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# Observations of the Mediterranean inflow into the Black Sea

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**Abstract**—The Mediterranean inflow issuing from the Bosphorus Strait has been documented to enter the Black Sea essentially confined in a 10-km long channel which is a continuation of the strait over the adjacent shelf. The width of the channel is between 500 and 1000 m. A 3.5-km-long sill, with a depth of 60 m, is situated in the channel at its beginning, just north of the end of the strait. The Mediterranean water flows into the Black Sea essentially on a continuous basis throughout the year, but it may be interrupted for short durations under unusually strong and persistent winds. After exiting from the channel, the Mediterranean inflow spreads in a thin layer above the bottom and continues in a generally northerly direction towards the shelf break.

## 1. INTRODUCTION

THE Strait of Bosphorus (Fig. 1), joining the Sea of Marmara and the Black Sea, is a pathway for the inflow of the saltier and denser Mediterranean water to the Black Sea. The inflow constitutes a vital component of the Black Sea water and salinity budgets. In order to evaluate the long-term effects of the reported reduction in the fresh water input (TOLMAZIN, 1985) and the associated changes of the Mediterranean inflow on the oceanography of the Black Sea, it is important to understand satisfactorily if the inflow is intermittent or continuous through the year. Lack of sufficiently frequent hydrographic observations and inadequate data on the bottom topography in the Bosphorus–Black Sea junction region appear to have been the reasons for the uncertainty and speculation concerning both the path and the temporal continuity of the inflow. The objectives of the studies reported here were to investigate the temporal continuity of the inflow and to determine its path in the vicinity of the northern end of the strait. The background and perspective of the problem are presented in section 2. Observations and results of the present investigations are given in section 3, and conclusions in section 4.

## 2. BACKGROUND AND PERSPECTIVE

The Bosphorus (Fig. 1) is approximately 31 km in length, with a sill at each end of the strait. The sill at the southern end, at the junction with the Sea of Marmara, has a depth of 32–34 m. The depth of the sill at the northern entrance of the strait, at the junction with the

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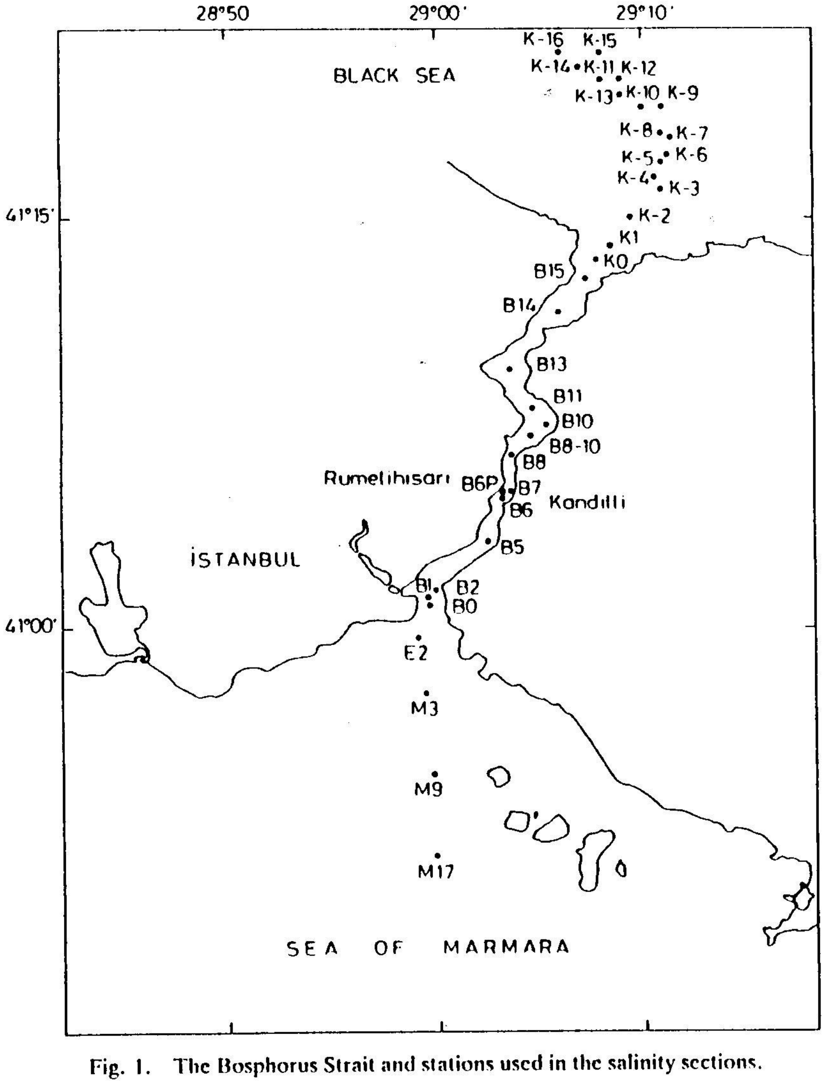


Fig. 1. The Bosphorus Strait and stations used in the salinity sections.

Black Sea, was earlier believed to be 47–50 m (SCHOLTEN, 1974; GUNNERSON and OZTURGUT, 1974; TOLMAZIN, 1985), but was determined to be 60 m in the present study. A two-layer flow regime exists in the strait, with the upper layer flowing from the Black Sea towards the Sea of Marmara, and the lower layer, of Mediterranean origin, flowing in the opposite direction. Under normal conditions, the interface depth at the southern sill is typically 10–15 m, and about 45 m at the northern sill. Strong northerly winds result in an increase in the sea surface elevation and lowering of the interface in the northern reaches of the strait. Southerly winds, on the other hand, result in moving the interface upwards and retardation or blockage of the upper layer flow (GUNNERSON and OZTURGUT, 1974; TOLMAZIN, 1985).

