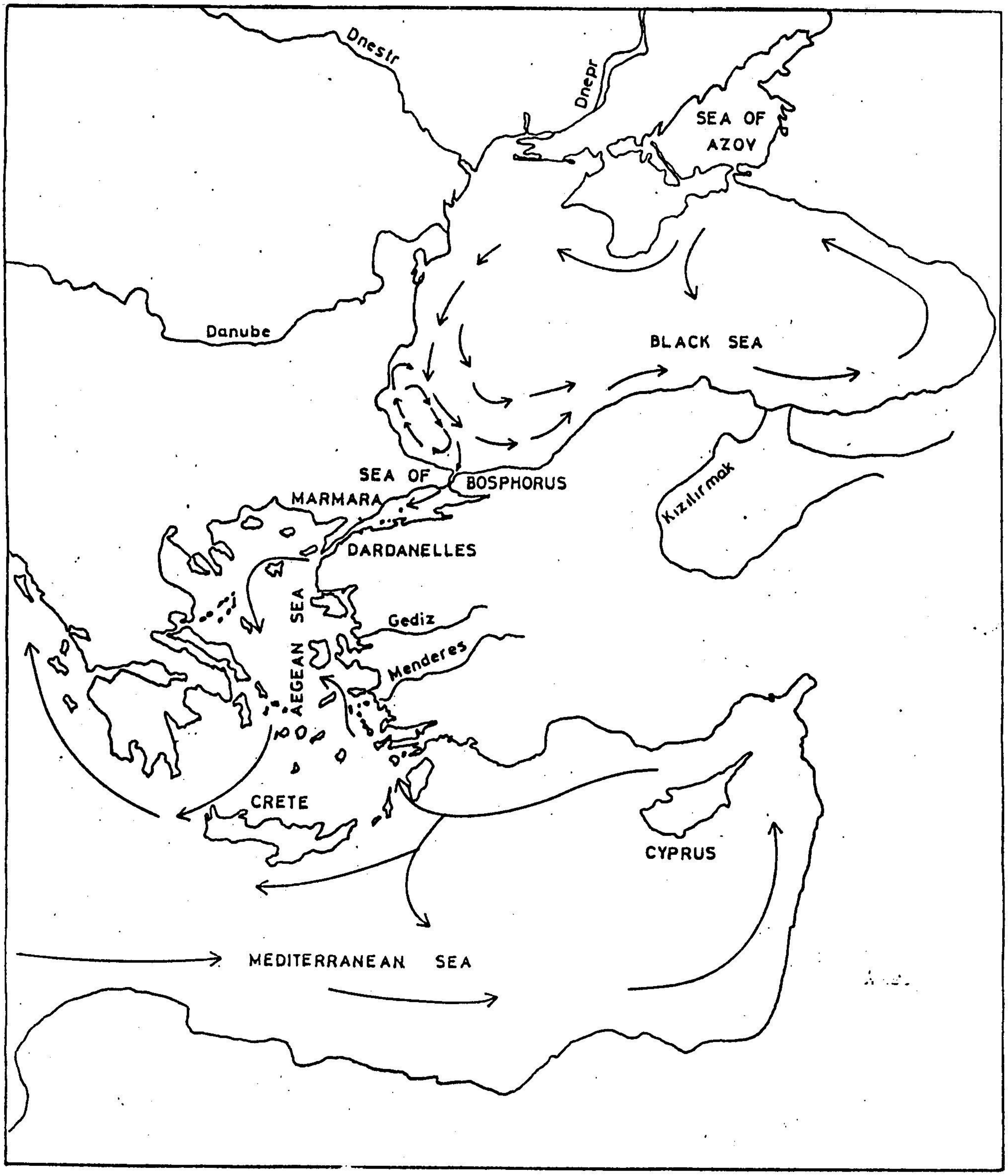


Fig.1. Location map of the Aegean Sea, the DMB region and the Black Sea system. Surface currents are indicated by arrows.

