ON THE PHYSICAL OCEANOGRAPHY OF THE TURKISH STRAITS

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ABSTRACT

The Bosphorus and the Dardanelles Straits and the Sea of Marmara constitute a system through which exchange of Mediterranean and the Black Sea waters takes place. The two layer flow regime displays temporal and spatial variability on a wealth of scales. An assessment of the volume fluxes for the various elements of the system, based on recent hydrographic investigations, shows that a major portion of the Mediterranean flow entering through the Dardanelles is transported back to the Aegean Sea due to upward mixing induced by internal hydraulic adjustments of the exchange flow in the straits and by wind in the Sea of Marmara proper. The jet-like Bosphorus outflow in the exit region of the Marmara Sea also has a substantial contribution to the overall upward mixing. A mesoscale anticyclonic eddy to the right of the outflow off the Thracian coast is a quasi-permanent feature of the system. Hydraulic controls in the Bosphorus strait result in a maximal exchange, while a submaximal exchange exists in the Dardanelles. The Mediterranean inflow enters the Black Sea on an essentially continuous basis, with only few, short interruptions.

1. INTRODUCTION

The Turkish Straits, formed by the Bosphorus and Dardanelles Straits and the Sea of Marmara, constitute an oceanographic system through which the exchanges between waters of the Aegean Basin of the Eastern Mediterranean and the Black Seas take place. The low salinity waters of the Black Sea, formed as a result of excess of precipitation and run-off over evaporation, are transported to the Mediterranean through the Turkish Straits System (TSS) as a surface flow. In return, the saltier and heavier waters of the Mediterranean Sea, generated by the excess of evaporation over fresh water input, flow as an undercurrent to the Black Sea to seek their density level.

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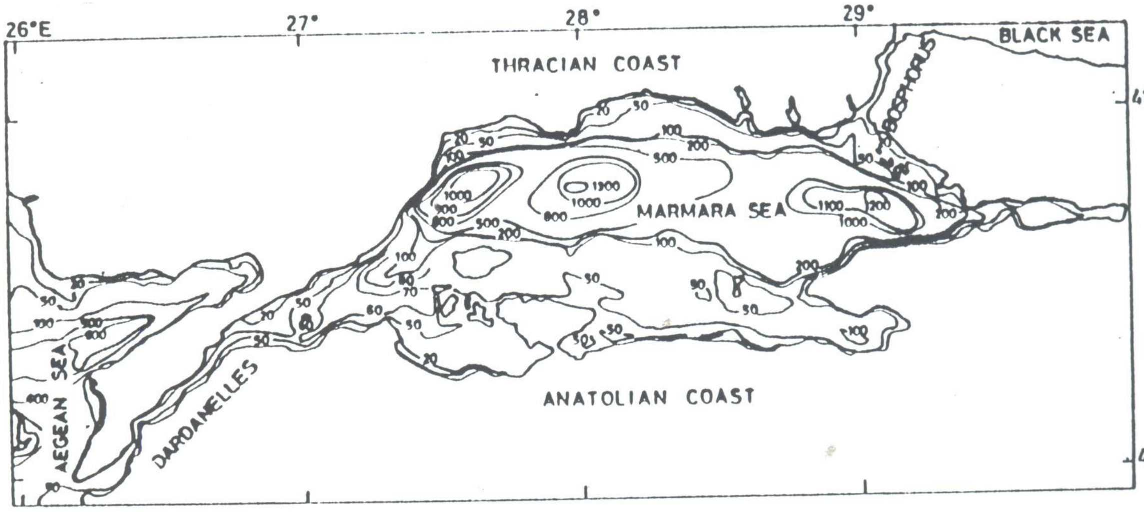

Figure 1. Location map for the Turkish Straits System composed by the Bosphorus and Dardanelles Straits and the Sea of Marmara.

In their evolution through TSS, the traversing water masses generate a unique oceanographic environment, representing a transitory state between the two extremes found in the adjoining seas, with constraints imposed by the hydrodynamical controls of the two straits as well as the interactions of the straits with the Sea of Marmara and the interactions of the entire system with the atmosphere.

The present review is concerned with the physical oceanography of the Turkish Straits. Sections 2 and 3 summarize the salient aspects of the morphometric and atmospheric setting, respectively. Hydrographic characteristics are considered in Section 4. Exchanges between the various components of TSS and with the adjacent seas, and mixing characteristics are covered in Section 5. The dynamics of the Bosphorus and Dardanelles Straits constitute the topics of Section 6. Sea level and current variability are discussed in Section 7. The interaction of the Bosphorus with the Black Sea is given in Section 8 which is followed by an overall summary and conclusions in Section 9. An evaluation of the volume fluxes described in Section 5 is provided in the Appendix.

It is worth mentioning that the present review is largely based on the investigations carried out in recent years by the Institute of Marine Sciences of the Middle East Technical University, Turkey. These continuing investigations commenced in 1986 and are primarily concerned with the evolution of the present state of health and the oceanography of TSS and the regions surrounding the junctions of the system with the adjacent seas. The research program, an exhaustive literature survey and the results to date (including chemical aspects) are given in detail in a series of reports published by the above mentioned Instute of Marine Sciences (Özsoy *et al.*, 1986, 1988; Ünlüata and Özsoy, 1986;

Latif *et al.*, 1989a; Baştürk *et al.*, 1986, 1988). The review by Ünlüata and Oğuz (1983) provides a summary of results prior to 1983.

2. MORPHOMETRIC CHARACTERISTICS

The Sea of Marmara (Fig. 1) is a relatively small inter-continental basin with a surface area of 11500 km^2 and a volume of 3378 km^3. It is connected to the Black Sea and the Aegean Sea through the straits of Bosphorus and the Dardanelles, respectively. The east-west length of the basin is roughly 240 km and the north-south width is approximately 70 km. The North Anatolian Fault crosses the region in the east-west direction, and "pull-apart" basins associated with this fault are located on the northern side of the sea. Here, three sub-basins with depths in excess of 1000 m (maximum depth 1300 m) have been formed, oriented also in the east-west direction. The southern half of the Marmara Sea is characterised by a relatively shallow shelf region with an average depth of 100 m. The length of the European shore-line is 264 km. The shore-line on the Asian side is longer (663 km).

The Bosphorus and the Dardanelles are narrow elongated Straits. The Bosphorus is nearly 31 km in length, and its width varies between 0.7-3.5 km, with a mean depth of 35 m and a maximum depth of 110 m. The narrowest width occurs at about 12 km north of the southern end. A sill of about 33 m depth is located approximately 3 km north of the southern end. while a sill of 60 m is located 4 km north of its northern end. The Dardanelles has a length of nearly 62 km and its width varies between 1.2-7 km, the average width being 4 km. The average depth of the strait is 55 m. The narrowest section occurs at the Nara Passage about 25 km east of its junction with the Aegean Sea.

3. ATMOSPHERIC SETTING

The region is affected by two distinct seasonal climatic regimes. During the winter, the weather is dominated by an almost continuous passage of cyclonic systems. During the summer, northerly winds from the Black Sea are dominant. Between 30-40 cyclonic systems, occurring during October through April, follow three main tracks (Trewartha, 1968). In the southern part of the straits system, the cyclones move eastward over the Aegean towards the eastern Levantine basin; in the north, the tracks are from the Balkans towards the eastern Black Sea, and the third route is northeasterly from the Aegean Sea towards the Black Sea. The systems affect the region for periods between three to ten days, and often result in winds of 8 m/s to 10 m/s (hourly average speeds) sustained over one to two days. Maximum speeds of 35 m/s have been observed as gusts.

On an annual basis, northerly winds (from the NW-NE sector) are dominant with a frequency of 60%, with southerlies (SW-SE sector) occurring 20% of the time (De Filippi *et al.*, 1986). However, during the winter, winds from either sector are equal in both frequency and strength. For the three year period 1985-1987, in winter (December-March) the average frequency was 35% for each of these directions (Büyükay, 1989).

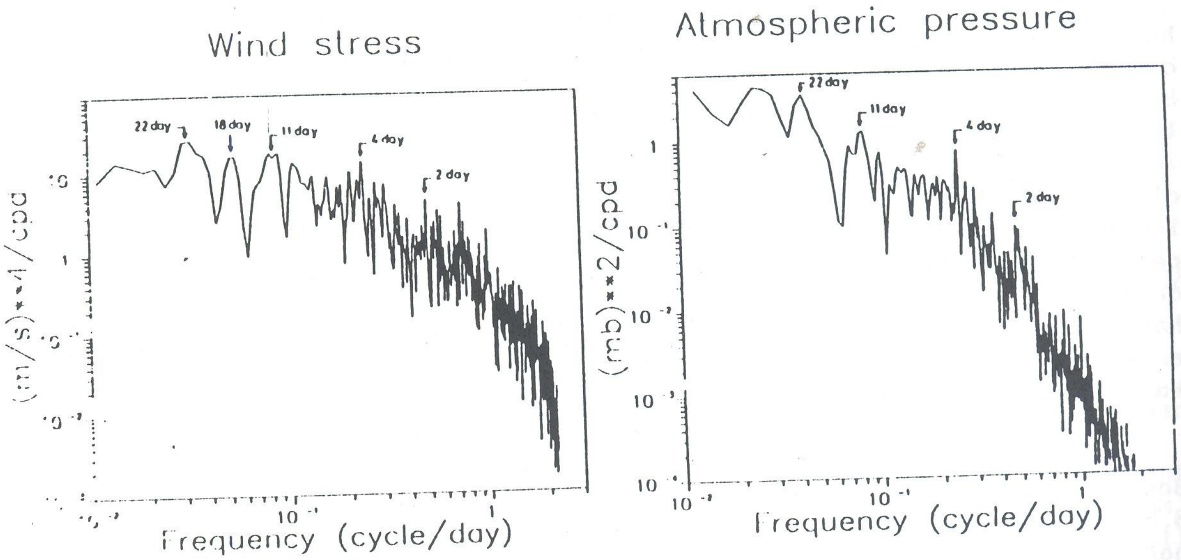

Figure 2. Wind stress and atmospheric pressure spectrum at Kumköy meteorological station, located at the Black Sea entrance of the Bosphorus Strait, for 1985.

Power spectra of wind stress and atmospheric pressure at the Kumköy meteorological station located near the Black Sea entrance of the Bosphorus shows peaks near 3, 4, 5, 7, 11, 15 and 20 days (Fig. 2). These spectra are based on the time series for the entire year of 1985. The observed spectral peaks correspond to the passage of cyclonic systems (Büyükay, 1989). Similar time scales have also been inferred by Gunnerson and Özturgut (1974).

Rainfall occurs mostly during October through March, leading to a precipitation of 7 km^3/yr over the Marmara Basin. The mean evaporation is estimated as 11 km^3/yr (Özsoy, *et al.*, 1988). These fluxes are negligible in comparision to the exchange flows with the adjacent basins (Section 5).

The mean air temperatures range from 5 °C in winters to 25 °C in summers, with a diurnal range of 2-10 °C. The solar radiation, the net long wave, evaporative heat and the sensible heat fluxes are estimated as 108, 50, 52. and 2.8 kcal per square centimeter per year (Özsoy, *et al.*, 1986).

4. HYDROGRAPHIC CHARACTERISTICS

The hydrographic characteristics of the Turkish Straits and their variability in space and time are discussed in detail by Özsoy *et al.* (1986, 1988) by utilizing all available data. A wealth of time scales, extending from the inertial period (18 hrs), to days, to months, to seasonal, to interannual and longer periods, exists. Variability on the seasonal or longer time scales has been shown to be related to the response of the region to local climatic changes as well as those occurring in the adjacent Aegean and Black Seas. The seasonal changes are mostly reflected in the upper layer and may further be modulated by the long-term or interannual variations in the climatology. Internal hydraulics of the Straits, jets in the exit regions, the general circulation of the Sea of Marmara, deep water renewals and double diffusive processes also generate a rich variety of spatial scales.

In this section we will be primarily concerned with the seasonal and the sub-basin scale variability in salinity and temperature including the effects of transient wind episodes of few days duration.