On an annual basis, the volume of the Mediterranean inflow to the Black Sea through the Bosphorus has been estimated as 310 $km^3 y^{-1}$, and the outflow to the Sea of Marmara as 612 $km^3 y^{-1}$ (ÜNLÜATA *et al.*, 1990). These values were determined by evaluating the salt and water budgets of the entire Turkish straits system, consisting of the Bosphorus, the Sea of Marmara and the Dardanelles Strait. The salinities used in the computation of the fluxes were obtained from monthly surveys in the Bosphorus and seasonal surveys in the Sea of Marmara and the Dardanelles Strait by R.V. *Bilim*, of the Institute of Marine Sciences, Middle East Technical University (IMS-METU), during 1985-88 (ÖZSOY *et al.*, 1986, 1988). The new inflow value is higher by about 65% than the earlier estimates of about 190 $km^3 y^{-1}$ (see references cited in ÜNLÜATA *et al.*, 1990) but is in agreement with results of independent mathematical models (SUMER and BAKIOGLU, 1981; OGUZ *et al.*, 1990b), utilizing sea-level difference values consistent with the observed average sea-level differential. A comprehensive discussion of the water budget components and a critical evaluation of the differences between the present and earlier estimates are given in ÜNLÜATA *et al.* (1990).

Previous investigations of the Mediterranean inflow revealed the presence of the saltier water as isolated patches in the Bosphorus–Black Sea junction region. TOLMAZIN (1985) reported results obtained as part of a 15-year program by the Soviet Institute of Biology of the Southern Seas (INBYUM). They observed that a patch of Mediterranean water was always present in a region located approximately between 41°20′N and 41°30′N, i.e. between 10–30 km offshore of the northern end of the Bosphorus. The possibility of a channel as an extension of the strait was considered but discounted by TOLMAZIN (1985) on the basis that a channel large enough to act as a conduit for the powerful Mediterranean flow would be seen on existing navigation charts. BUYUKOZDEN *et al.* (1985a,b) also reported patches of the Mediterranean water and considered the possibility of a channel, however its presence was not documented in their study.

While documentation of actual cases of blocking of the Mediterranean inflow is not found in the literature, the possibility and the frequency of blocking has been a central question since the earliest investigations of the Bosphorus. ULLYOTT and ILGAZ (1943a,b, 1946) and ILGAZ (1944) maintained that a major fraction of the Mediterranean effluent would be returned to the Sea of Marmara as a result of almost continuous blocking of the lower layer. PEKTAS (1953, 1956) argued that blocking would occur only during March–August when there is high runoff into the Black Sea, causing a sufficiently large elevation difference between the two ends of the strait. BOGDANOVA (1963), utilizing measurements obtained at a series of stations located about 10 km offshore of the northern entrance of the Bosphorus, concluded that the Mediterranean inflow should reach the Black Sea almost continuously. Results of model studies also support the view that blocking can not be a frequent occurrence (BOGDANOVA and STEPANOV, 1974; SUMER and BAKIOGLU, 1981; OGUZ *et al.*, 1990b).

It is seen from the foregoing that two questions were unresolved by the previous investigations: (1) whether there exists an essentially continuous or intermittent inflow of the Mediterranean water through the Bosphorus and (2) what is the reason for the existence of the saltier water to the northwest of the end of the strait. The measurements referred to by BOGDANOVA (1963) and TOLMAZIN (1985) were taken too far away from the exit to determine satisfactorily the spatial continuity of the flow between the exit and their stations. The measurements reported by BÜYÜKÖZDEN *et al.* (1985a,b) were obtained in the vicinity of the exit, however the frequency of the surveys and the spacing between the stations were not sufficient to resolve either temporal or spatial continuity of the flow.

## 3. PRESENT INVESTIGATIONS

### 3.1. *The field program*

In keeping with the objectives of the present investigations a series of hydrographic surveys was carried out during 1985–88 using the R.V. *Bilim* of IMS-METU. The Sea Bird Model 9 SBE CTD system was used for obtaining property profiles. The probe measures the pressure, temperature, conductivity and dissolved oxygen simultaneously at a rate of 24 data points per second as it is lowered into the water column. With a lowering rate of about 0.5 m $s^{-1}$, the vertical resolution is of the order of a few centimeters. The raw data were bin-averaged over 1-m depth intervals. The sensors were calibrated by the manufacturer and an independent calibration was not carried out during the surveys. Station location fixes were obtained using the ship's radar and satellite navigation system. Bathymetric data were obtained using at Atlas echo sounder. During the surveys, the probe was lowered very close to the bottom at each station. In the region away from the exit, where the thickness of the Mediterranean water was expected to be small, the probe was carefully lowered until it touched the bottom. A total of 40 surveys were carried out between November 1985 and December 1988. The data sets for the surveys are given in ÖZSOY *et al.* (1986, 1988) and in LATIF *et al.* (1989a,b).

### 3.2. *Bottom topography in the Bosphorus–Black Sea junction region*

It was found during the course of the field investigations that the available data on the bathymetry in the Bosphorus–Black Sea junction lacked in both accuracy and detail. In the region of the northern sill, the map given by SCHOLTEN (1974) shows the depth to be less than 50 m, while depths of 59 m are shown in the Turkish navigation chart no. 1811. Neither map has sufficient detail to define a possible extension of the strait over the adjacent shelf. The depth measurements obtained in the present study revealed the existence of a narrow channel with steep banks extending for about 10 km over the adjacent Black Sea shelf, as a continuation of the Bosphorus Strait (Fig. 2). For the first 8 km, the channel has the same orientation as the strait, the axis lying approximately in a northeast–southwest direction. It then turns towards the north and continues for about 2 km in this direction, and finally fans out towards the northwest, joining the shelf topography in a formation similar to the morphology of a river delta. The width of the channel varies between 500 and 1000 m. A sill of 60 m depth and length of about 3.5 km is located in the beginning of the channel, just north of the end of the strait. The maximum depth of the channel at the Bosphorus exit section is about 75 m; beyond the sill the channel gradually deepens to 80 m.