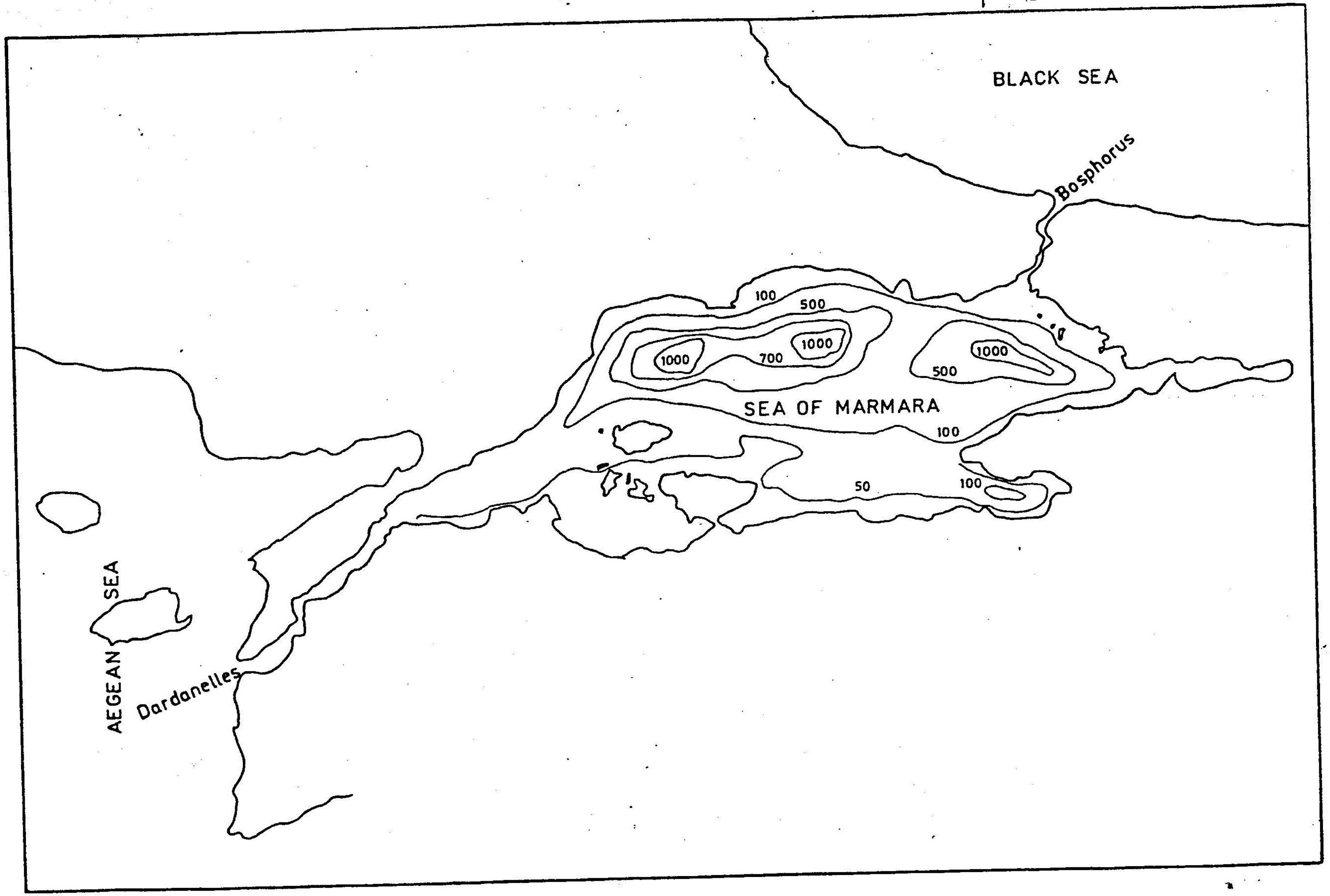


Fig.2. Location map of the DMB region with the bathymetry of the Sea of Marmara

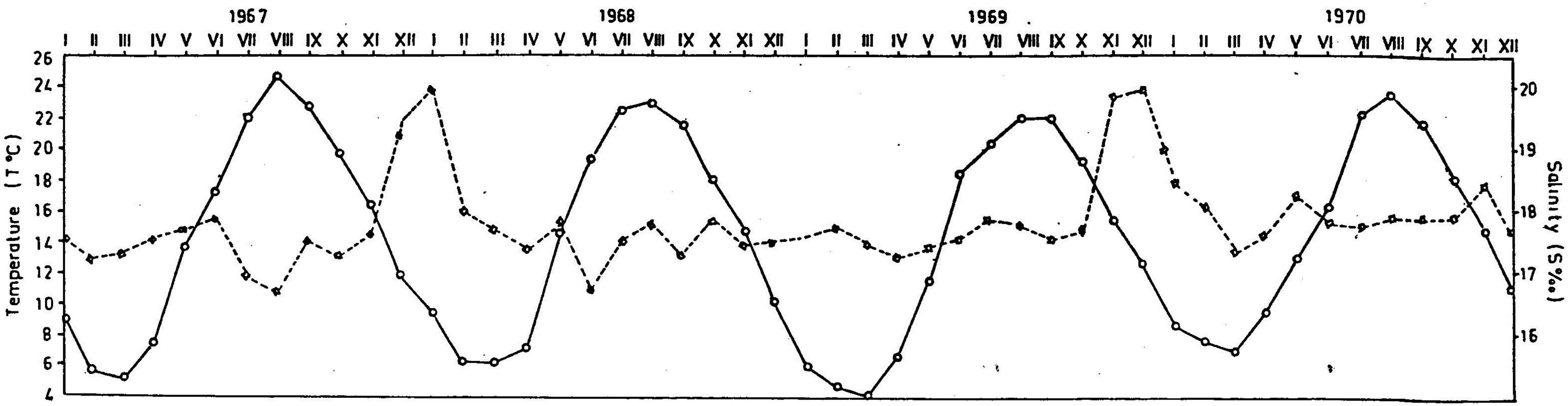


Fig.4. Montly mean surface temperature(———) and salinity (----) variations for the years 1967-1970 at Baltalimanı (after Artüz and Uğuz, 1976).

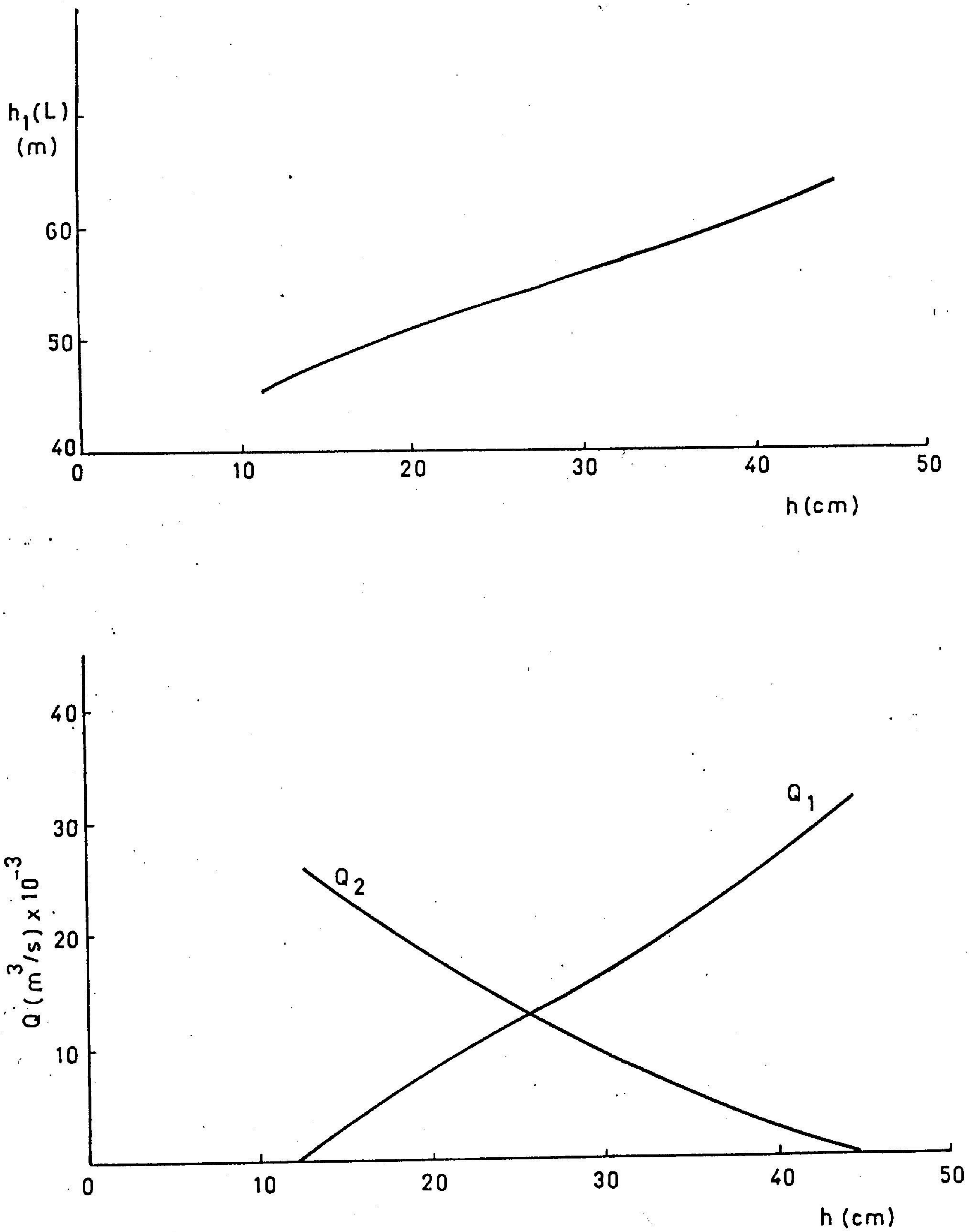


Fig.8. Depth of interface at the Black Sea end of the Bosphorus (above), and flow rates of the layers (below) as a function of the surface elevation difference between two ends of the strait (after Sümer and Bakioğlu, 1981).