In general, TSS is stratified in two layers with a sharp pycnocline whose depth changes from 50 m at the Black Sea entrance to 10 m at the Aegean exit, with a depth of 20-25 m within the Marmara proper. The density changes across the pycnocline are mainly accounted by the differences of salinity between the layers, with the lower salinity waters of Black Sea origin overlying the high salinity Mediterranean waters below the halocline. The degree of stratification changes seasonally depending mainly on the conditions in the adjacent deep basins.

4.1 Local and Seasonal Variability

Seasonal variability in the TSS is presented in Fig. 3 using the profiles of temperature and salinity at two stations located within the central parts of the Bosphorus and Dardanelles Straits. These figures demonstrate that the upper layer has considerable seasonal variations together with additional shorter term changes in response to local meteorological conditions. Specifically, the upper layer deepens occasionally during the periods of increased surface inflow caused by strong northerly winds in the winter months (as indicated by the profiles numbered 2 and 3 in Fig. 3). In the opposite case, the upper layer structure is lost due to short term effects of southwesterly winds as shown by the profiles numbered 1 at the Bosphorus station.

In general terms, the temperature of the upper layer undergoes greater changes in response to the surface heating/cooling. In winter, from November till May, the surface layer becomes colder than the lower layer with temperatures decreasing to about 4 °C. After May, the temperature of near-surface levels increases up to 24 °C as a result of radiative heating. A remnant of cold water is however observed between

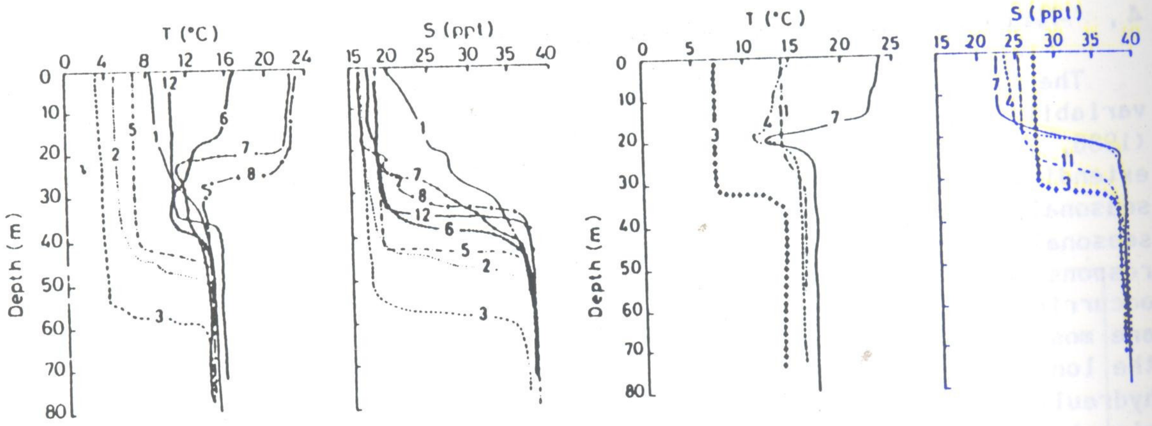

Figure 3. Profiles of temperature and salinity at the Bosphorus Strait (left) and the Dardanelles Strait (right) during 1986. (Numbers indicate the month).

the warm surface layer and the interface. This subsurface cold layer is in fact partially formed within the TSS and is partially advected from the Black Sea. The upper layer salinity varies within the range of 16-18 ppt in the Bosphorus station and 23-28 ppt in the Dardanelles station through the year. Relatively larger surface salinities of the winter period generally decrease somewhat in the late spring and summer as a result of increased fresh water inflow from the Black Sea.

The lower layer properties display their most pronounced seasonal changes in the Dardanelles Strait in response to the seasonal changes in the properties of the inflowing Aegean waters (Fig. 3). The lower layer average temperature in the Dardanelles, for a total of 7 surveys during 1986-1987, indicates the lowest temperature (13.1 °C) in March and the highest temperatures of about 16.5 °C in July-August. The variability in the lower layer average salinity occurs within the range of 38.5-38.7 ppt. As compared to the variability observed in the Dardanelles, the subhalocline waters of the Sea of Marmara possess much more stable properties having average temperature and salinity of 14.48 °C and 38.52 ppt with variations of ±0.04 °C and ±0.03 ppt. The seasonal variability of the lower layer properties along the Bosphorus occurs within the temperature and salinity ranges of 12.5-14.5 °C and 35-37.5 ppt depending on the intensity of local vertical mixing across the interface (Fig. 3).

4.2 Spatial Variability

Apart from the temporal variability, the water masses also change their identities while they are traversing the system in both directions. Many of the changes in the lower layer waters of Mediterranean origin take place in the Dardanelles Strait before they exit into the deep Marmara basin and within the Bosphorus as they eventually join into the Black Sea. In contrast, the most significant changes of the upper layer waters of the Black Sea origin take place in the southernmost reaches of the Bosphorus, its exit region to the Marmara Sea, and the southwestern part of the Dardanelles. The upper layer water masses are particularly modified in localized regions of the system where the flow is hydraulically controlled and is, therefore, subject to significant vertical mixing in the regions of supercritical flow and the subsequent internal hydraulic jumps.

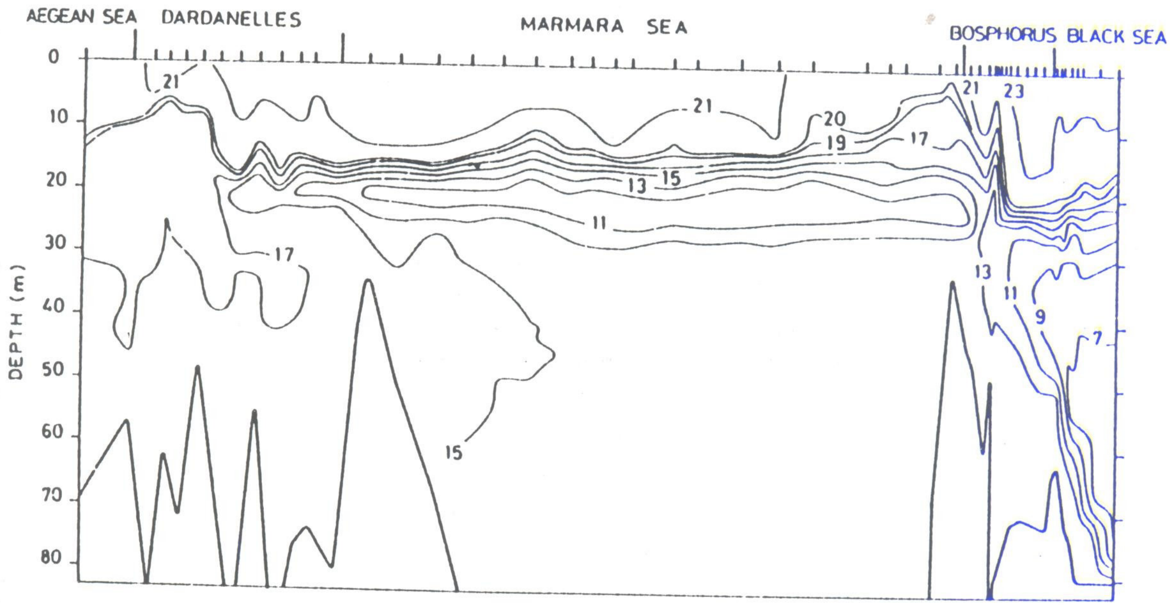

Figure 4a. The longitudinal variation of temperature in the Turkish Straits System during July 1986.

The above aspects of the TSS are displayed in Figs. 4a,b where typical longitudinal transects of temperature and salinity in TSS, extending from the pre-Bosphorus area of the Black Sea to the Aegean exit, are given. It is seen that near the Black Sea entrance of the Bosphorus, the upper layer is deep and the interface level is only slightly above the sill depth (60 m). The transport from the Black Sea of the cold intermediate layer (Tolmazin, 1985) is seen in the temperature transect. Towards the southern end of the Bosphorus, significant changes take place with respect to the position of interface, and stratification. The interface tilts almost linearly towards the free surface and the interfacial layer becomes much thicker, with a typical value of about 20m.

Relatively uniform conditions prevail within the Marmara Sea proper up to the central part of the Dardanelles Strait as implied by the horizontal distributions of the isotherms and the isohalines in Figs.

4a,b. The surface layer attains salinity values of about 22-23 ppt which is an increase of almost 3-4 ppt as compared with further upstream in the vicinity of the Bosphorus southern entrance. The temperature structure presents a radiatively heated warm layer of about 15-20 m with temperatures of 20-21 °C below which a layer of colder water resides immediately above the halocline level, with a minimum temperature of approximately 10 °C. The uniformity of the properties within the Dardanelles is destroyed as the flow passes through the elbow-shaped Nara Burnu section after which, up to the Aegean exit of the Strait, the temperature and salinity display asymmetric distributions similar to those observed in the southern Bosphorus. The upper layer flow joins the Aegean Sea with 27-28 ppt surface salinity which indicates almost 10 ppt surface salinity difference between two extreme ends of the TSS.

The underflow entering into the TSS from its Aegean end also attains most of its significant characteristics in the Dardanelles and the Bosphorus Straits. The relatively denser Aegean waters enter below the depth of 15-20 m and undergo gradual changes through the Dardanelles Strait and its transition region to the western Marmara basin. Along the topographic slope adjoining the wide channel region to the Marmara Sea, they sink towards the density level where they reside in the form of a dense plume. The sinking plume subsequently takes part in the renewal of the subhalocline waters of the Marmara Sea by spreading horizontally in the form of intrusive layers at the corresponding depths to which it sinks (Ünlüata and Özsoy, 1986; Özsoy, *et al.*, 1988).

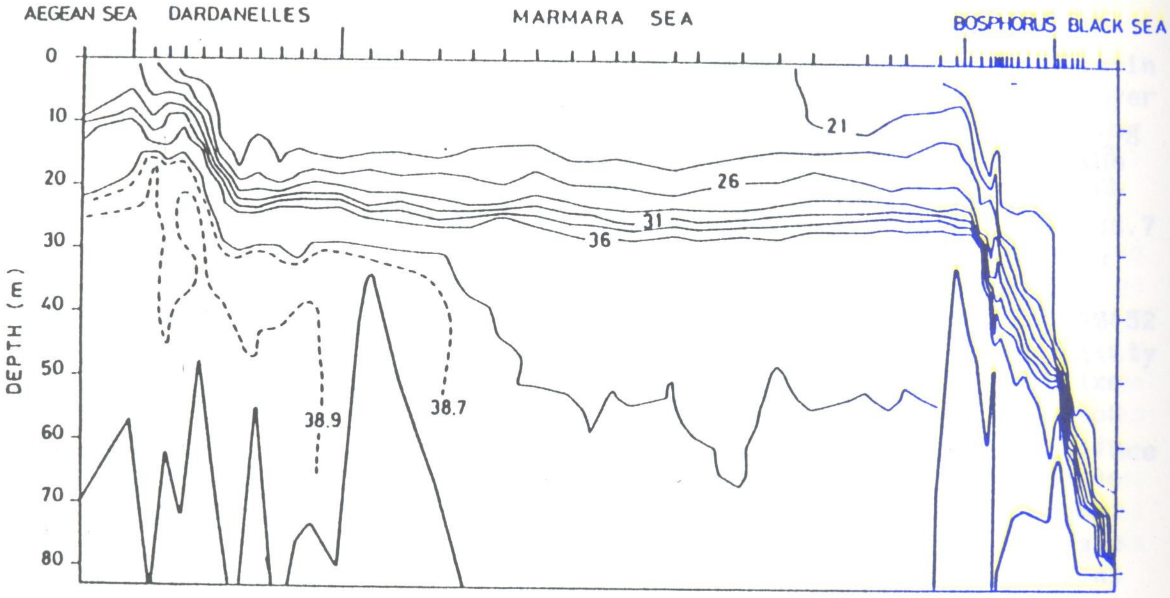

Figure 4b. The longitudinal variation of salinity in the Turkish Straits System during July 1986.