### 3.3. *Path of the Mediterranean effluent*

The path of the Mediterranean inflow after its exit from the Bosphorus can be seen in Fig. 3 in which salinity values greater than 24 ppt near the bottom from some of the surveys

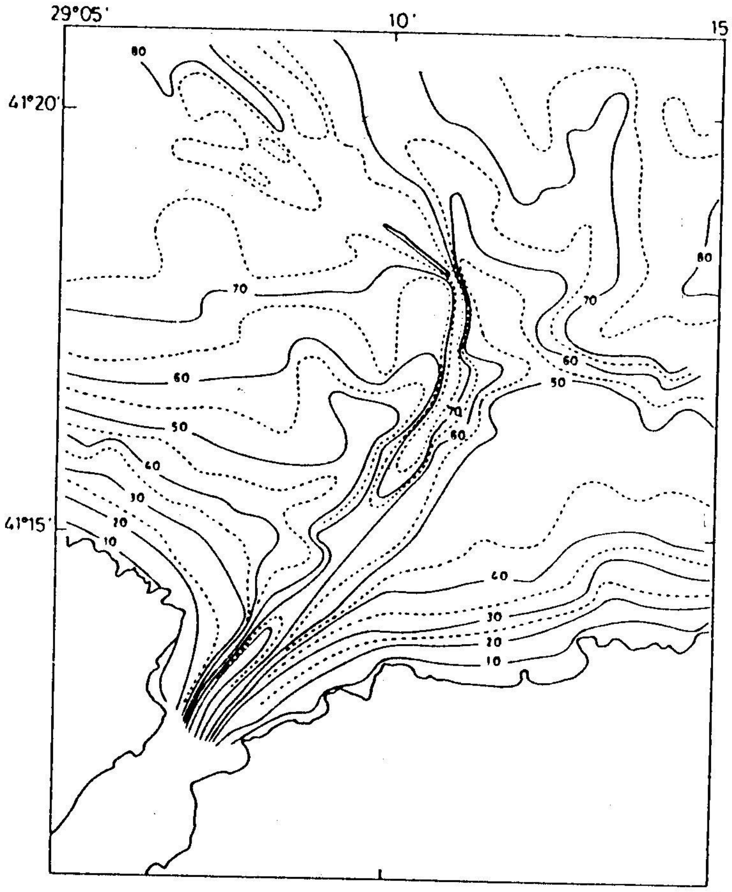


Fig. 2. Bottom topography of the Bosphorus–Black Sea junction region obtained in the present investigation (depth in m).

are shown, together with the depth contours outlining the channel. The distributions from the other surveys were similar and are not included for the sake of clarity in the figure. It is evident that the Mediterranean inflow is transported over the shelf essentially confined within the channel. At the end of the channel, the effluent spreads towards the northwest, being guided by the orientation of the channel at its terminal point.

The course of the effluent over the shelf after the end of the channel is influenced by the shelf topography, Coriolis acceleration, and bottom friction (SMITH, 1975) as well as the prevailing currents in the southwestern part of the Black Sea. Further observations and theoretical studies are needed to understand the dynamics of the flow over the shelf. An example of the distribution of the effluent over the shelf and the path of the main flow, as indicated by the bottom salinity values, is given in Fig. 4 from a cruise in June 1988.*

The spreading of the effluent as it exits from the channel is indicated by the high salinity values at the four stations located along 41°22.5'N. The relatively high salinity values in the

*The June 1988 cruise of the R.V. *Bilim* was conducted in coordination with cruise 4 of the R.V. *Knorr*, as part of the joint U.S.–Turkey Oceanographic Expedition to the Sea of Marmara and the Black Sea.

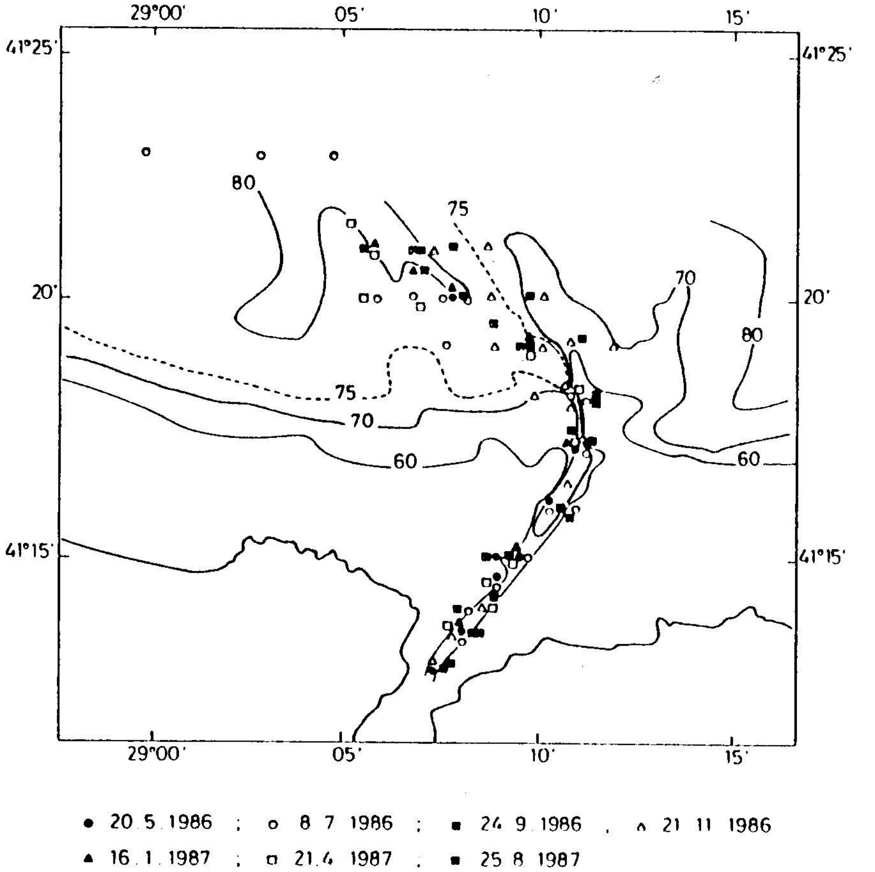


Fig. 3. Location of stations with bottom salinity greater than 24 ppt for some surveys.