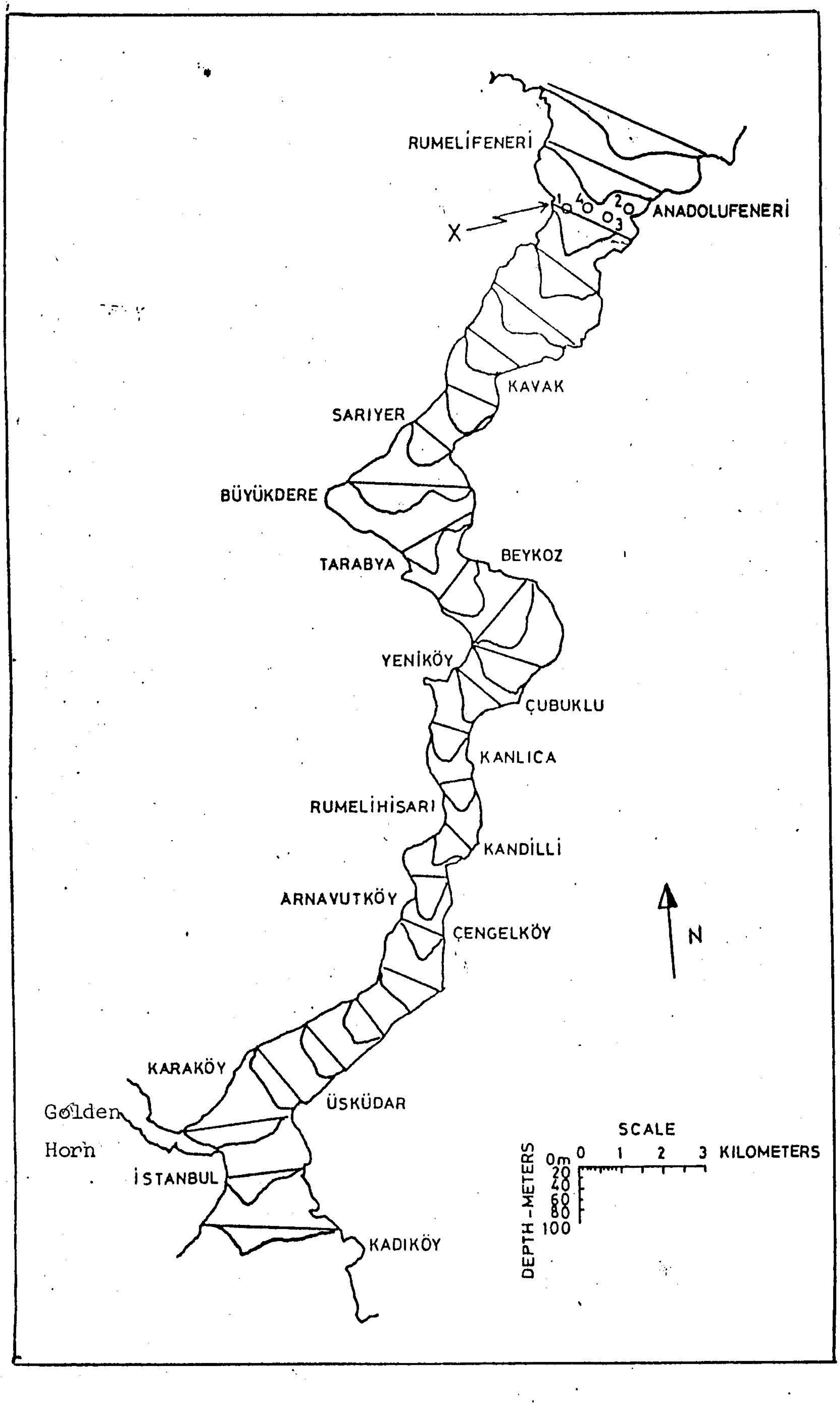
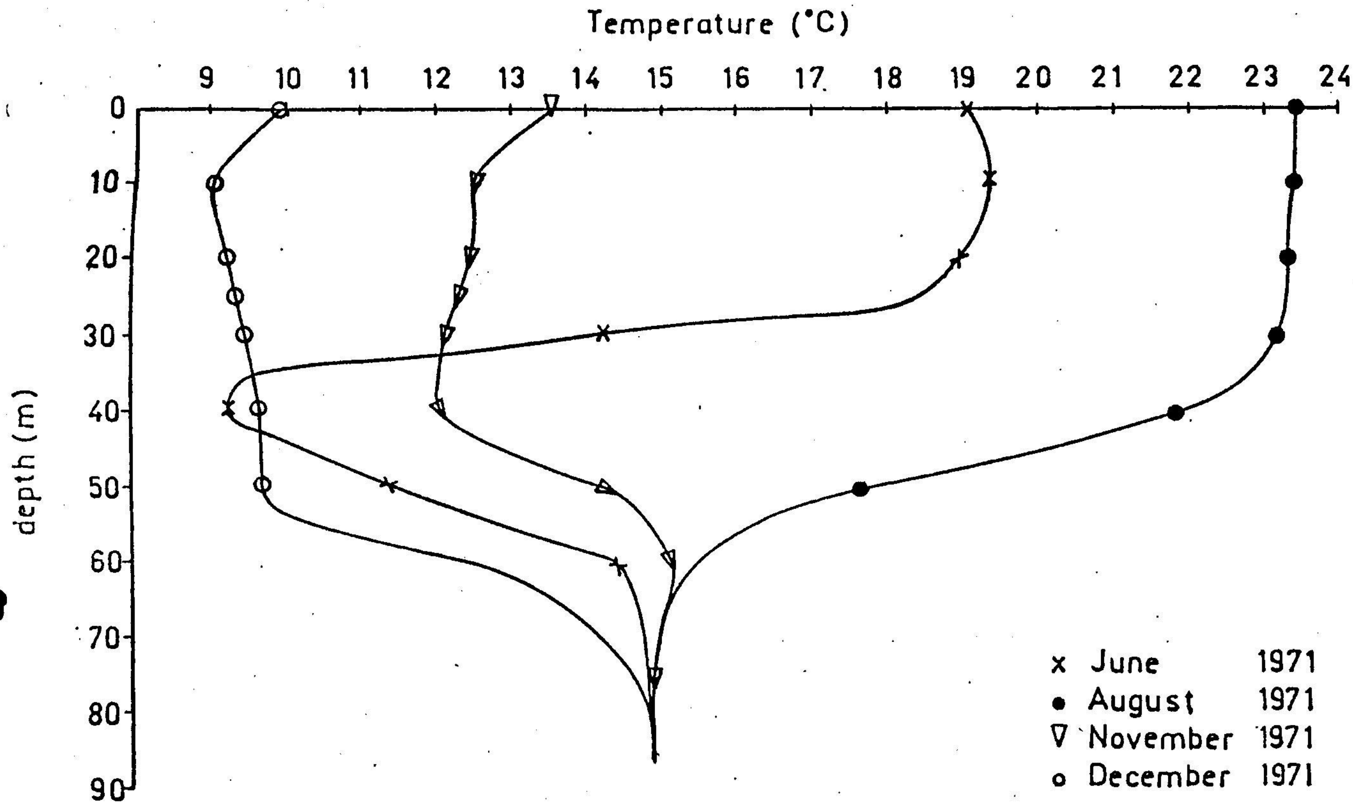


Fig.3. The Strait of Bosphorus. The transverse bathymetric variations at various sections are also shown.