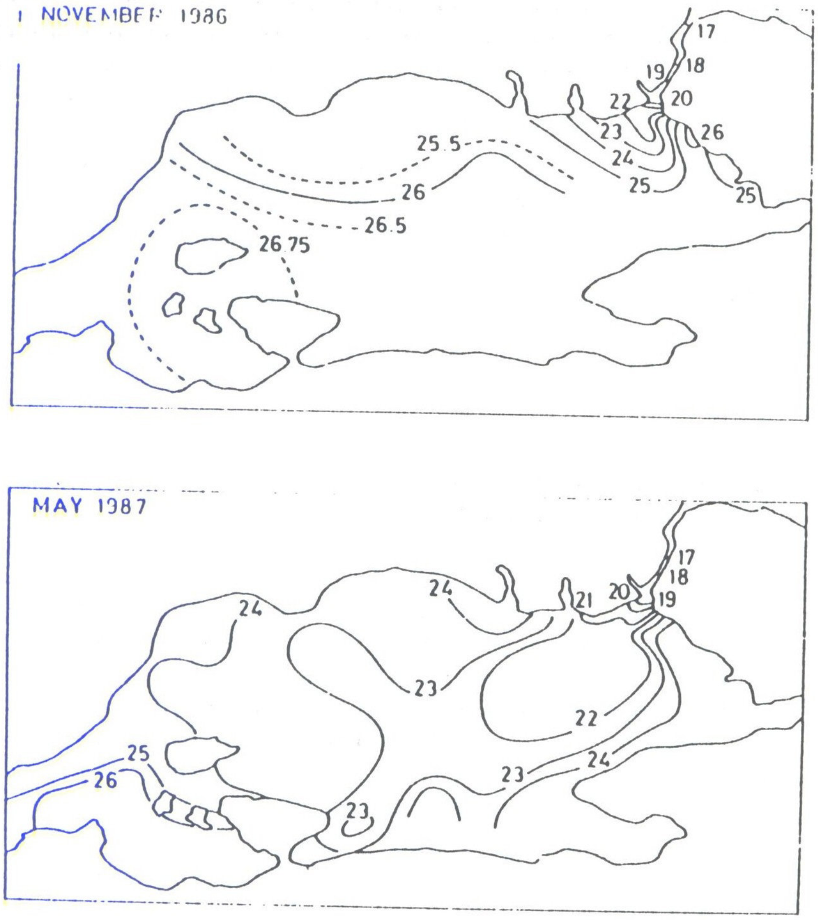

Figure 5a. Distribution of surface salinity in the Turkish Straits System for November 1986 and May 1987.

Upon reaching the Bosphorus-Marmara junction region, the lower layer waters flow into the Bosphorus through the submarine canyon. Thereafter, the underflow interacts with local topography at the southern and northern sill regions of the Bosphorus, becomes progressively diluted and enters the Black Sea shelf as a thin plume. Further characteristics of the Mediterranean effluent exiting from the northern end of the Bosphorus are described separately in Section 8.

The surface flow from the Bosphorus enters the triangular-shaped Marmara junction region in the form of a shallow and narrow turbulent buoyant jet with currents in excess of 2 m/s at the surface. It can be inferred from the surface salinity distributions (Fig. 5a) and from relevant measurements (Ünlüata and Oğuz, 1983; De Filippi, *et al.*, 1986; Özsoy *et al.*, 1986, 1988) that, immediately south of the Bosphorus exit section, the surface jet tends to spread asymmetrically, with more intense flow on the side of the Anatolian coast. The surface outflow proceeding in the southerly direction then bifurcates into two branches.

As one branch continues to flow in the south-southwesterly direction, the other branch of the jet turns anticyclonically and proceeds north-northwest towards the Thracian coast.

Figure 5b. Conceptual sketch of the upper and lower layer circulations in the Bosphorus-Marmara junction region.

The surface waters that are inshore of the northwestward curling main flow form a quasi-permanent anticyclonic mesoscale eddy (Ünlüata and Oğuz, 1983). The size of the eddy and the intensity of the flow dispersing within the region may however vary depending on the atmospheric conditions and the strength of the Bosphorus surface outflow. Most notable changes evidently occur during winter months when the Bosphorus surface outflow is appreciably weaker and during southerly and southwesterly winds prevailing over the region. Under these conditions, the jet core exiting from the Bosphorus does not deflect to the east and concentrates directly towards the northern (Thracian) coast. The presence of anticyclonic circulation within the Bosphorus-Marmara junction (BMJ) region is also supported by recent current measurements (De Filippi *et al.*, 1986; cf. Section 7).

It is worth mentioning that there is evidence to the effect that a secondary cyclonic circulation exists in the lower layer below the anticyclonic eddy at the surface (Ünlüata and Oğuz, 1983; De Filippi *et al.*, 1986). These features are illustrated conceptually in Fig. 5b.

The eastward intensification of the flow emanating from the Bosphorus as well as the subsequent anticyclonic eddy will be reconsidered in Sec. 6.

5. VOLUME FLUXES AND MIXING CHARACTERISTICS

Upon modelling the Turkish Straits as a two-layer system and decomposing it into three coupled compartments, corresponding to the Bosphorus, the Sea of Marmara and the Dardanelles. the horizontal and vertical volume fluxes defining the time-averaged exchanges between the elements of the system as well as the exchanges of the entire system with the adjacent seas have been estimated by Özsoy et al. (1986, 1988).

The fluxes are computed by making use of the steady state salt and mass conservation equations. The recent measurements carried out during 1986-1987 are utilized for the average salinity values at the junctions of the system. The results are summarized in Fig. 6.

The present estimates of the Bosphorus flows differ from most previous estimates by nearly 40 %. This is due to the utilization of different net fresh water input values for the Black Sea. The present estimates are, however, consistent with the separate and independent numerical computations that are based on the sea level differences at the two ends of the Bosphorus. These points are discussed in the Appendix.

It is seen from Fig. 6 that, in the mean, the Black Sea water with salinity ≈17.8 ppt flowing through the Bosphorus as a surface layer enters the Sea of Marmara with ≈19.4 ppt salinity. While crossing the Sea of Marmara its salinity increases by nearly 6 ppt. After increasing by another 4 ppt, it exits from the Dardanelles with a salinity of 29.62 ppt. These changes are in reasonable accord with those reported by Defant (1961, p.523). On the other hand, the Aegean water with a salinity of 38.9 ppt entering the Dardanelles traverses the strait with little changes in its salt content. Within the Marmara basin a reduction of nearly 2 ppt is observed in the salinity of this water. After getting diluted by another 2 ppt in transit through the Bosphorus, the Mediterranean waters enter the Black Sea with nearly 35 ppt salinity.

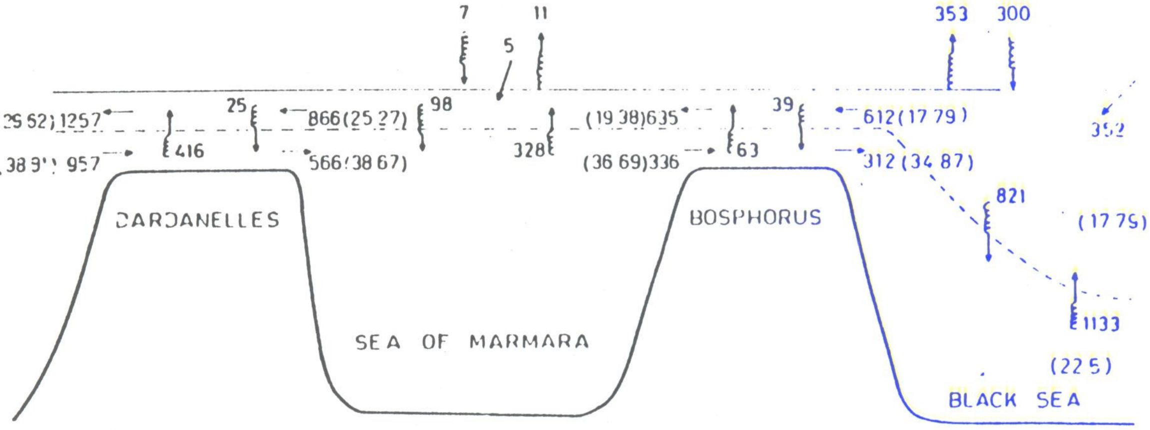

Figure 6. Volume fluxes across the compartments of the Turkish Straits System. The numbers are in km³/yr. The numbers in parentheses indicate salinities in ppt.

The flow rate of 612 km³/yr of the surface layer at the Black Sea-Bosphorus junction does not differ much from that of 636 km³/yr at the Bosphorus-Marmara junction. The surface flow entering the Dardanelles at its junction with the Sea of Marmara is larger than the flow exiting the Bosphorus by an amount of 230 km³/yr, and increases further by 391 km³/yr at the Dardanelles-Aegean Junction. Mediterranean waters entering the Dardanelles at a rate of 957 km³/yr exit into the Sea of Marmara and enter into the Bosphorus at the rates of 566 km³/yr and 336 km³/yr, respectively. Such substantial reductions in flow rates do not occur along the Bosphorus.

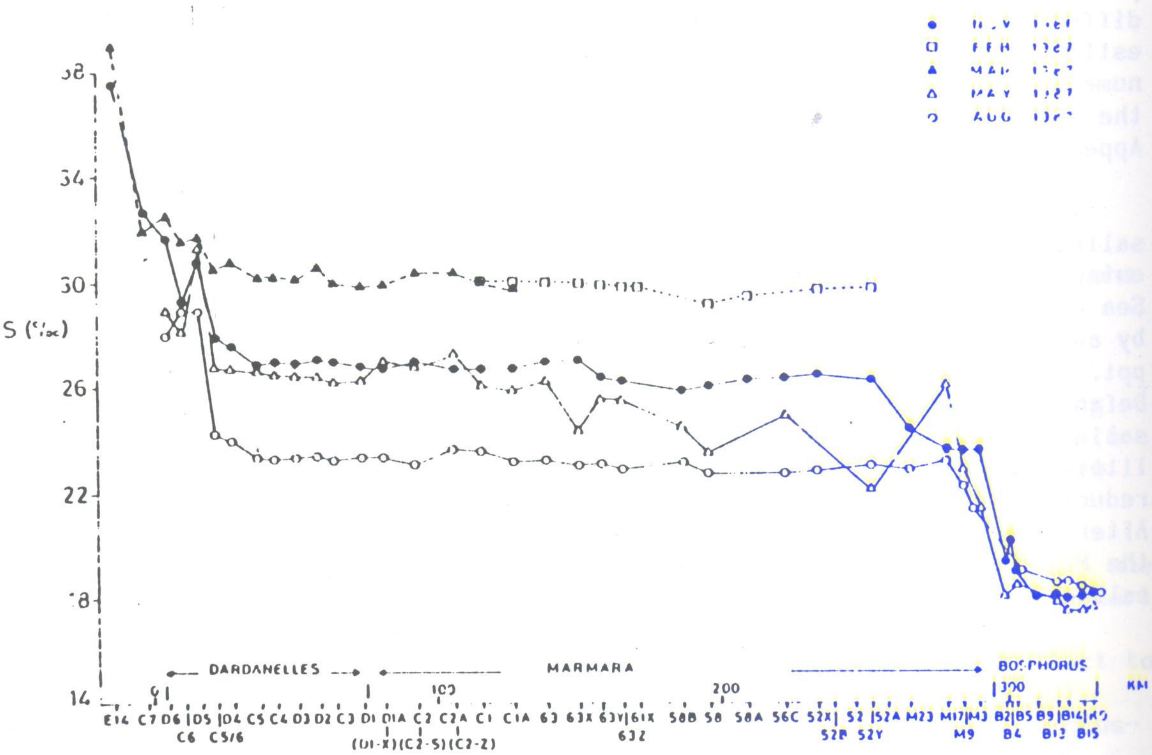

Figure 7. Upper layer averages of salinity along the Turkish Straits System.

In view of the relatively small precipitation and evaporation fluxes (cf. Section 3), the increases in the flow rates of the surface layer, together with increases in salinities, clearly indicate entrainment of the subhalocline waters into the surface layer, especially within the Dardanelles and the Sea of Marmara. Indeed, the most striking aspect of the water budget of the system is that nearly seventy percent of the underflow entering from the Aegean Sea is returned back before reaching the Black Sea, the values of the inflow being recirculated back to the Aegean within the Dardanelles, Marmara and the Bosphorus being 41, 24, and 3 percent, respectively.