vicinity of Sta. A along the 100-m contour are apparently due to the spreading of the effluent from its main course towards the east, however, due to lack of stations, a clear pattern can not be established. The path of the main part of the flow, delineated by the dashed line joining the higher salinity locations, is seen to be towards north, reaching the 100-m contour at 41°32′N, 29°2′E, approximately 35 km north-northwest of the Bosphorus exit. The effluent becomes highly diluted and progressively thinner as it moves towards the shelf break. The near-bottom temperature and salinity profiles for Stas A and B are shown in Fig. 5. In order to present sufficient detail, these profiles have been drawn using the full data rather than the 1-m bin-averaged values. At Sta. A (41°27′N, 29°14′E), the Mediterranean water is present only in the last 1.5 m of the profile, while at Sta. B (41°31.2′N, 29°4′E) the temperature and salinity begin to increase at a depth of 94 m, with the maximum increase taking place in the last 2 m.

The rapid dilution of the Mediterranean effluent over the shelf implies the formation of a water mass dense enough to sink to, and hence cause renewal of, the deeper layers of the Black Sea. In a manner similar to that employed by OSTLUND (1974), an approximate estimate of the renewal time of the deep Black Sea waters can be obtained using the salinities measured in the present study.

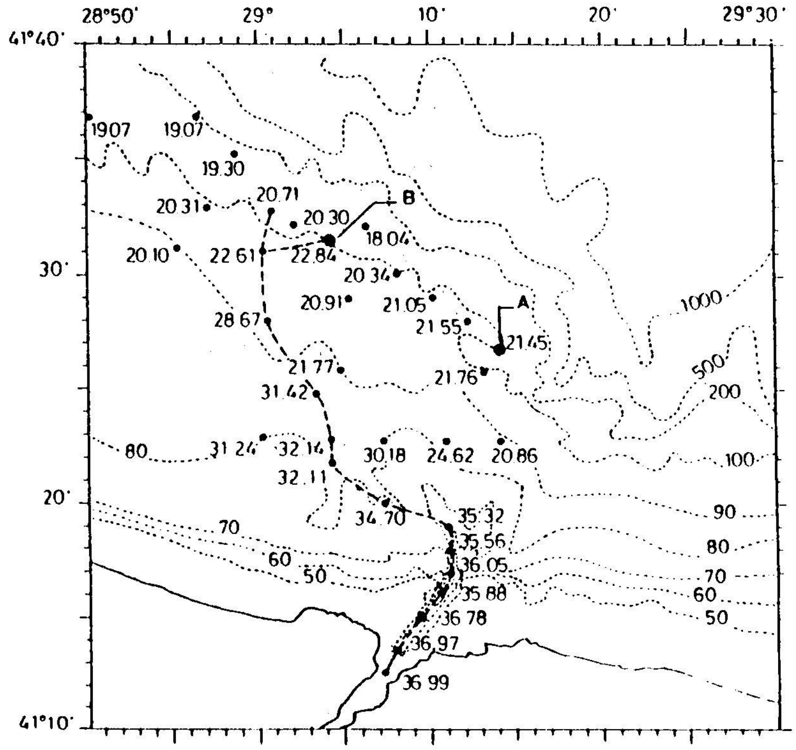


Fig. 4. Bottom salinity values, 8 June 1988. The dashed line joining locations with high bottom salinity indicates the path of the Mediterranean effluent.

The average salinity of the Mediterranean inflow in the channel, based on seasonally representative surveys, was found to be close to 35 ppt. The salinity of the ambient shelf water near the bottom is about 18.8 ppt, and that of the deep Black Sea water is 22.3 ppt (OGUZ *et al.*, 1990a). Thus the mixing ratio of the effluent with the ambient is about 1:3.5. For an inflow of 310 $km^3$ (cf. section 2) the rate of formation of the mixture is 1100 $km^3$ annually, and with a volume of 450,000 $km^3$ for the basin, excluding the bottom water (OSTLUND, 1974), the renewal time is found to be about 410 years. OSTLUND (1974) using the same approach determined a renewal time of 475 years. In spite of the obviously approximate nature of these estimates it is noteworthy that both values are about half of the residence time obtained through radiocarbon dating (OSTLUND, 1974, 1986). The disagreement is important as it indicates that the linear mixing assumed in the calculations may not be representative of the actual process, and that the ultimate distribution of the Mediterranean effluent in the Black Sea and its role in the renewal of the Black Sea waters are questions for further study.