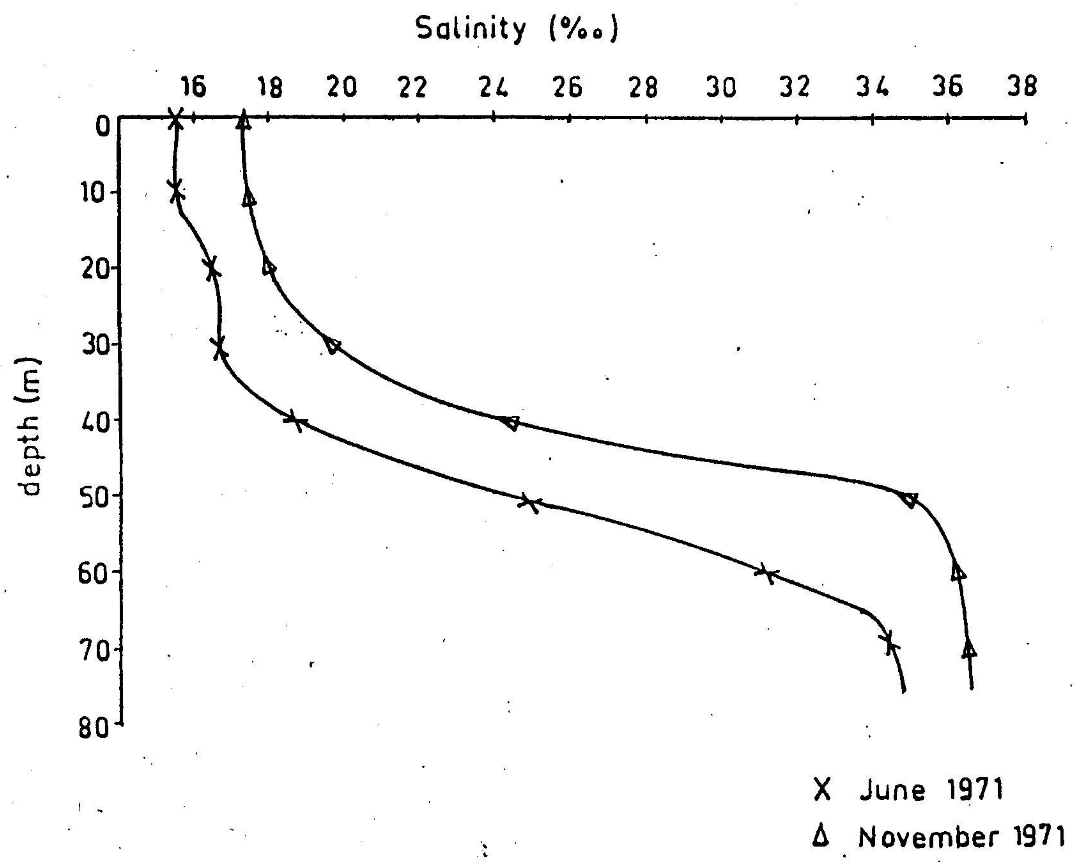
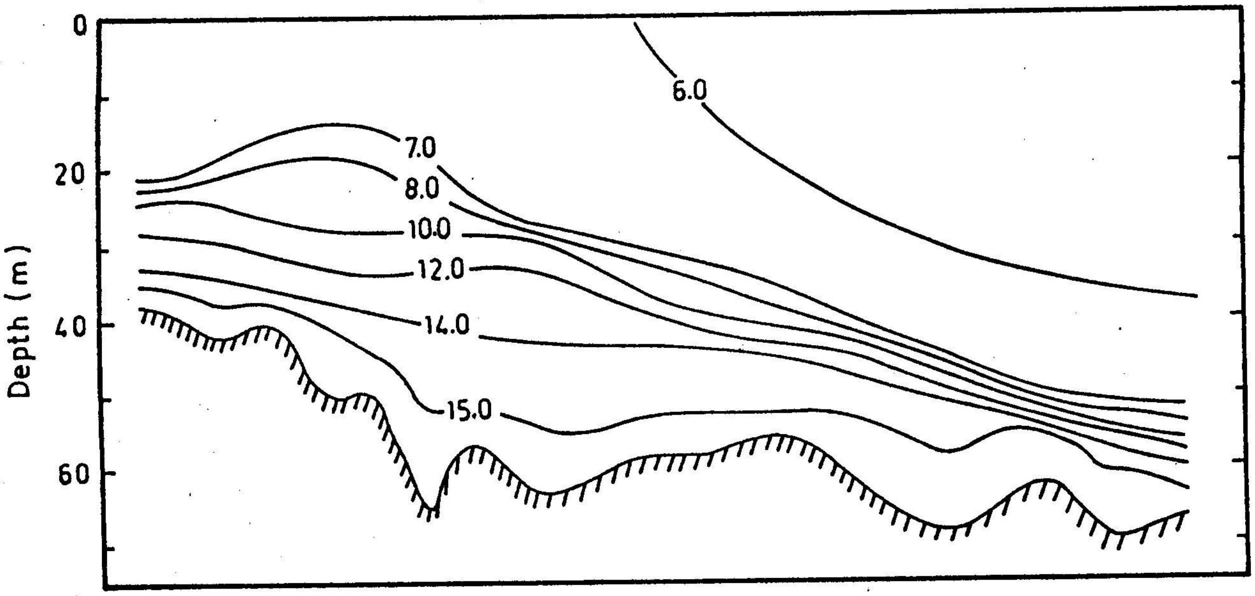


Fig.5. Typical seasonal variations of the Bosphorus temperature and salinity at a station north of Tarabya (data taken from Artüz, 1974)



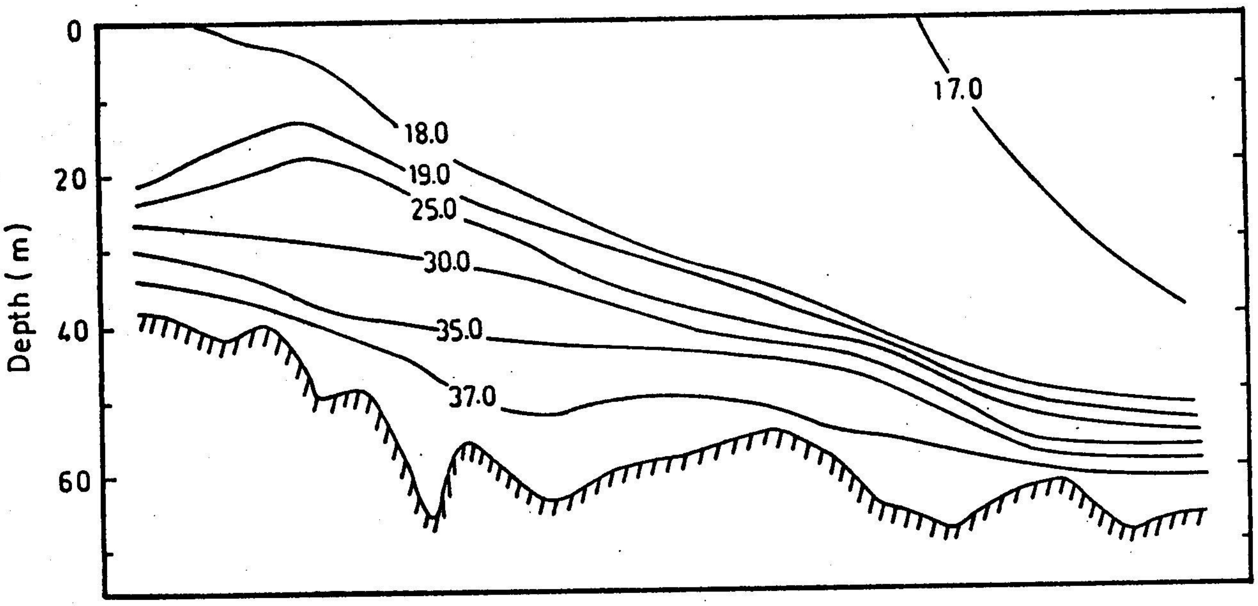


Fig.6. Vertical temperature (above) and salinity (below) distributions along the Bosphorus during January, 1980 (data taken from Çeçen, et al , 1981)