With the exception of the Bosphorus, the upward mixing dominates in the system. The upward and downward mixing in the Bosphorus do not differ much from each other, the net upward flux being 24 km³/yr which is 7 % of the inflow from the Marmara basin.

Previous assessments of the exchanges of the Black Sea with the Mediterranean have been based on the fluxes through Bosphorus (Sverdrup *et al.*, 1946; Tixeront, 1970; Ovchinnikov, 1974). A comparison of the Bosphorus flows with the flows through the Dardanelles, especially at the junction with the Aegean, reveals significant differences. The outflow into the Aegean is found to be nearly twice the Bosphorus outflow into the Sea of Marmara, while the inflow from the Aegean is three times larger than the Bosphorus underflow.

Utilizing the fluxes reported in Fig. 6, the residence times are estimated as ≈3 months for the surface layer of volume 230 km^3 and ≈5 years for the lower layer waters of volume 3148 km^3. It may be of interest to note that the estimated residence times for the Mediterranean and the Black Sea deep waters are 70 and 500-2000 years, respectively (Lacombe *et al.*, 1981; Östlund, 1969, 1986).

It is important to note that even though the budgetary calculations indicate significant upward mixing in the Dardanelles and the Sea of Marmara, the physical mechanisms leading to the entrainment as well as the region of their predominance cannot be inferred from them.

The upward mixing within the Sea of Marmara is due to 3 mechanisms. An internal hydraulic jump (see Section 6) initiated at the southern entrance of the Bosphorus as well as the surface jet emanating from the Bosphorus inject the saltier subhalocline waters into the surface layer. These two mechanisms operate on a continuous basis and induce intense and rapidly varying upward mixing and are effective within the Bosphorus exit region adjoining the Sea of Marmara. Their influence can be inferred from the longitudinal variations of the upper layer salinity across the Turkish Straits displayed in Fig. 7 where it is seen that the salinity of the surface layers rapidly change by as much as 6 ppt within

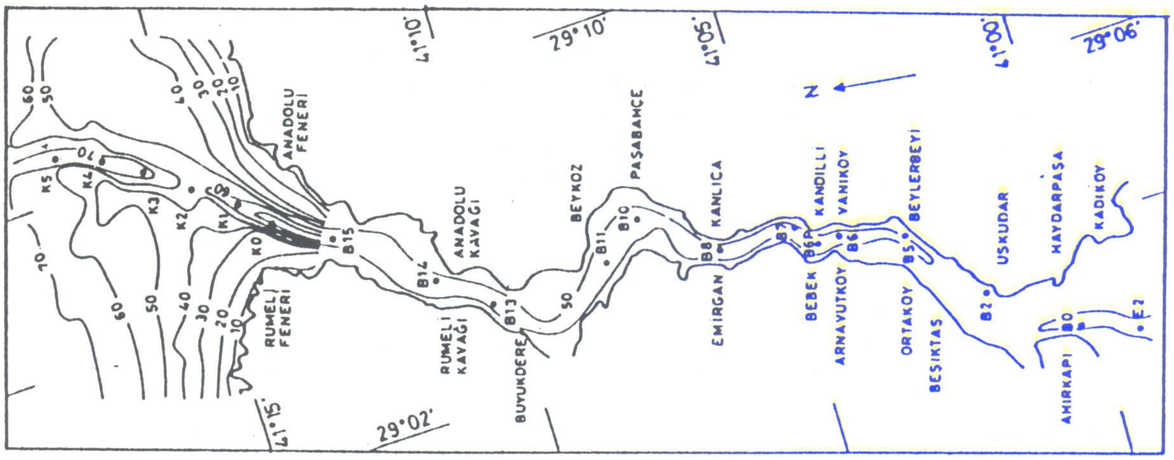

Figure 8a. Plan view of the Bosphorus geometry and locations of hydrographic stations.

20 km of the Marmara junction of the Bosphorus (Özsoy *et al.* 1986, 1988). The third mechanism of vertical entrainment involves the influence of winds down to the shallow halocline (20 m).

The upward mixing within the Dardanelles is induced by internal hydraulic adjustments of the flow initiated at the narrowest section of the Strait (Nara Passage) located at station D4 in Fig. 7 and at the abruptly widening Aegean exit region (Özsoy *et al.* 1986, 1988; Oğuz and Sur, 1989).

6. DYNAMICAL CHARACTERISTICS

The dynamics of the two layer water exchange through the Turkish Straits constitute one of the classical examples in oceanography. The differential surface elevation across TSS due to the net fresh water input to the Black Sea provides a barotropic pressure gradient, leading to the southerly flow of brackish waters. The opposite underflow of denser waters, on the other hand, arises due to the baroclinic pressure gradient established in response to marked salinity differences between the Aegean and the Black Seas. A simple dynamical account of this system of exchange flow was first studied in a two layer model by Defant (1961) in which the hydrostatically derived pressure gradient is balanced by friction. Recent related works are reviewed by Tolmazin (1985) and Özsoy *et al.*, (1986).

An important dynamical feature regarding the overall structure of the water exchange through TSS is the presence of internal hydraulic transitions of the two way exchange flow within the Bosphorus and the Dardanelles Strait. Observations carried out monthly in the Bosphorus and seasonally in the Dardanelles during 1986-1989, indicate the existence of a series of internal hydraulic adjustments of the exchange flow at various sections, similar to those encountered in the Strait of Gibraltar (Armi and Farmer, 1985, 1988). The internal hydraulic controls in the Bosphorus and the Dardanelles are inferred from the asymmetrical characteristics of the measured property fields, rapid transitions at the interface depth, and the associated intense vertical mixing at certain locations (Figs. 8a,b and Fig. 10a; cf. Figs. 4a,b) as well as from the quantitative evidence (Figs. 9a,b and Fig. 10b) provided by the two layer numerical models developed by Oğuz and Sur (1989) and Oğuz *et al.* (1989).

The TSS in general, and the Bosphorus in particular exhibit a complex flow system with considerable temporal and spatial variability. While the seasonal variability is related with the changes in the conditions in the adjacent basins, the low frequency variations on the time scales of few days, associated with the wind and atmospheric pressure changes, may dominate the flow and give rise to substantial modification of the regional flow structure. This is particularly observed in winter at the times of pronounced northerlies and southerlies. In the Bosphorus, when they are sufficiently intense, they

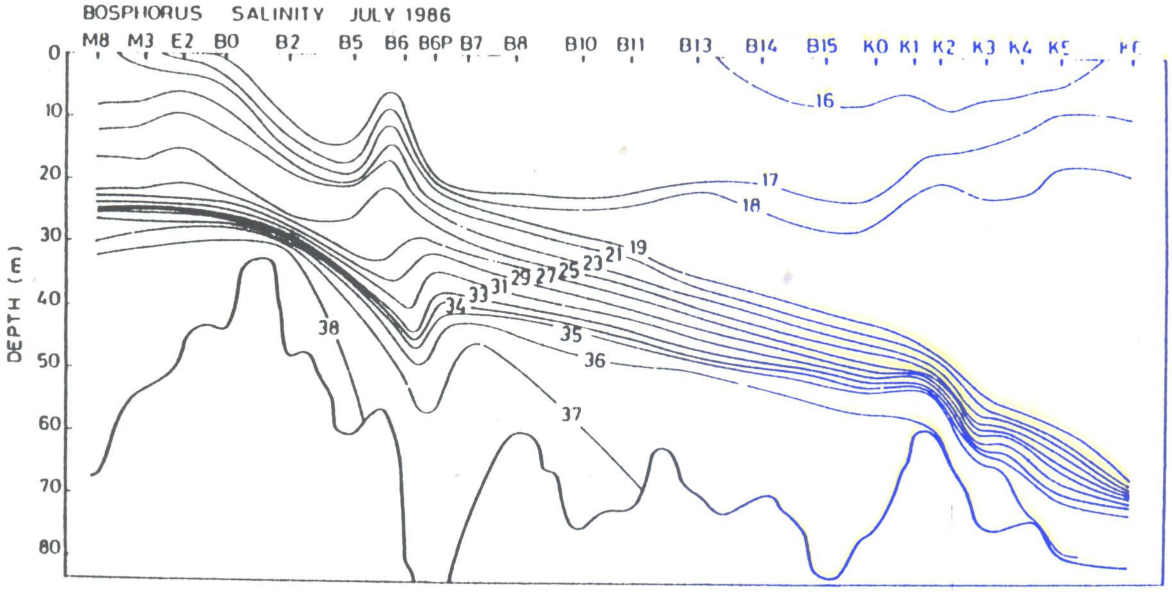

Figure 8b. Salinity transect in the Bosphorus and its exit regions during July 1986, corrsponding to Fig. 4b in expanded scale.

lead to the blockage of either the lower or upper layer depending on the direction of the wind. These cases resemble the solutions with the so-called "intermediate and strong barotropic forcing" given by Farmer and Armi (1986). They further reflect the significance of the time dependent adjustment process during such events. The tidal signal is weak, on the order of 10 cm, and does not have any important contribution to the flow field.

Hydrographic observations carried out recently in the Bosphorus on a monthly basis with a closely spaced station network consistently reveal considerable nonlinearity in the position of the interface and increased vertical mixing, which may possibly be associated with the internal hydraulic jumps and/or lee waves. These features are particularly pronounced in the southern half of the strait, to the south of station B8, where there are certain morphological features (horizontal and vertical constrictions and abrupt expansion of the width) which may lead to the internal hydraulic adjustment of the exhange flow (Fig. 8b). The observations indicate that the Bosphorus Strait possesses interesting internal hydraulic characteristics whose satisfactory description requires current velocity profiles of sufficient resolution and duration, in addition to the existing closely spaced CTD casts.

The two-layer model results (cf. Oğuz *et al.*, 1989) indicate that the Bosphorus possesses distinct regions of supercritical flows (Figs. 9a,b). The upper layer flow is first controlled at the constricted region (between stations B8 and B6). The interface, which is located at

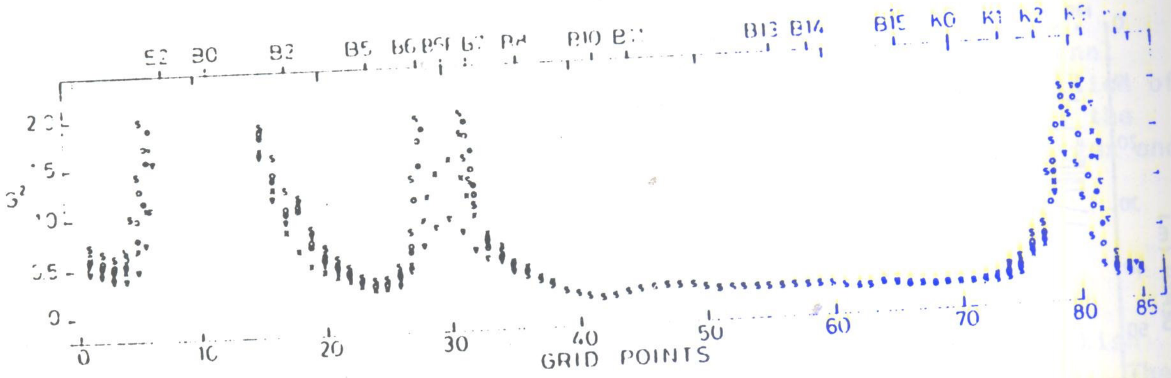

Figure 9a. The computed composite Froude number distributions along the Bosphorus for various net barotropic flow (after Oğuz et al., 1989).