### 3.4. *Variability and blocking of the Mediterranean effluent*

The characteristics of the Mediterranean effluent depend upon the hydrographic structure in the strait. During the course of the investigations, two cases of the blockage of the Mediterranean inflow and one case of blocking of the upper layer flow in the

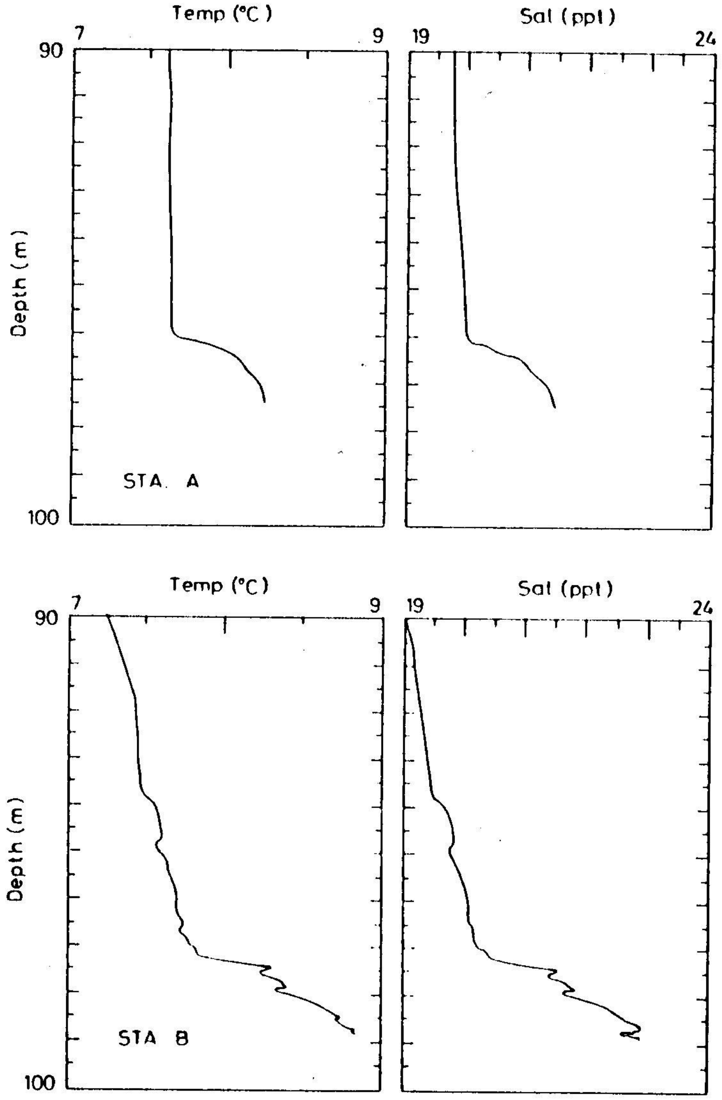


Fig. 5. Temperature and salinity profiles for Stas A and B (locations shown in Fig. 4).

Bosphorus were documented. These are described here to illustrate the hydrographic structure in the strait under extreme conditions and the associated variability in the characteristics of the Mediterranean effluent.

Under calm or moderate winds, the well-known two-layer flow regime prevails in the strait. Figure 6 shows the salinity section for 21 November 1986. The measurements were taken after 5 days of weak northerly winds, ranging between 5 and 10 knots. The Mediterranean inflow can be followed from Sta. M-17 in the Sea of Marmara to Sta. K-15 in the Black Sea as a well-defined plume. The 20-ppt isohaline, which may be taken as the beginning of the interface between the two layers, is at a depth of 42 m in the sill region

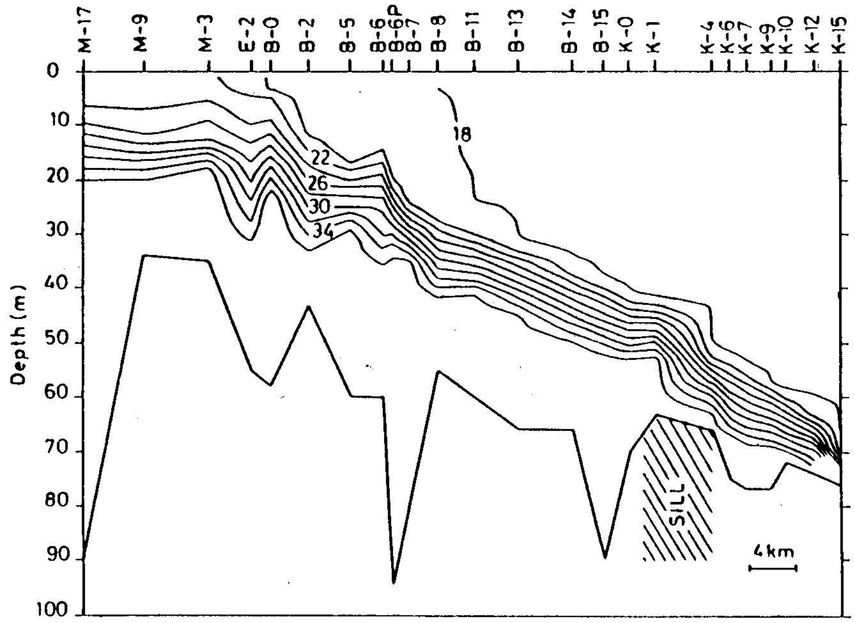


Fig. 6. Salinity section, 21 November 1986.

(Sta. K-1). The salinity increases rapidly across the interface, reaching a value of 36 ppt at 52-m depth. The average salinity of the Mediterranean effluent is about 36.6 ppt at the sill.