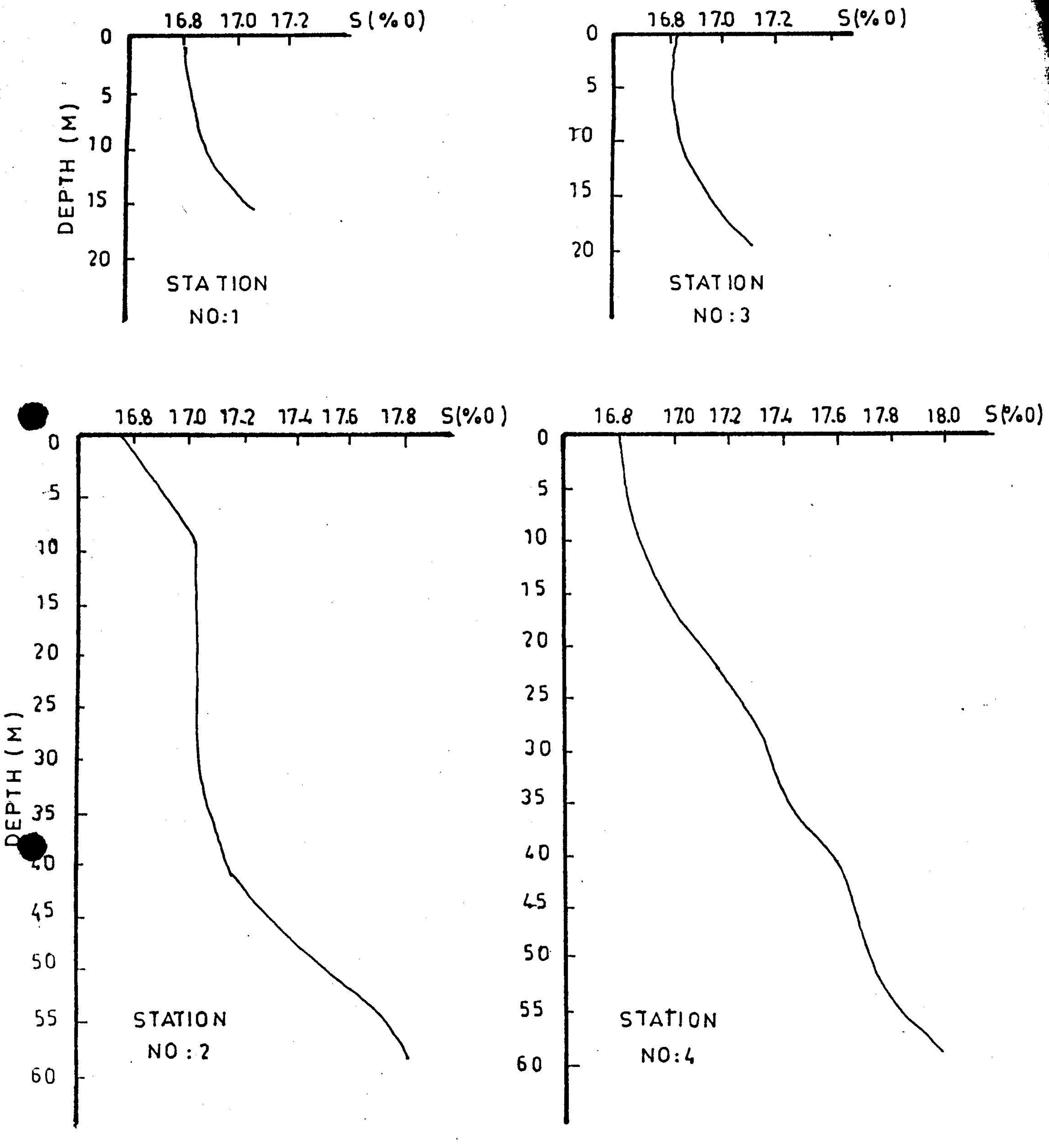


Fig.7. Vertical salinity profiles at stations located along the transect X during May,1981 (after Beyazıt and Sümer, 1982).

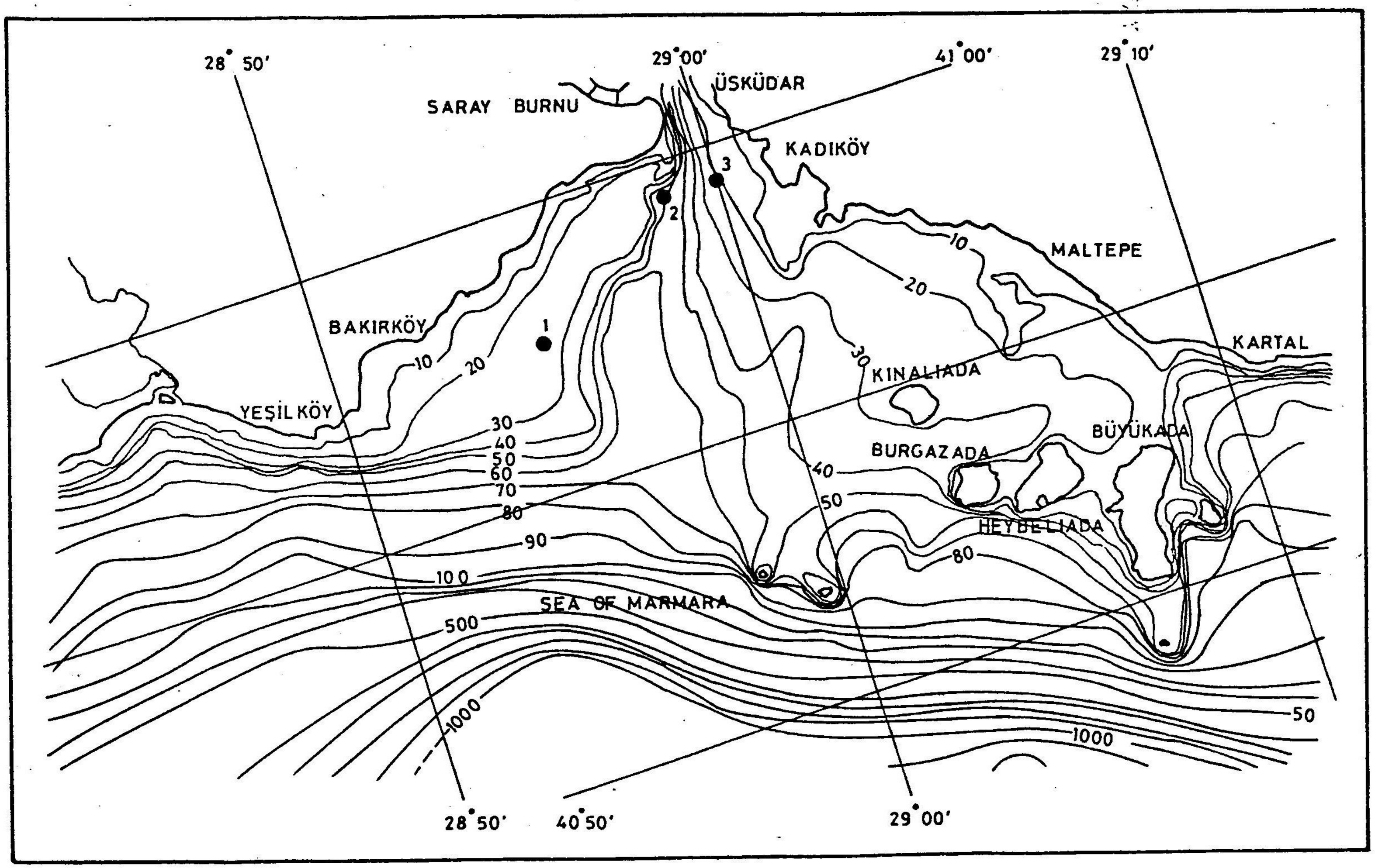


Fig.9. Bathymetry of the BMJ region.