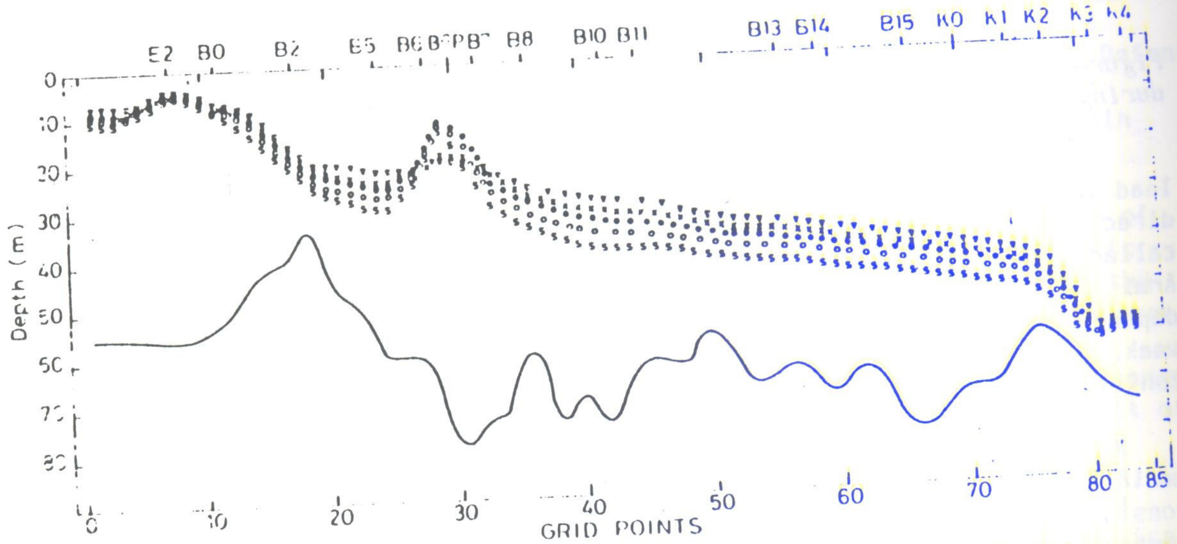

Figure 9b. The computed variations of interface along the Bosphorus for various values of net barotropic flow (after Oğuz et al., 1989).

deeper levels to the north of this region, is sharply elevated. In this way, the flow adjusts itself to the critical hydraulic condition and the upper layer flow becomes supercritical immediately to the south of the constriction. Thereafter, the interface depth declines and the surface layer undergoes an internal hydraulic jump so that it passes through another critical section at the southern exit region (generally, between stations B2 and E2). The model computations show the supercritical region at the abruptly widening Marmara exit region comprises a distance of about 3 km covering a recirculation zone in the surface layer immediately upstream of the exit. The supercritical exit flow is subsequently matched farther downstream (near station M3 in the

Bosphorus-Marmara junction region) to the equilibrium conditions of the Marmara Sea through another internal hydraulic jump.

Further hydraulic controls in the Bosphorus Strait occur due to the effect of the sill on the lower layer flow. The underflow traverses the Dardanelles Strait and the Marmara Sea in its subcritical state. After it enters into the Bosphorus Strait, it proceeds northward in a progressively thinner layer towards the Black Sea, and controlled over the northern sill. The absence of controlled flow at the southern sill could be either a genuine feature of the model or could be associated with the computed position of interface which leads to an inadequate representation of the bottom layer in the model. The effect of southern sill on the flow structure remains to be explored by future computational and observational studies.

The underflow may be blocked by the northern sill under extreme conditions (cf. Section 8). The two layer model by Oğuz *et al.* (1989) indicates that the blockage may occur when the net barotropic flow exceeds about 27000 m^3/s, corresponding to the case of 45 cm maximum surface elevation difference between the ends of the Bosphorus. Similar results have been obtained earlier by Sümer and Bakioğlu (1981). A continuous flow of the Mediterranean effluent into the Black Sea is also supported by the salt wedge analysis given by Bogdanova and Stepanov (1974) implying that the blockage can only occur when the upper layer average current exceeds a value of 60 cm/s, which occurs only in cases of very strong northerly wind conditions.

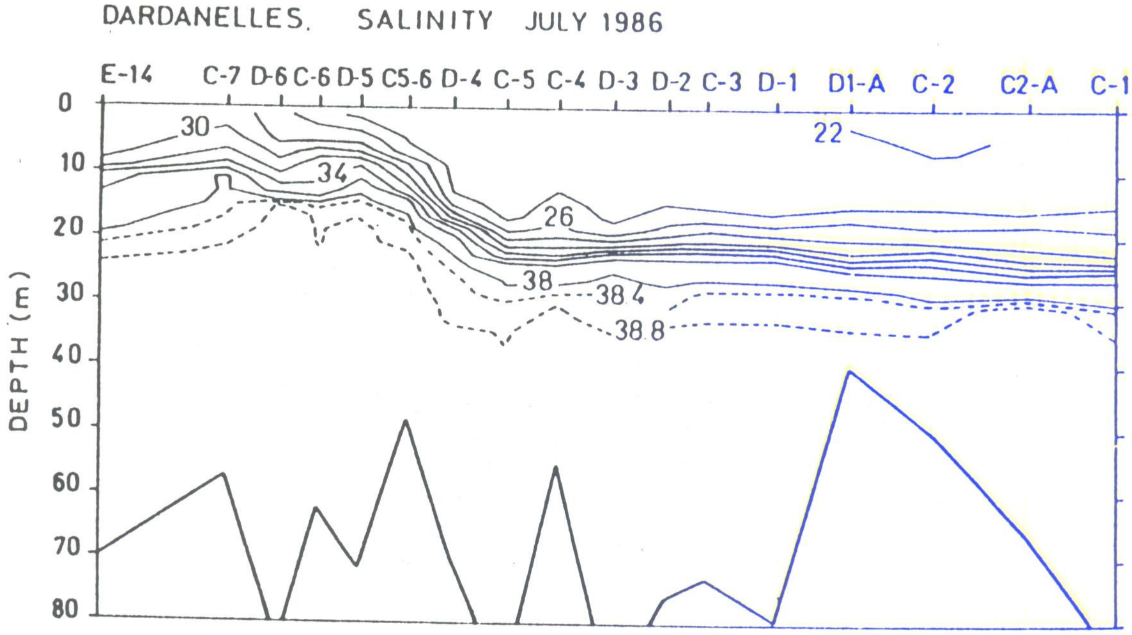

Figure 10a. Salinity transect in the Dardanelles Strait during July 1986, corresponding to Fig. 4b in expanded scale.

The upper layer flow passes through the Marmara Sea subcritically without much change in its character. However, features similar to those observed in the Bosphorus are also found in the Dardanelles (Figs. 10a,b). The Marmara inflow, which is subcritical at the northeastern part of the strait, reaches the critical state at the Nara contraction located just south of station D4 (corresponding to the point 58 in the computational grid of the model). The flow becomes supercritical downstream of the narrowest section and is then followed by an internal hydraulic jump. This sequence is repeated at the Aegean termination of the strait when the upper layer flow passes through the abruptly expanding exit section.

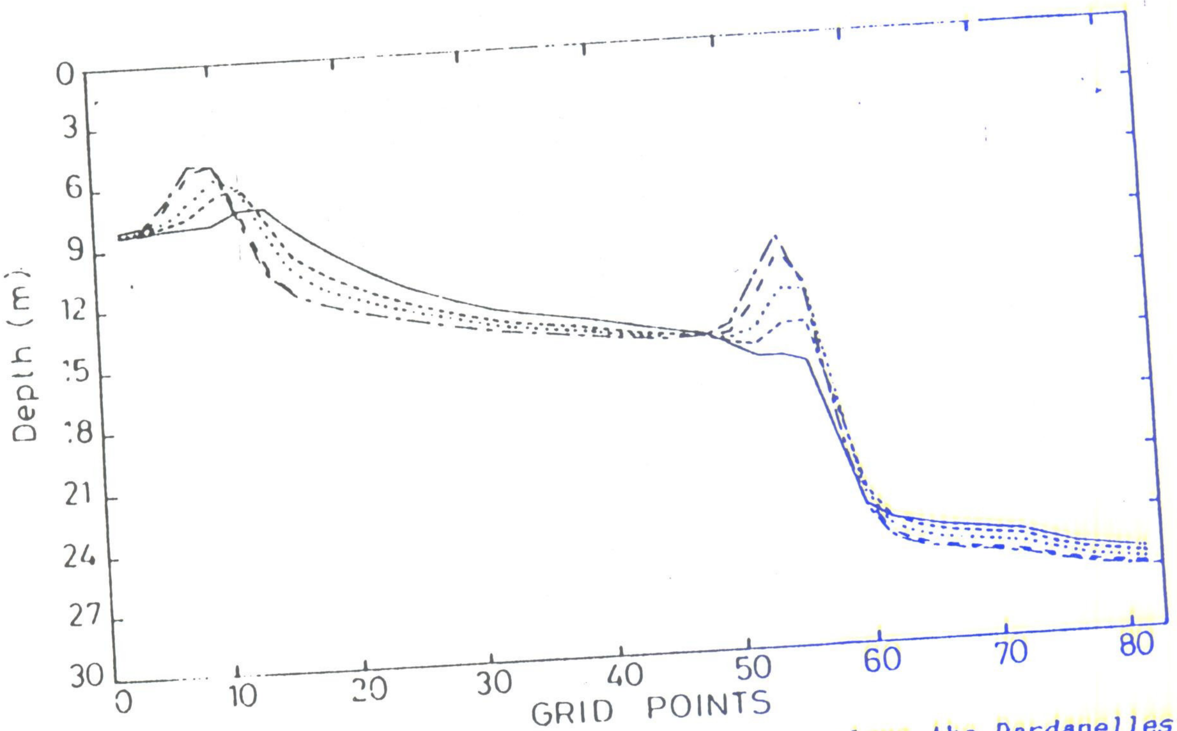

Figure 10b. Computed positions of the interface along the Dardanelles for various values of horizontal eddy viscosity coefficent (After Oğuz and Sur, 1989).

It is seen in Fig. 10c that the internal hydraulic adjustment of the flow is basically a nonlinear process; the horizontal advection term together with partial contribution of the interfacial stress balance the pressure gradient term in the upper layer momentum equation. It appears that the horizontal momentum diffusion and the interfacial momentum transfer due to the entrainment process have negligible effects throughout the channel. A weak balance of terms generally exists in the subcritical regions.

The overall picture of internal hydraulics of the TSS is consistent with the theoretical analyses of Farmer and Armi (1986), Armi and Farmer

(1987) who outline the conditions imposed by the hydraulic controls for maximal and submaximal exchanges in steady, frictionless and immiscible flows through a gradually varying channel between two basins. In accordance with the results of Farmer and Armi (1986), Armi and Farmer (1987), the Bosphorus possesses maximal exchange because of the presence of the combination of the northern sill and the contraction and also the combination of the southern sill and the abrupt expansion to the Sea of Marmara. The latter combination may not be crucial to the issue because of the close proximity of the two controls which, at times, appear to merge and generate a complex situation.

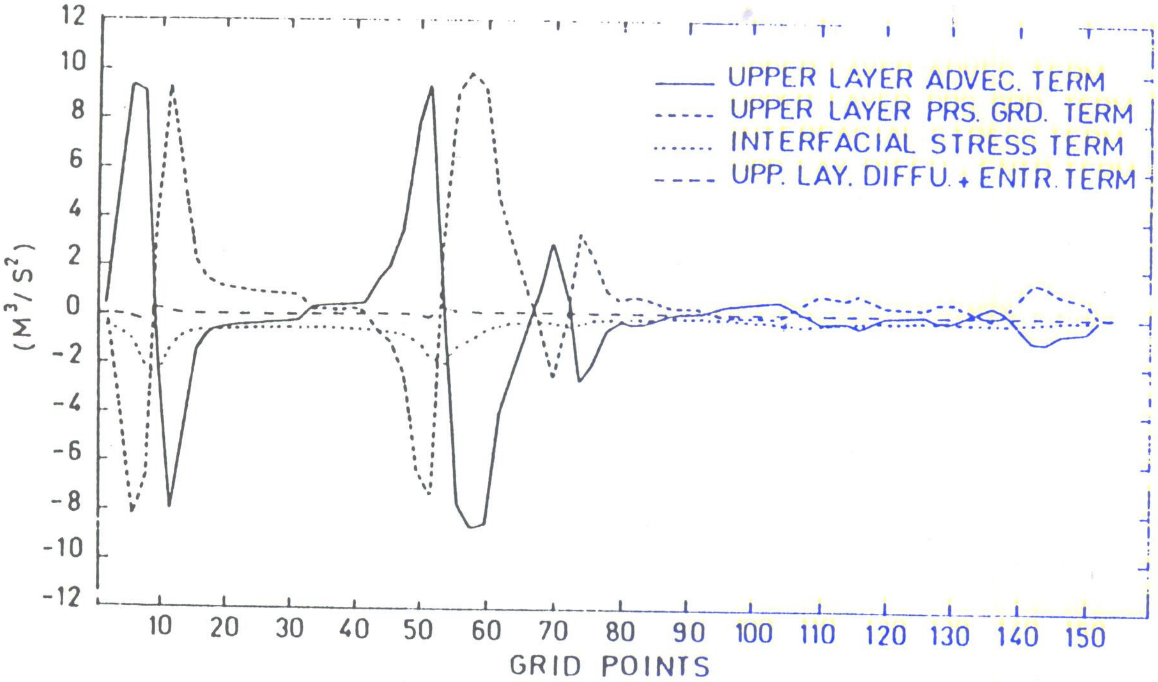

Figure 10c. The variations of the terms in the upper layer momentum equation for the two layer Dardanelles model (after Oğuz and Sur, 1989).