The salinity section for 16 January 1987 (Fig. 7) depicts the conditions after a period of strong southwesterly winds which resulted in the blocking of the upper layer flow of Black Sea origin. The daily average wind speed ranged between 10 and 20 knots in the 4 days prior to the cruise. The sea-level difference is expected to be small during this month, thus

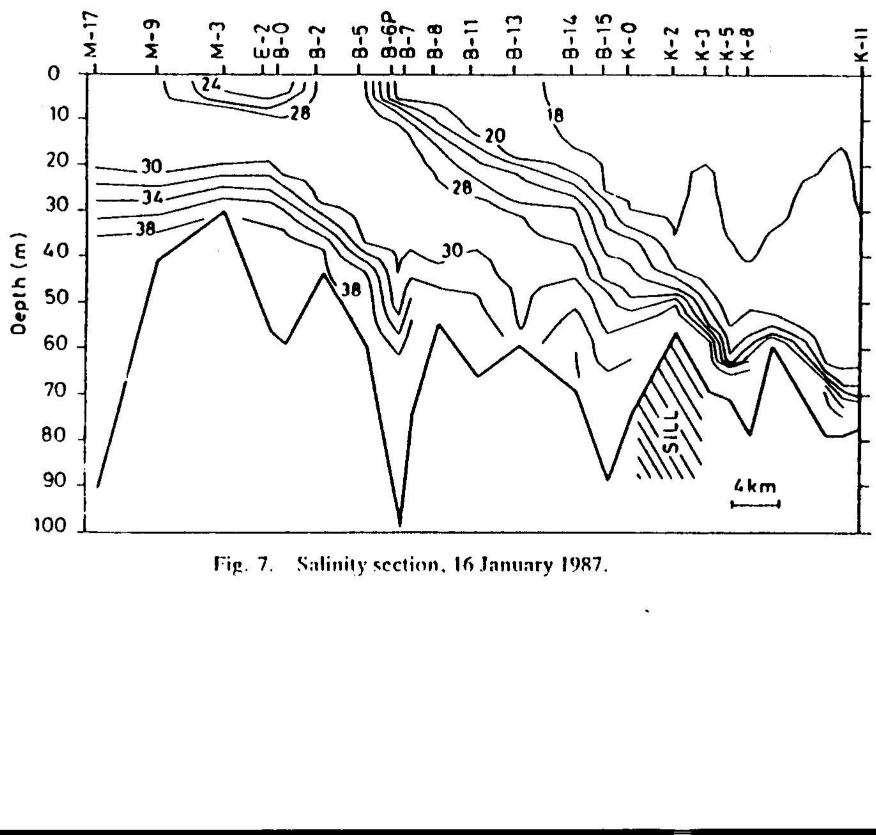


Fig. 7. Salinity section, 16 January 1987.

the effect of the southwesterly winds is enhanced. This combination resulted in an unusual structure in the strait, which is markedly different from the one observed in the November cruise (Fig. 6). A salinity front is observed at the surface near the southern end of the strait (Sta. B-6) indicating the blocking of the upper layer at this location. The greater penetration of the Marmara Sea water is indicated by the higher than normal salinities in the major portion of the strait. It is also evident that greatly increased vertical mixing has taken place, resulting in an average salinity of 31.5 ppt of the effluent over the sill (Sta. K-2), about 5 ppt less than in the case under normal conditions.