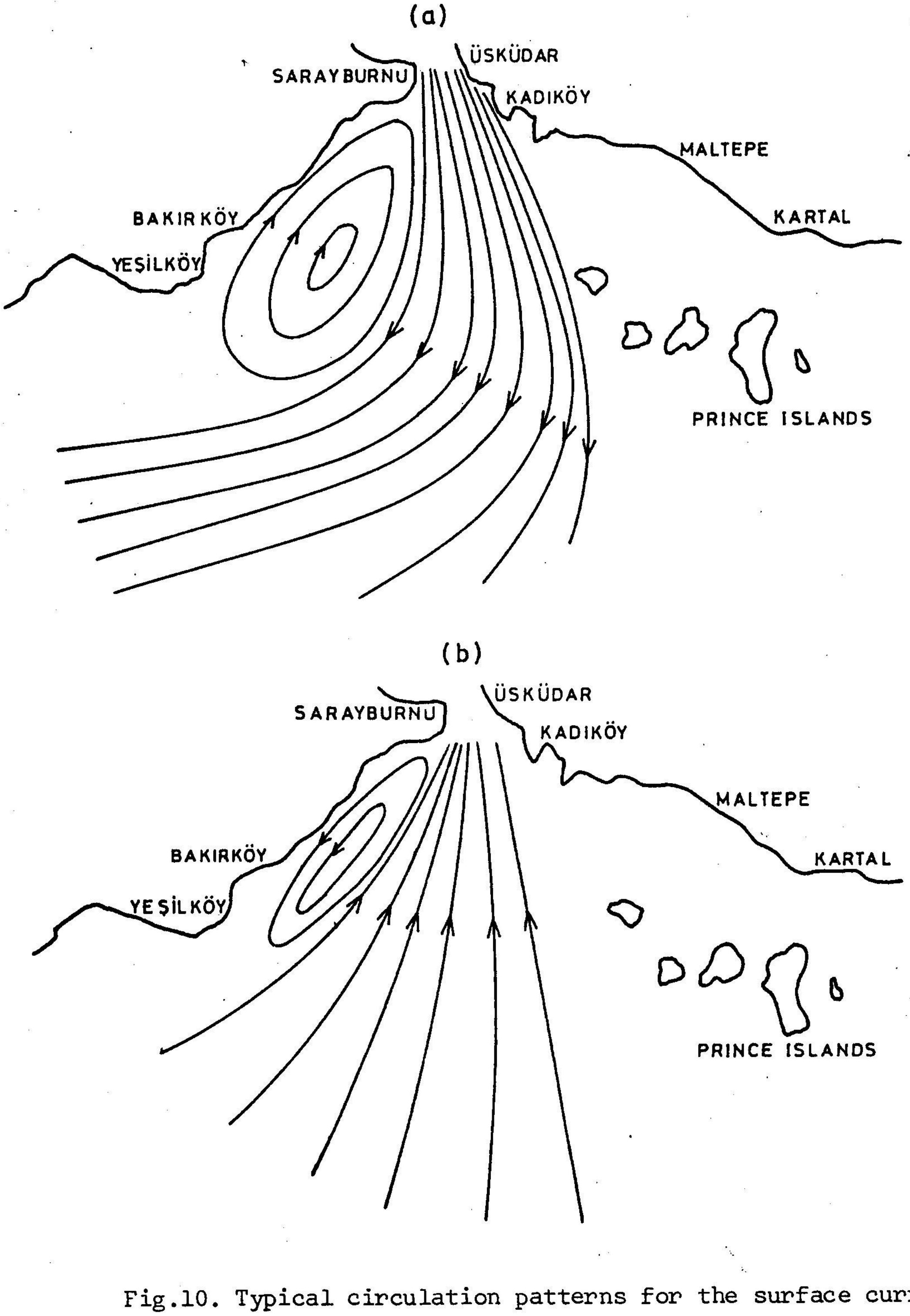


Fig.10. Typical circulation patterns for the surface current (above), and the bottom current (below) in the BMJ region.