Because of the maximal exchange conditions in the Bosphorus, the exchange between the Marmara and the Black Seas will be determined by the conditions within the Bosphorus itself, and not by the conditions at the adjacent basins. On the other hand, the Dardanelles possesses a submaximal exchange since the lower layer flow is not subject to an internal hydraulic control near its Marmara exit. In this case, the conditions within the Marmara Sea also contribute to the exchange along the strait, and the flow is therefore no longer fully determined by the conditions within the strait.

In addition to the two layer model studies, the qualitative features of the baroclinic flow structure in the Bosphorus have also been studied by continuously stratified, two dimensional numerical models (Tolmazin, 1981; Johns and Oğuz, 1989). The model given by Johns and Oğuz (1989) is not able to produce observed penetration of sufficiently high salinity lower layer water into the Black Sea, and does not predict the layer transports in consistency with the results of two-layer models (Çeçen *et al.*, 1981; Oğuz *et al.*, 1989) as well as of the box model (cf. Section 5). However, it simulates a two layer system of exchange separated from each other by an intermediate entrainment layer. The numerical model identifies quantitatively the effect of the southern sill on the resulting flow structure. It is shown that an important part of the incoming lower layer flow from the Marmara Sea (about 34%) is returned back as a part of the surface layer transport to the south of the sill. This rate of upward transport appears to be higher than the two-layer model estimates cited above and arises due to the underprediction of upper and lower transports in the model.

The Johns and Oğuz (1989) model indicates that at some height above the sill, both horizontal and vertical components of the mean flow become vanishingly small, giving rise to a complete stagnation of a part of the mean flow, and predominance of turbulence and associated intense vertical mixing in the exchange flow system. Prediction of stagnant flow and important vertical mixing above the sill seem to be consistent with a feature of the temperature transect shown in Fig. 4a. A gap is observed between the subsurface cold layer temperature contours at the sill region, coinciding approximately with the location of intermediate layer simulated by the model. Significant vertical mixing is evident in Fig. 4a since the 7 °C core temperature of the cold layer on the Black Sea side of the sill is increased to about 10 °C on the Marmara side.

Turning our attention now to the dynamical aspects of surface outflows from straits pertaining to the Bosphorus outflow in the Marmara exit region, Whitehead and Miller (1979) describe several laboratory experiments to show that when the strait opening is less than the baroclinic radius of deformation, buoyant jets tend to form an anticyclonic gyre. Beardsley and Hart (1978), Nof (1978), Preller (1985) and Wang (1987) all relate the left hand attachment of an exit flow and resulting generation of an anticyclonic eddy outside a channel-open sea junction region to the presence of sufficiently large negative relative vorticity (comparable to the Coriolis parameter) of the exit flow. For surface outflows having an internal hydraulic control at the exit of channel, the negative relative vorticity is generated by strong upward vertical velocity induced during the critical transition of the outflow (Wang, 1987). Apart from the three dimensional, continuously stratified model of Wang (1987), the other models are based on the two-layer dynamics. They however do not incorporate the energy loss associated with the entrainment mechanism taking place between the surface jet and the ambient waters.

7. SEA LEVEL AND CURRENTS

The sea level and current variability of the Turkish Straits have been only partially studied in the past. Möller (1928) estimated average sea level differences of 6 cm and 7 cm, respectively, between the two ends of the Bosphorus and of the Dardanelles. More recent estimates yield higher elevation differences. Bogdanova (1965) (quoted in Yüce, 1986) has found a mean sea level difference across the entire TSS of 42 cm with considerable seasonal variations ranging between a minimum value of 35 cm in October and a maximum value of 57 cm in June. Bogdanova's (1965) estimates are the only available recent sea level information for the entire TSS. The others are related to the sea level measurements in the Bosphorus Strait alone (Gunnerson and Özturgut, 1974; De Filippi *et al.*, 1986; Büyükay, 1989).

Based on tide gauge measurements during July 1966-February 1968, Gunnerson and Özturgut (1974) estimated the average sea level difference between the two ends of the Bosphorus as 35 cm. Çeçen *et al.* (1981) report a value of 33 cm with a standard deviation of 13 cm. De Filippi *et al.* (1986) determined an average sea level difference of 37 cm for April-August, 1984 period. Analysing the sea level data for 1985 and 1986, Büyükay (1989) finds the seasonally-mean sea level differences and their standard deviations (the latters are shown in parantheses) as:

	(1985)	(1986)
Winter (Dec.-Feb.)	18 (12)	26 (13)
Spring (Mar.-May)	26 (7)	34 (8)
Summer (Jun.-Aug.)	34 (10)	28 (4)
Autumn (Sep.-Nov.)	35 (10)	--
Annual average	28 (10)	29 (8)

While the average sea level difference between the ends of the Bosphorus is typically of the order of 30-40 cm, the slope of free surface is found to be nonlinear by both Gunnerson and Özturgut (1974) and De Filippi *et al*, (1986) who have indicated that the surface slope in the southern half is much steeper than in the northern half.

The sea level spectra (Fig. 11) indicate significant variability in the 3-14 day period range which appears to be related to the variations in the barometric pressure and winds (cf. Section 3). Similar spectral bands have also been reported by Gunnerson and Özturgut (1974).and De Filippi *et al*, (1986). The high frequency tidal oscillations of 24 hr and 12 hr periods are also dominant in the sea level signals. The wind influence on the sea level variations and, particularly, notable effects of strong southwesterlies in diminishing or even reversing the sea surface slope are emphasized by Gunnerson and Özturgut (1974) and Büyükay (1989).

As compared with the sea level, currents and their variability within the Turkish Straits are less known. The classical study of currents in the Bosphorus and Dardanelles Straits by Merz (Möller, 1928; cf. Defant, 1961) reveals the upper layer average current increasing from 50 cm/s in the northern end to about 200 cm/s at the southern end

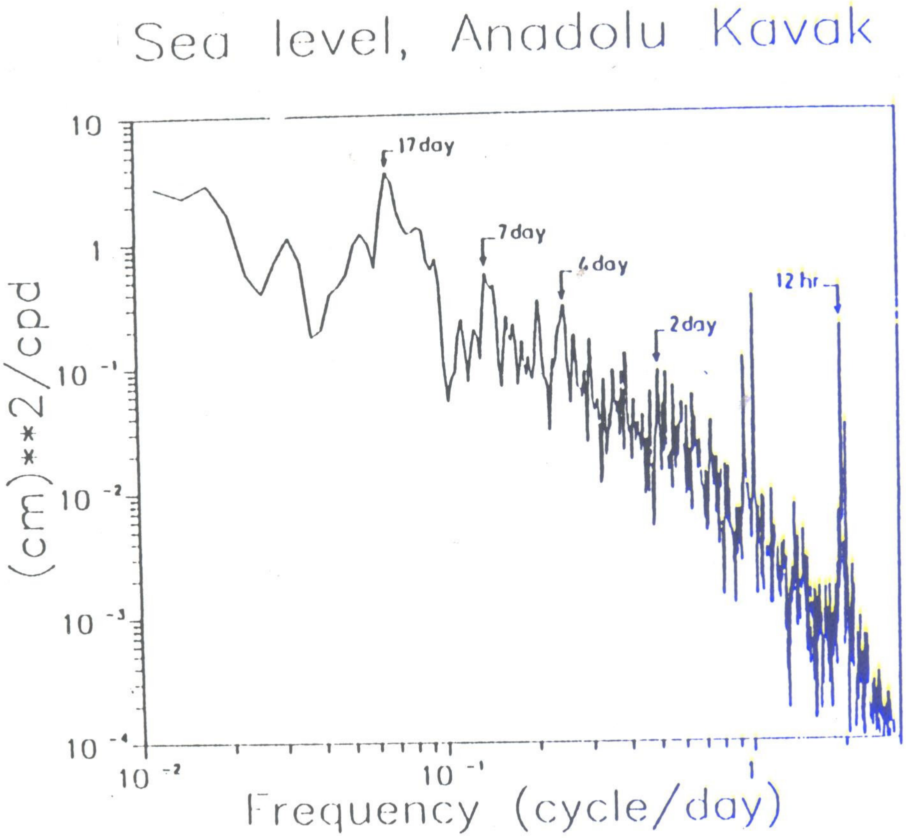

Figure 11. Sea level spectrum at Anadolu Kavağı, located near the Black sea end of the Bosphorus for 1985.

of the Bosphorus Strait. The speed of the undercurrent decreases from 40 cm/s to 20 cm/s in the opposite direction. The upper layer current in the Dardanelles Strait is weaker and varies from about 80 cm/s near the northern entrance to 100 cm/s at the Aegean exit section. The northerly flowing lower layer current speed attains typically a value of 30 cm/s. In both straits, regions of intensification of the upper and lower layer currents are present associated with the internal hydraulic structure of the flow (cf. Section 6). More recent current measurements described in DAMOC (1971) and De Filippi *et al.* (1986) yield similar values of currents in the layers within the Bosphorus Strait.

The measurements carried out by De Filippi *et al.* (1986) in the Marmara exit region of the Bosphorus indicate that the surface currents possess significant variability due to forcing by winds, inertial and tidal oscillations.

8. MEDITERRANEAN INFLOW INTO THE BLACK SEA

The Mediterranean waters emanating from the Bosphorus play a crucial role in the Black Sea salinity and water budgets. The nature of the flow, i.e, whether continuous or sporadic, has been a controversial and poorly understood matter since the early studies of the subject (Ullyott and Ilgaz, 1943, 1946; Pektaş, 1953; Bogdanova and Stepanov, 1974 and the references cited therein). A summary of the various conflicting views is given in Ünlüata and Oğuz (1983). Uncertainties in more recent results do not allow a firm settlement of the issue because of incomplete information on the bottom topography of (Büyüközden *et al.*, 1985) and the lack of hydrographic data in (Tolmazin, 1985) the near-field region of the discharge.

An extensive oceanographic investigation has been conducted recently in the Bosphorus-Black Sea junction region, with a primary purpose of studying the bottom topographical features and determining the path of the Mediterranean effluent on the adjacent Black Sea shelf (Latif, *et al.*, 1989a, 1989b). It is found that the Mediterranean flow entering the Black Sea is initially confined in a channel that is a natural extension of the Bosphorus. For the first 8 km, the channel is directed towards the northeast, which is the same orientation as the Strait, and subsequently turns towards the northwest, eventually joining the shelf topography in a formation similar to the morphology of a river delta (Fig. 12).

The initial confinement of the Mediterranean flow can be inferred from Fig. 13) where the distribution of bottom salinity values greater than 24 ppt measured during various cruises are displayed together with the depth contours defining the channel (Latif, *et al.*, 1989a, 1989b). The higher salinity values are found only in the channel and the correspondence between the flow track and the channel is clearly seen.