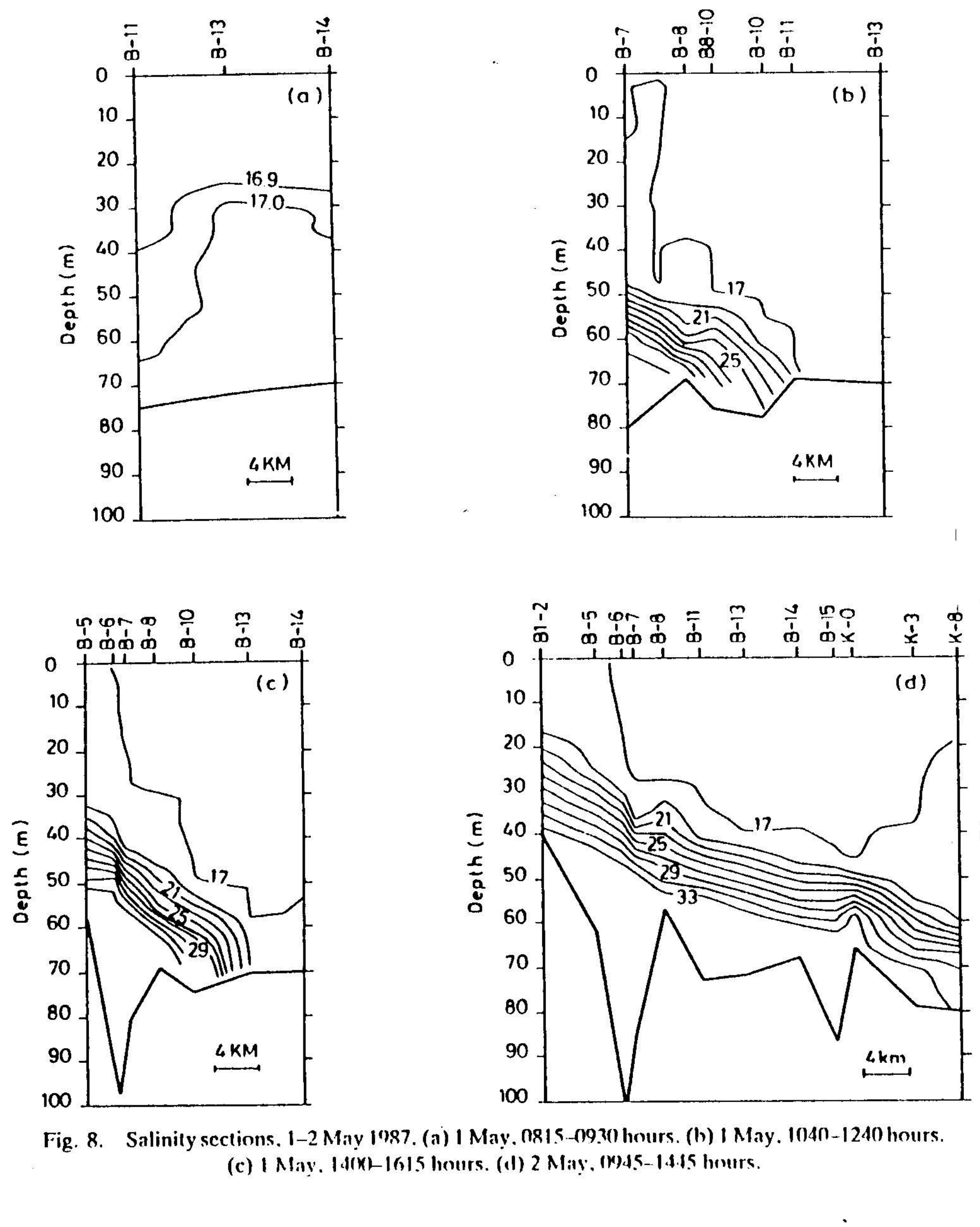


Fig. 8. Salinity sections, 1–2 May 1987. (a) 1 May, 0815–0930 hours. (b) 1 May, 1040–1240 hours. (c) 1 May, 1400–1615 hours. (d) 2 May, 0945–1445 hours.

The blocking and resumption of the Mediterranean inflow was documented in a series of surveys carried out during 1–2 May 1987. The sequence is described below to provide an estimate of the time-scale of the blocking event. The measurements were carried out after 4 days of strong and persistent winds from the NNE–NNW sector, with daily average speeds of 10–15 knots. The first set of data was taken on 1 May, between 0815 and 0930 hours. The northern reach of the strait, north of Sta. B-11, was occupied entirely by Black Sea water with a salinity of about 17 ppt (Fig. 8a). In each case, the measurements were carried out in the deepest locations of the cross-section in order to assure detection of the Mediterranean water.

The next survey, on the same day between 1040 and 1240 hours, covered the region between Stas B-7 and B-13. The salinity at Sta. B-11 was 21 ppt near the bottom, indicating that the Mediterranean water was just reaching this location (Fig. 8b). The following survey, carried out during 1400–1615 hours, showed that the salt wedge had progressed to Sta. B-13 (Fig. 8c). The following day, on 2 May, light southerly winds of about 5 knots prevailed. A survey of the strait, carried out between 0915 and 1445 hours showed that the lower layer flow had resumed (Fig. 8d). Since the total duration of the northerly winds was 4 days, the duration of the blocking was of the order of 2–3 days.

Another case of the blocking of the lower layer, observed on 13 March 1986, is illustrated in the salinity section in Fig. 9. The Mediterranean inflow is blocked at the sill, and the interface has been lowered below the sill level in the major part of the strait. The sharpness of the interface from the northern entrance till Sta. B-7 indicates little mixing between the layers during blocking of the lower layer. The abrupt upward sloping of the isohalines and increased mixing downstream of Sta. B-7 are due to the internal hydraulic control exerted over the flow at this location (Oguz *et al.*, 1990b).

## 4. CONCLUSIONS

Detailed investigations of the Mediterranean inflow through the Bosphorus to the Black Sea, and of the bottom topography in the Bosphorus–Black Sea junction region have

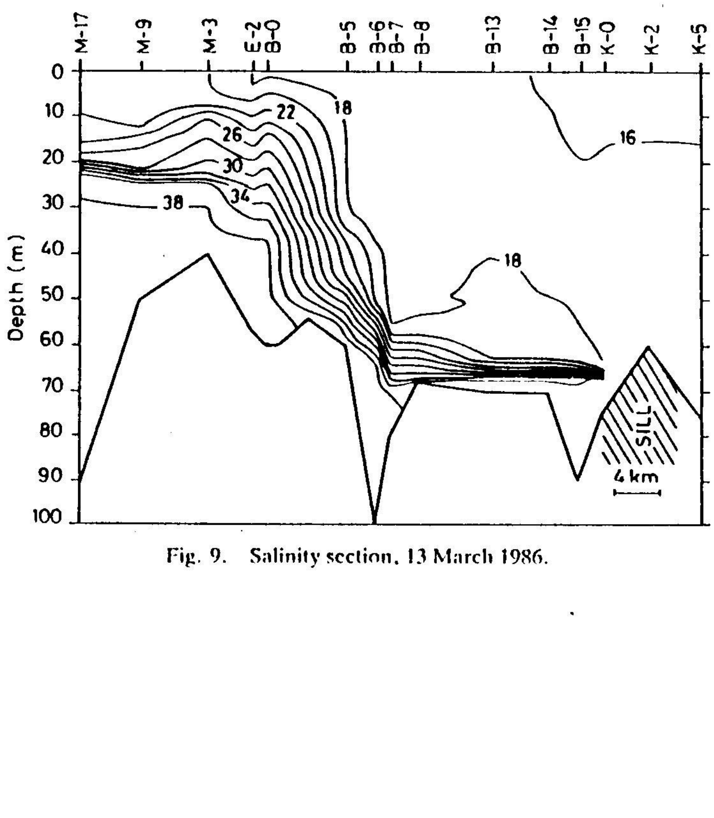


Fig. 9. Salinity section, 13 March 1986.

shown that the inflow enters the Black Sea essentially on a continuous basis throughout the year. The inflow is confined in a narrow channel extending for about 10 km over the adjacent shelf from the northern end of the strait. The details of the channel morphology were not present in the earlier maps, which may have been the reason for the failure of previous investigations to detect the presence of the Mediterranean inflow at the shelf adjacent to the northern entrance of the Bosphorus, and hence to erroneously conclude that the inflow took place intermittently. Blocking of the Mediterranean inflow was found to occur only rarely, under strong and persistent northerly winds. The blocking is short-lived, with a time-scale of the order of about 2–3 days. The findings of the present investigations should be a useful basis for further investigations of the large-scale and long-term distribution of the Mediterranean in the Black Sea.

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## REFERENCES

BOGDANOVA A. K. (1963) The distribution of Mediterranean waters in the Black Sea. *Deep-Sea Research*, **10**, 665–672.