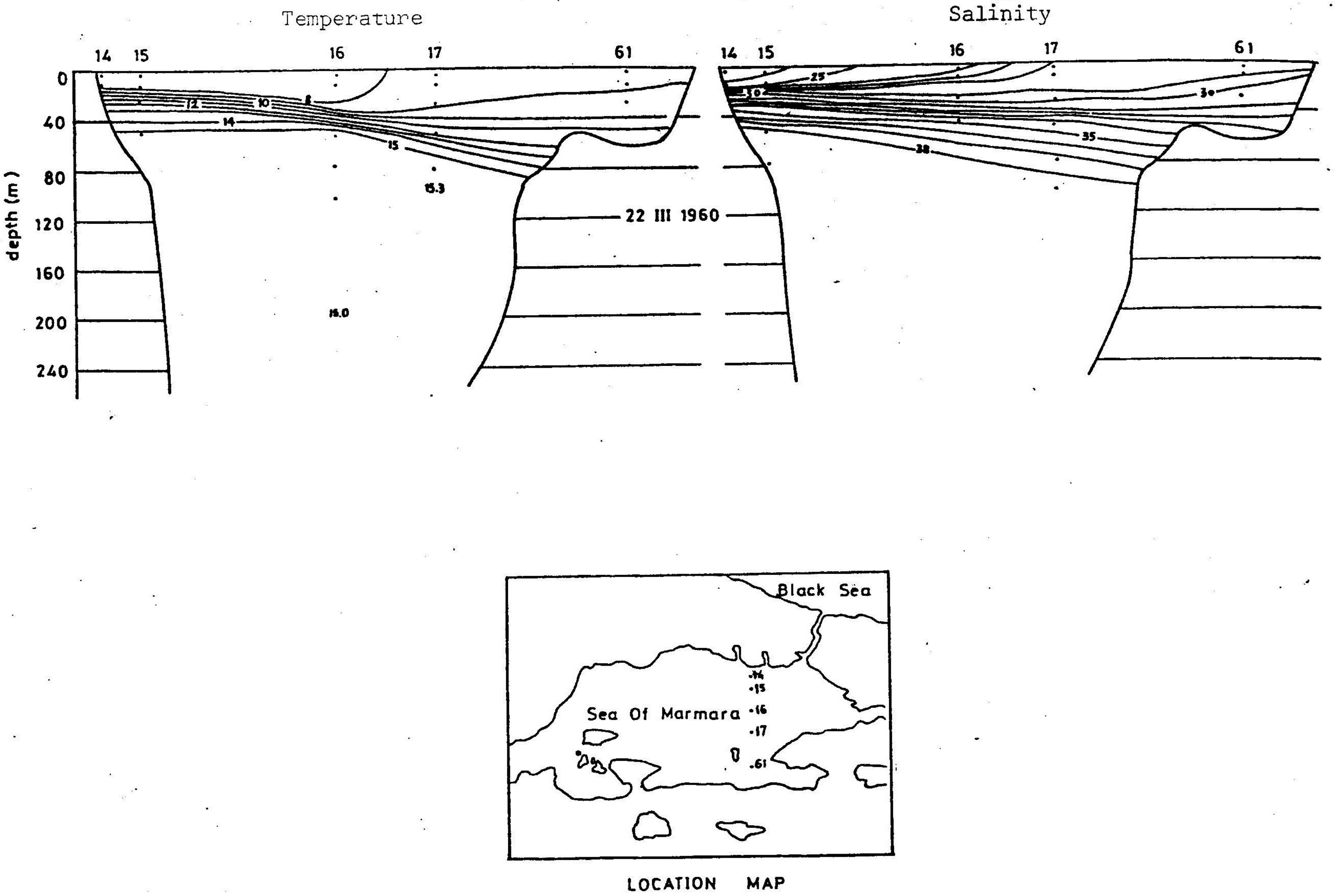


Fig.11. Cross-sectional temperature and salinity distributions at eastern Sea of Marmara during March, 1960 (after DAMOC Report, 1961).

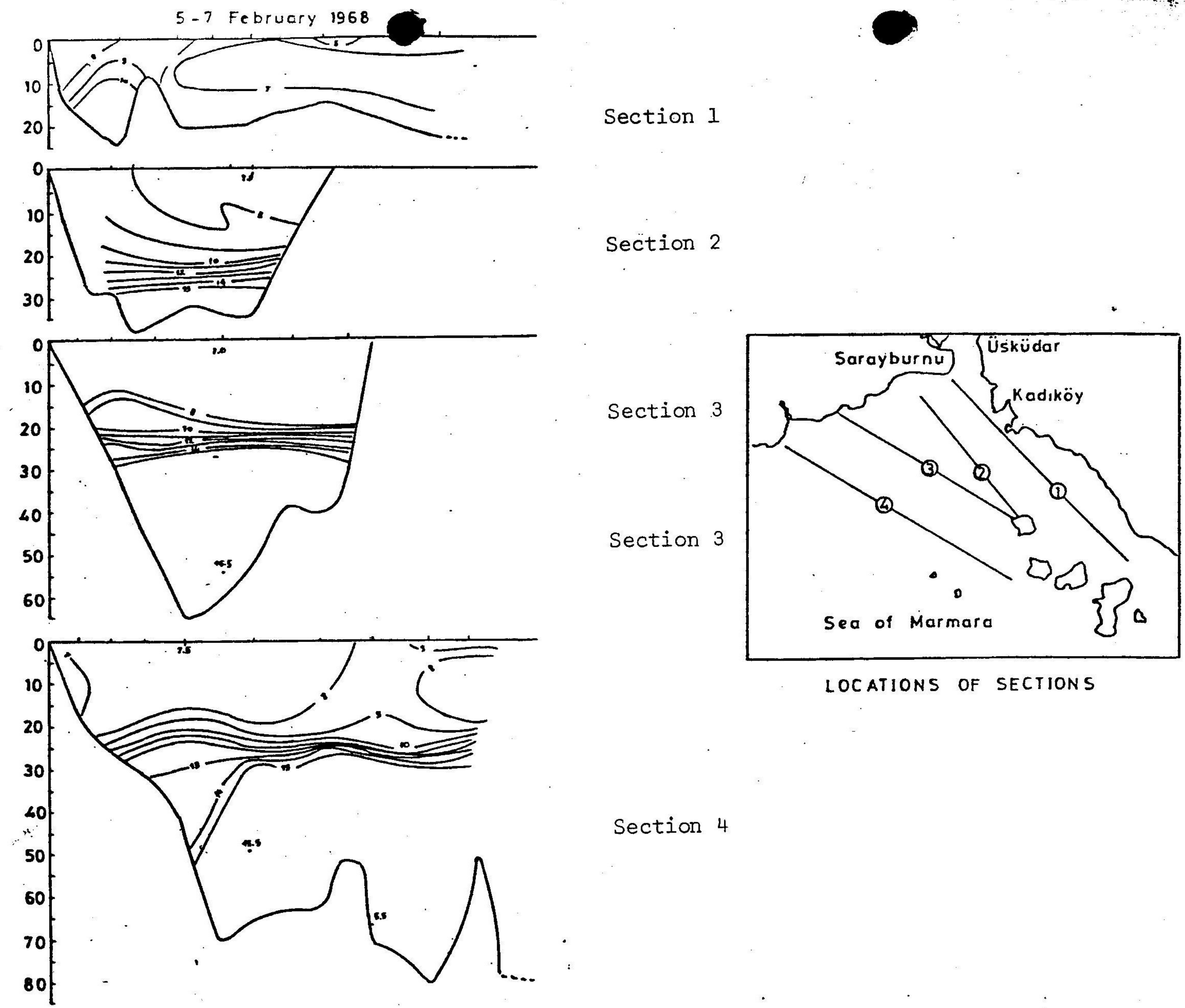


Fig.12. Cross-sectional temperature distributions along four transects in the BMJ region during February, 1968 (after DAMOC Report, 1971).