A sill at 60 m depth in the channel is seen in Fig. 12. Under sufficiently strong and persistent winds, the interface may be lowered below 60 m depth, resulting in blockage of the lower layer flow. Three such cases, in March 1986, April 1987, and Jan. 1989 have been observed (Latif, *et al.*, 1989a, 1989b). The salinity transect during the blocking on 13 March, 1986, is shown in Fig. 14. The Mediterranean inflow, delineated by the 20 ppt isohaline, is seen to be compressed close to the bottom in the northern half of the Strait. The flow resumes quickly after the northerly winds cease or change direction; this was documented in the April 1987 episode; the time scale for the blockage appears to be of the order of two days (Latif, *et al.*, 1989a).

The blocking of the Mediterranean inflow at the sill had been earlier believed, by some researchers, to be a frequent occurrence (Ünlüata and Oğuz, 1983). The reason for this appears to be that the sill depth was incorrectly known as 50 m, after Scholten (1974). Since the interface between the two layers is often located at 50 m in the northern end of the Bosphorus, a blocking situation may be inferred if the Black Sea water is found in the 50 m depth region, when in fact, such is most probably not the case. The fact that the blocking of the Mediterranean inflow is a rare occurrence can be seen from Fig. 15, where the depth of the 20 ppt salinity defining the lower limit of the surface layer, measured during a series of cruises between 1986-88, is displayed (Latif, *et al.*, 1989a, 1989b).

After leaving the channel, the Mediterranean effluent spreads out as a thin gravity current over a relatively flat shelf area and maintains a generally northwesterly track towards the shelf break. It is seen from the bottom salinity values measured during a cruise in June, 1988

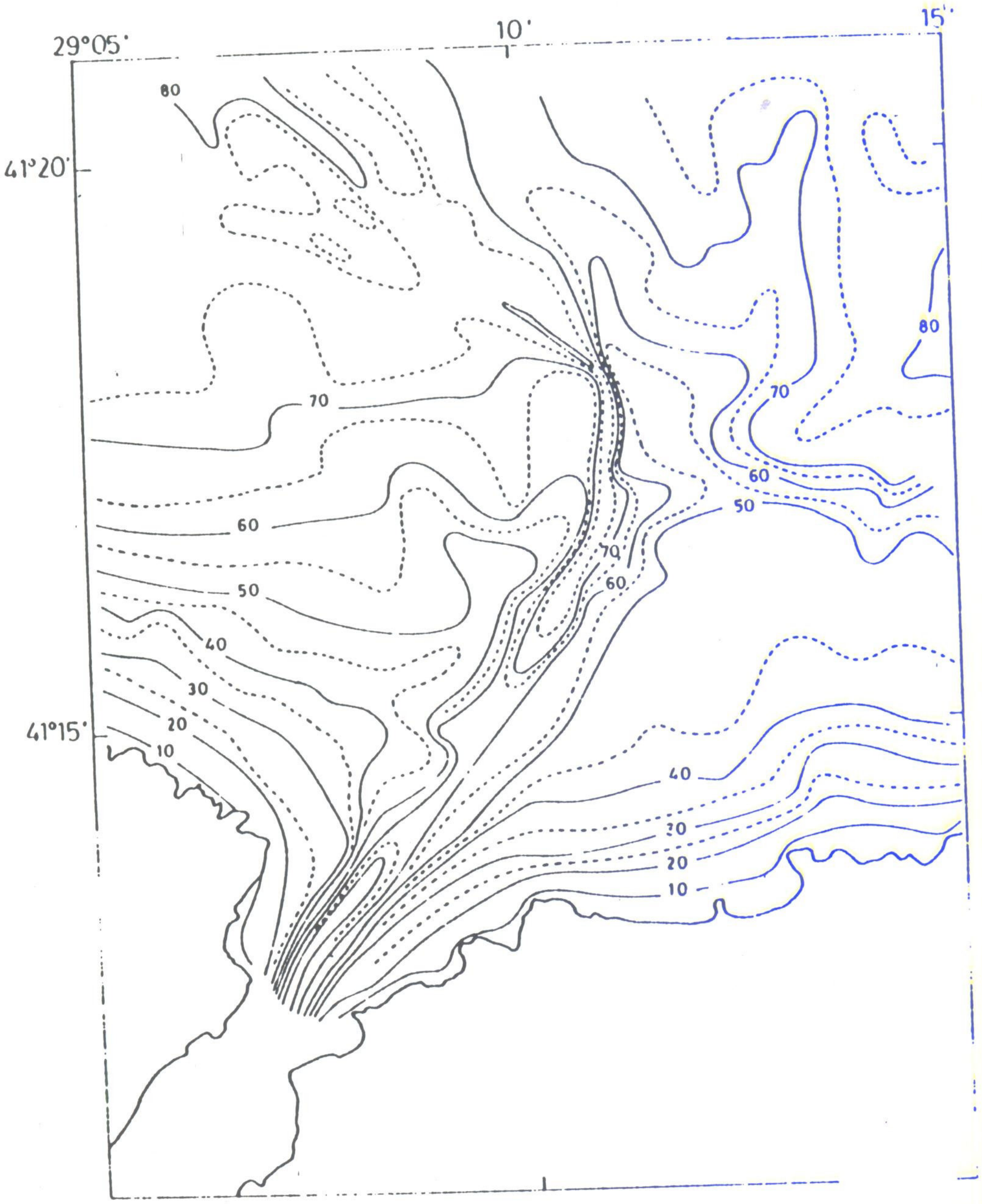

Figure 12. Bottom topography in the Bosphorus-Black sea junction region (depths in meters) (After Latif et al., 1989a).

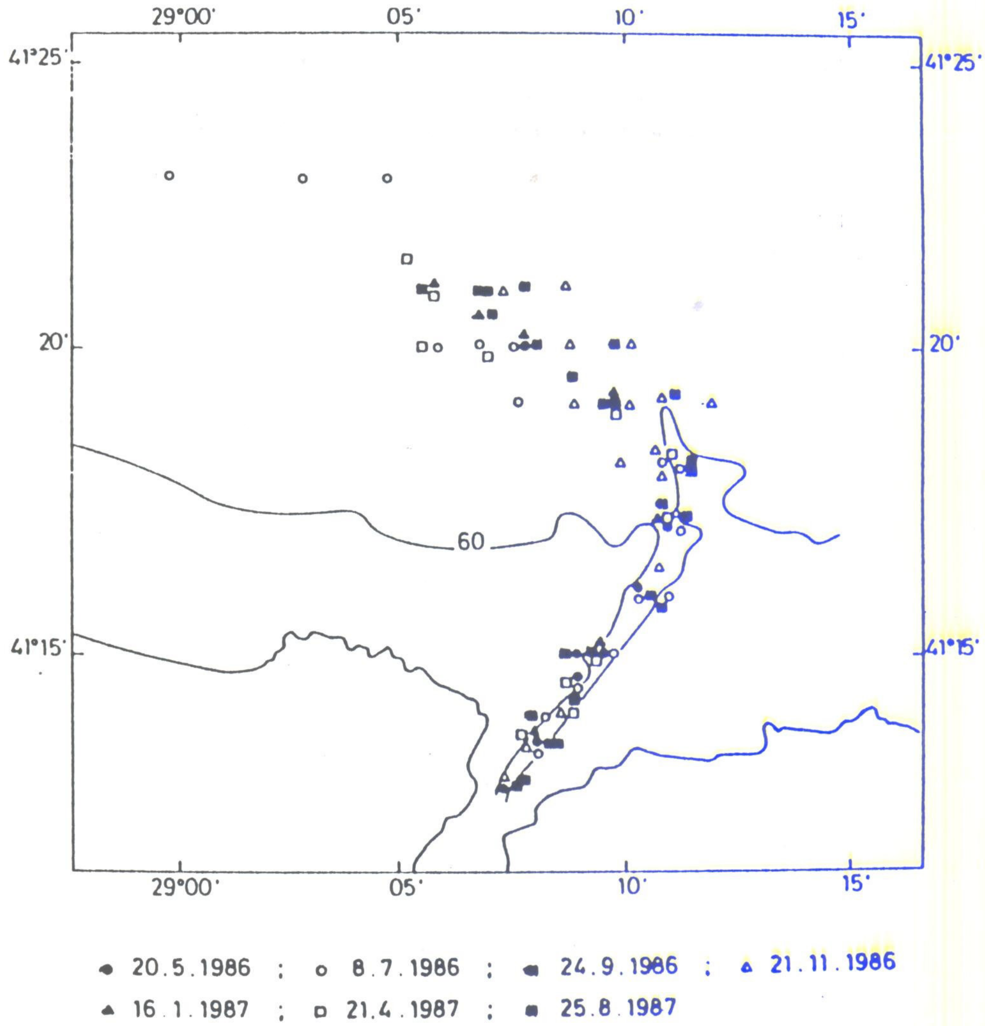

Figure 13. Distribution of bottom salinity values greater than 24 ppt from several cruises, superimposed on the contours defining the channels (After Latif et al., 1989a).

(Fig. 16) that, while in the channel, the Mediterranean water mixes only slightly and essentially vertically with the ambient water because of its confinement (Latif, *et al.*, 1989a, 1989b). After leaving the channel, a more rapid dilution takes place. The salinity decrease between the exit from the Strait and the end of the channel is 1.7 ppt, while the decrease in a comparable distance after leaving the channel is 3.2 ppt (from 35.3 to 32.1 ppt). In the close proximity of the shelf break, the salinity of the effluent is reduced down to 22.6 ppt which does not differ much from the 22.4 ppt salinity of the Black Sea bottom waters. Beyond the shelf, the Mediterranean flow is evidently

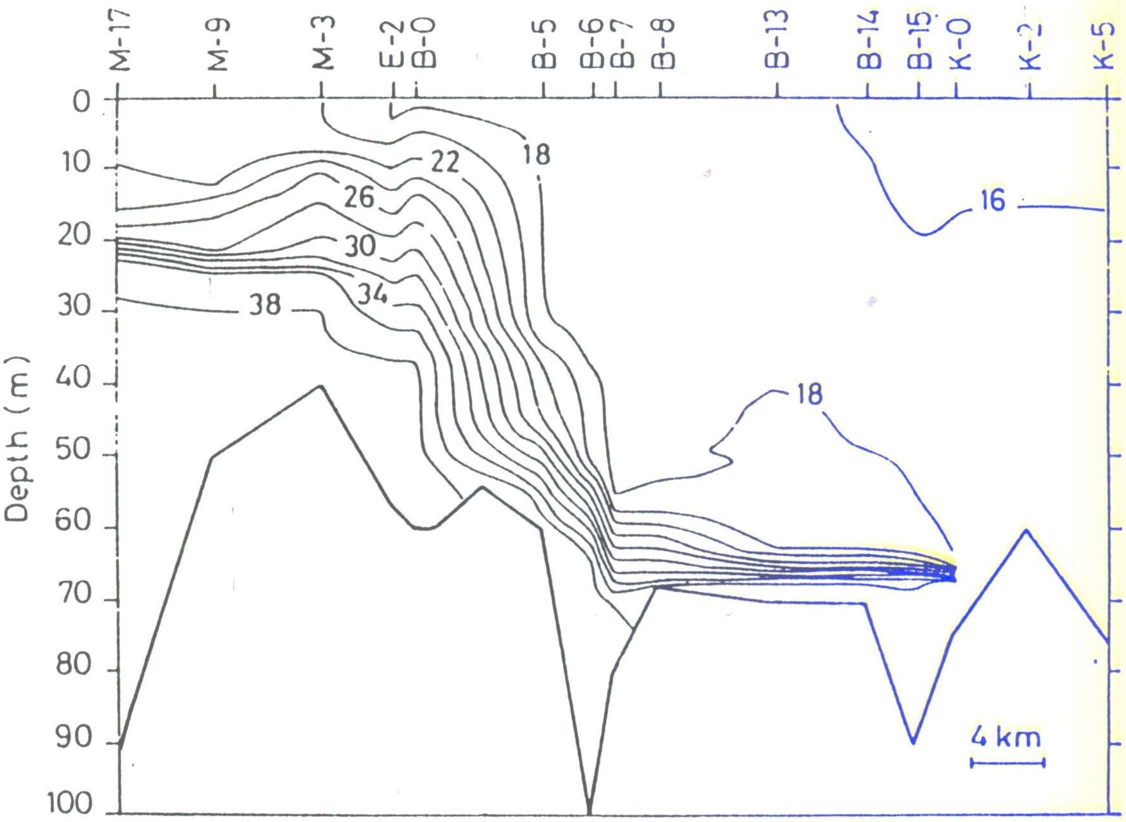

Figure 14. Salinity transect in the Bosphorus and its exit regions during a lower layer blocking, 13 March 1986 (After Latif, et al., 1989a)