BOGDANOVA A. K. and V. N. STEPANOV (1974) Hydrodynamic estimate of the blocking conditions of the lower Bosphorus current. *Oceanology*, **14**, 37–40.

BÜYÜKÖZDEN A., H. YÜCE and T. BAYRAKTAR (1985a) Investigation of the Mediterranean water along the Bosphorus and the Black Sea. *Doga Bilim Dergisi, Seri B*, **9**, 312–324 (in Turkish).

BÜYÜKÖZDEN A., H. YÜCE and T. BAYRAKTAR (1985b) Investigation of the Mediterranean water along the Bosphorus and the Black Sea. Final report, submitted to the Turkish Scientific and Technical Research Council (in Turkish).

GUNNERSON C. G. and E. OZTURGUT (1974) The Bosphorus. In: *The Black Sea—geology, chemistry, and biology*, E. T. DEGENS and D. A. ROSS, editors, A.A.P.G. Memoir 20, Tulsa, Oklahoma, pp. 99–114.

ILGAZ O. (1944) Notes on the entry of water from the Black Sea and the Bosphorus. *Turk Cografya Dergisi*, **6** (in Turkish).

LATIF M. A., E. ÖZSOY, T. OGUZ, Ü. ÜNLÜATA, O. BASTURK, C. SAYDAM, A. YILMAZ and I. SALIHOGLU (1989a) Oceanographic characteristics of the region surrounding the northern entrance of the Bosphorus as related to the planned sewage outfalls. First annual report, Institute of Marine Sciences, Middle East Technical University, 111 pp.

LATIF M. A., E. ÖZSOY, T. OGUZ, Ü. ÜNLÜATA, O. BASTURK, C. SAYDAM, A. YILMAZ and I. SALIHOGLU (1989b) Oceanographic characteristics of the region surrounding the northern entrance of the Bosphorus as related to the planned sewage outfalls. Final report, Institute of Marine Sciences, Middle East Technical University, 62 pp.

OGUZ T., M. A. LATIF, H. I. SUR, E. ÖZSOY and Ü. ÜNLÜATA (1990a) On the dynamics of the Southern Black Sea. In: *The Black Sea oceanography*, E. IZDAR and J. MURRAY, editors, NATO/ASI Series, Kluwer, Netherlands.

OGUZ T., E. ÖZSOY, M. A. LATIF and Ü. ÜNLÜATA (1990b) Modelling of hydraulically controlled exchange flow in the Bosphorus Strait. *Journal of Physical Oceanography*, **20**, 945–965.

OSTLUND H. G. (1974) Expedition "Odysseus 65": radiocarbon age of Black Sea deep water. In: *The Black Sea—geology, chemistry, and biology*, E. T. DEGENS and D. A. ROSS, editors, A.A.P.G. Memoir 20, Tulsa, Oklahoma, pp. 127–132.

OSTLUND H. G. (1986) Renewal rates of the Black Sea deep water, extended abstract. In: *The chemical and physical oceanography of the Black Sea*, Goteborg.

ÖZSOY E., T. OGUZ, M. A. LATIF and Ü. ÜNLÜATA (1986) Oceanography of the Turkish Straits. First annual report, Vol. 1, Institute of Marine Sciences, Middle East Technical University, 269 pp.

ÖZSOY E., T. OGUZ, M. A. LATIF, Ü. ÜNLÜATA, H. I. SUR and S. BESIKTEPE (1988) Oceanography of the Turkish Straits. Second annual report, Vol. 1, Institute of Marine Sciences, Middle East Technical University, 110 pp.

PEKTAS H. (1953) Surface currents in the Bosphorus and the Sea of Marmara. *Hydrobiology, Seri A*, **1**. Hydrobiology Research Institute, Faculty of Sciences, University of Istanbul, pp. 154–169 (in Turkish).

PEKTAS H. (1956) The influence of the Mediterranean water on the hydrology of the Black Sea. Fourth technical papers meeting, Fisheries Center of Istanbul, Mediterranean General Fisheries Council, 15 pp.

SCHOLTEN R. (1974) The role of the Bosphorus in Black Sea chemistry and sedimentation. In: *The Black Sea—geology, chemistry, and biology*, E. T. DEGENS and D. A. ROSS, editors, A.A.P.G. Memoir, Tulsa, Oklahoma, pp. 115–126.

SMITH P. C. (1975) A streamtube model for bottom boundary currents in the ocean. *Deep-Sea Research*, **22**, 853–873.

SUMER B. M. and M. BAKIOGLU (1981) Sea-strait flow with special reference to Bosphorus. Technical report, Faculty of Civil Engineering, Technical University of Istanbul, 25 pp.

TOLMAZIN D. (1985) Changing coastal oceanography of the Black Sea. In: *Progress in Oceanography*, Vol. 15, M. V. ANGEL and R. L. SMITH, editors, Pergamon Press, Oxford, pp. 217–276.

ULLYOT P. and O. ILGAZ (1943a) Observations on the Bosphorus, I: a definition of standard conditions throughout the year. *Hydrobiology, Seri B*, **8**. Faculty of Science, University of Istanbul, pp. 229–255 (in Turkish).

ULLYOT P. and O. ILGAZ (1943b) Observations on the Bosphorus, II: Review of geographical and hydrographical conditions. *Turk Cografya Dergisi*, **2** (in Turkish).

ULLYOT P. and O. ILGAZ (1946) The hydrography of the Bosphorus: an introduction. *Geographical Review*, **36**, 44–60.

ÜNLÜATA Ü., T. OGUZ, M. A. LATIF and E. ÖZSOY (1990) On the physical oceanography of the Turkish straits. In: *NATO ASI Series Volume: The physical oceanography of sea straits*, L. J. PRATT, editor, Kluwer, Netherlands.