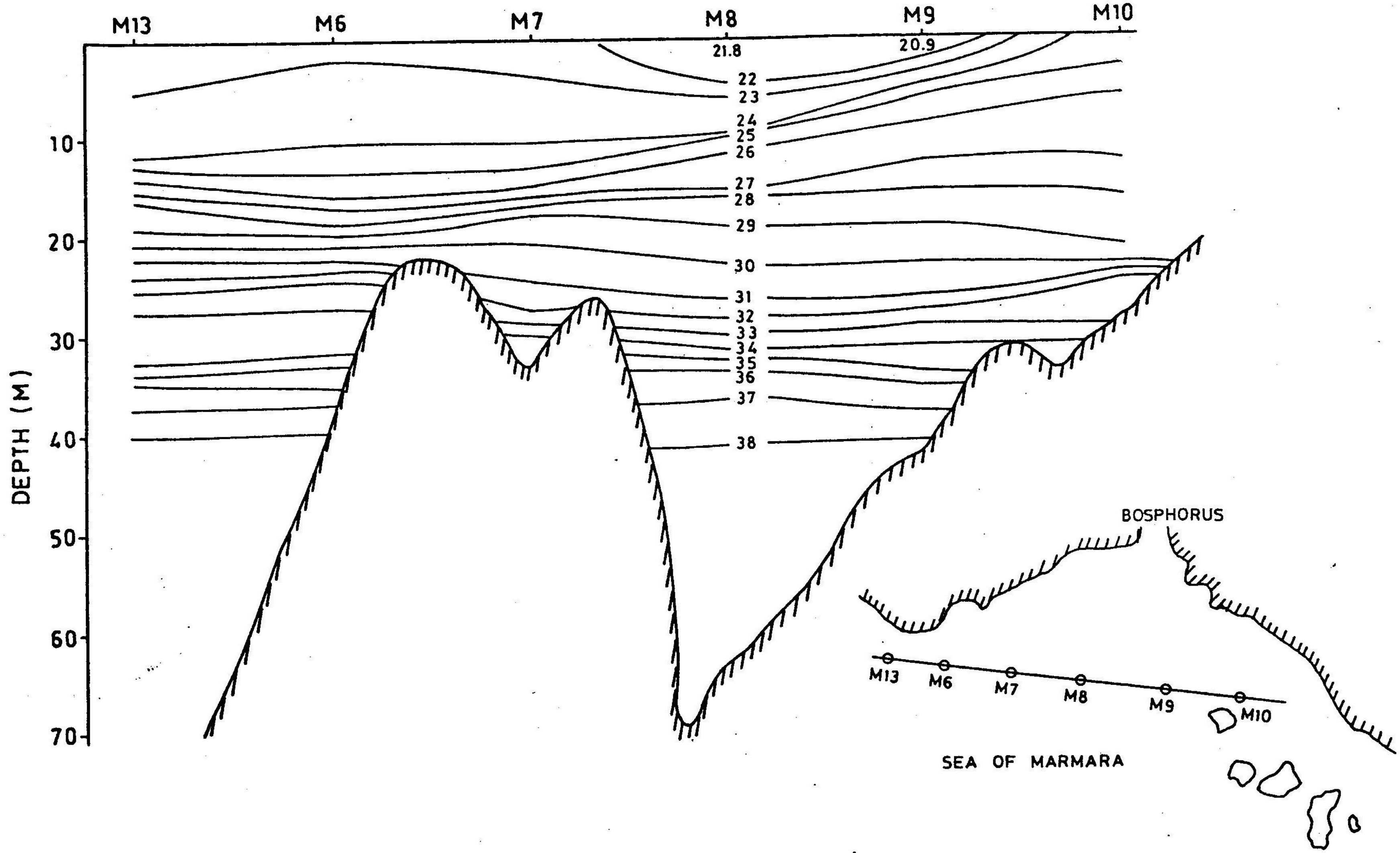


Fig.13. Cross-sectional salinity distribution along a transect in the BMJ region during June, 1983 (after Unlüata et al , 1983).

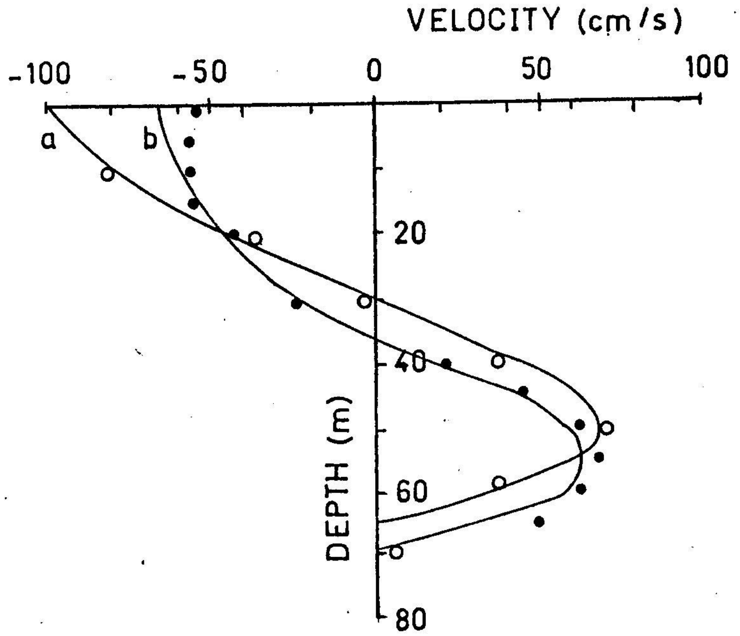


Fig.14. Computed (solid lines) and observed (black and white circles) velocity profiles at the central part (curve a) and the northern part (curve b) of the Bosphorus (after Tolmazin 1981).

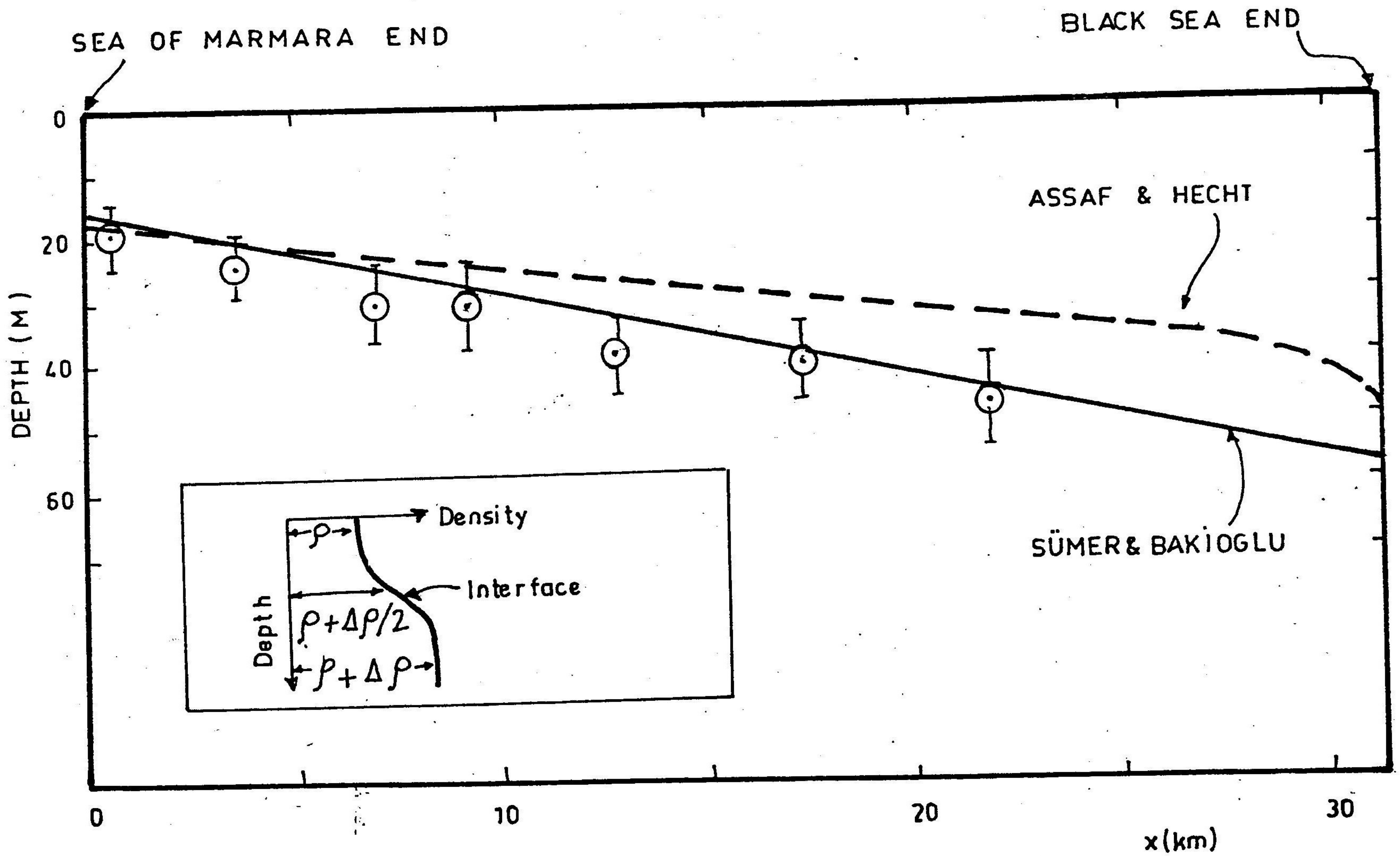


Fig.15. Position of the interfacial profile along the Bosphorus (after Sümer and Bakioğlu, 1981).