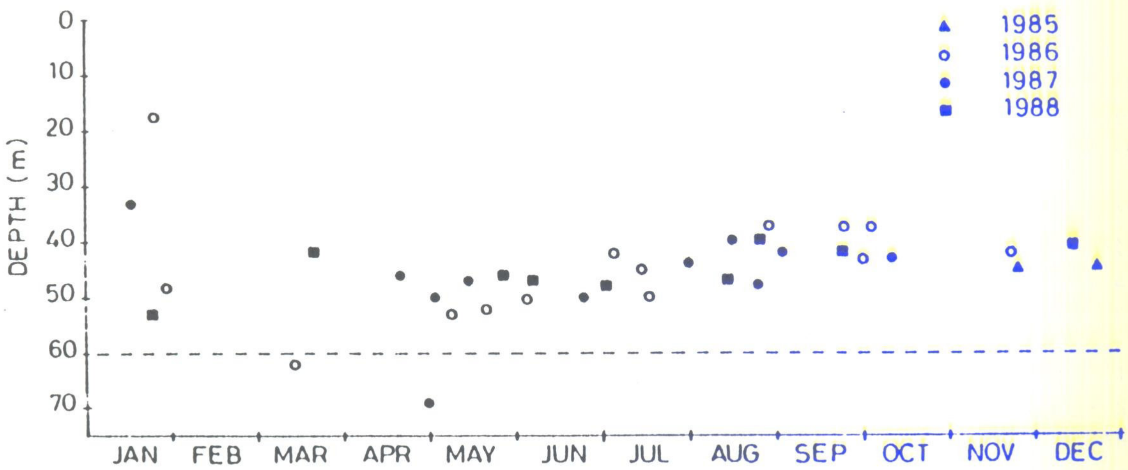

Figure 15. Depth of 20 ppt distribution in the northern exit of the Bosphorus. Depth of the sill (60m) is indicated by the dotted line. Total depth at this location is 75m (After Latif et al., 1989a).

incorporated into the prevailing eastward general circulation of the Black Sea (Tolmazin, 1985).

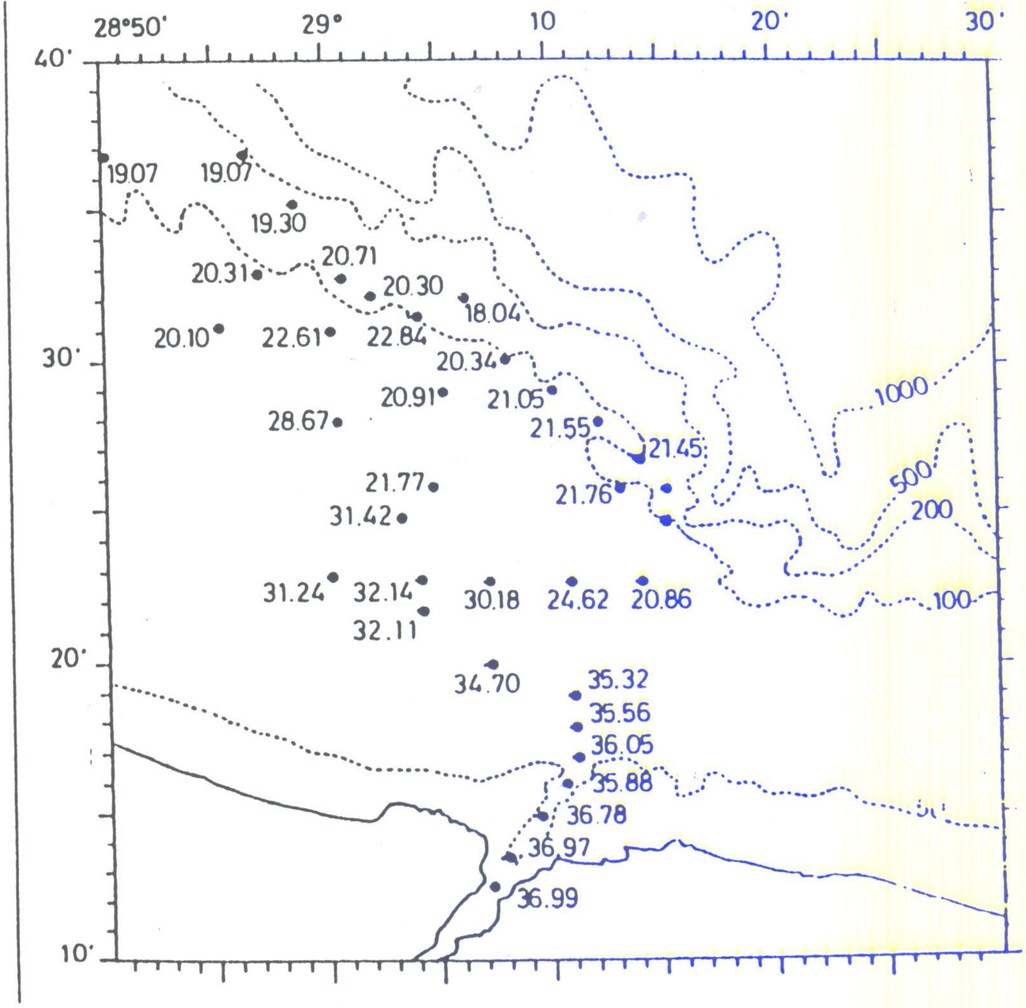

Figure 16. Distribution of bottom salinity values in the Black Sea shelf region during June 1988; the track of the Mediterranean effluent is indicated by high salinity values (After Latif, et al., 1989a).

9. SUMMARY AND CONCLUSIONS

The Turkish Strait System, joining two of the world's largest isolated seas with extremely different water mass properties, presents a wealth of oceanographic phenomena which have only recently begun to be understood.

The two layer flow regime in the straits displays seasonal variability as well as short-term fluctuations in response to meteorological forcing. The sea level difference is at its maximum in spring and early summer, and is minimum in winter, corresponding to the fresh water inflow changes in the Black Sea. Strong southerly winds cause a rapid rise in sea level in the southern part of the Bosphorus, while northerlies result in high levels at the other end. Blockage of either layer may occur under sufficiently strong and sustained winds; such episodes are, however, infrequent and short-lived. Specific cases for the blockage of the upper layer (e.g. during January 16, 1987) and of the lower layer (e.g. during March 13, 1986) have been presented in Latif et al. (1989a).

Internal hydraulic controls greatly influence the flow regime and intensity of mixing in the Turkish straits. The Bosphorus possesses maximal exchange because of the presence of the combination of the constriction and the northern sill and also the combination of the southern sill and the abrupt expansion to the Sea of Marmara. The internal hydraulic adjustments of the Bosphorus exchange flow are however time dependent and can generate a complex situation. In the Dardanelles, the upper layer attains critical state in the Nara contraction region, however, since the lower layer is not subject to an internal hydraulic control at its Marmara exit, a submaximal exchange exists. Intense vertical mixing in regions of supercritical flows and internal hydraulic jumps associated with the controls are inferred from property transects.

The Bosphorus upper layer enters the Sea of Marmara in a jet-like flow and forms an anticyclonic eddy on the Thracian side; the scale of the eddy varies dependent upon the strength of the outflow and the prevailing winds. At the northern end, the Mediterranean flow entering the Black Sea is transported onto the shelf region confined in a narrow channel with steep banks in the seabed for about 10km; at the termination of the channel, the Mediterranean water spreads out in a thin layer, becomes highly diluted, and is incorporated into the prevailing Black Sea circulation.

Estimates of the exchange between the Bosphorus and the Black Sea reported in the literature vary widely. In the present study, the time-averaged exchanges of the various components of the System have been estimated using steady state salt and mass conservation equations. Recent measurements were utilized for the average salinity values at the junctions of the system.

The present estimates of the Bosphorus flows differ from most previous ones. This is due to the utilization of different net fresh water input values for the Black Sea. The present estimates are, however, consistent with the separate and independent numerical computations that are based on the sea level differences at the two ends of the Bosphorus.

The computations show that the upper layer volume flux increases significantly between its exit at the Bosphorus - Marmara junction and its entrance into the Dardanelles, and again during its transit through the Strait. The increases in the flux, together with the increases in salinities, indicate entrainment of the subhalocline waters into the surface layer during its traverse through the Sea of Marmara and the Dardanelles. Indeed, the most striking aspect of the water budget of the system is that a major portion of the underflow entering from the Aegean Sea is returned back before reaching the Black Sea.

The upward mixing within the Sea of Marmara is due to the influence of winds down to the halocline, the internal hydraulic jump at the southern entrance of the Bosphorus as well as the surface jet emanating from the Bosphorus. These mechanisms lead to the entrainment of the saltier subhalocline waters into the surface layer. Similarly, the upward mixing in the Dardanelles is induced by an internal hydraulic jump in the Nara constriction region.

The Turkish Straits System, as seen from the material presented here, possesses a number of interesting processes whose further study should be scientifically rewarding. In particular, the distribution of the bottom waters on and beyond the Black Sea shelf, the dynamics and mixing in the Bosphorus-Marmara junction region, interaction between the Dardenelles and the Aegean Sea, and the possible formation of water mass as related to the outflow form topics for future research which, it is believed, would contribute much towards our understanding of the System as well as of interactions between the Mediterranean and the Black Seas.

ACKNOWLEDGEMENTS

This work was supported by the Department of Water and Sewer Works, Municipality of Istanbul as a part of a five year programme aimed at documenting the present state of health and the oceanography of the Turkish Straits. Partial support was also provided by the Scientific and Technical Research Council of Turkey.

APPENDIX

The differences between the present estimates of the Bosphorus flows and the previous ones are due to the differences in the Net Fresh Water Input (NFWI) values employed for the Black Sea. NFWI is equal to the volume fluxes of rainfall plus run-off minus the evaporation. The transports within the Turkish Straits are directly proportional to and crucially depend on the estimates of the NFWI to the Black Sea.

The estimates of the Black Sea rainfall, run-off and evaporative fluxes and NFWI as well as the Bosphorus flows from various sources are given in Table 1. It is seen in Table 1 that the various estimates of the run-off as well as the precipitation do not significantly differ from each other. With the exception of Pora and Oros (1974), however, the precipitation estimate of Özturgut (1971) significantly differs from the others. The higher precipitation value of Özturgut (1971) leads to nearly 300 km^3 of NFWI to the Black Sea and, within the accuracy of the estimates, this is sufficiently close to NFWI values by Bruevich (1963) and Pora and Oros (1974) but, again, significantly different from others.

Özturgut's (1971) estimate of the rainfall is based on a mean annual precipitation of 71.4 cm found by averaging the rainfall measured at the Black Sea coastal stations. Multiplication of this average precipitation by the surface area of 4.2×10^5 km^2 of the BLack Sea yields 300 km^3/yr. The result of a separate computation that utilizes the long-term rainfall data recorded at stations along the perimeter of the Black Sea (provided in *Weather in the Black Sea*, 1963 and *The Black Sea Pilot*, 1969) agrees well with Ozturgut's value for precipitation. Needless to say, the utilization of rainfall data based on measurements at coastal stations for estimating precipitation at sea leaves much to be desired. What is surprising, however, is that the utilization of the annual rainfall distribution over the surface of the Black Sea as given in the Morskoi Atlas (1950) leads to an average precipitation of 294 km^3/yr. This is in agreement with Ozturgut (1971).

In view of the wide range of estimates of NFWI to the Black Sea, we resort to the results obtained by different methods. Sümer and Bakioğlu (1981) and Oguz *et al.* (1989) have computed numerically the volume fluxes in the upper (:Q1) and the lower (:Q2) layers of the Bosphorus as a function of the difference (:Δh) at the two ends of the strait. Their results are reproduced in Figs. 17a,b. In studying Fig. 7 it should firstly be borne in mind that, based on sufficiently long measurements (Cacen et al., 1981), the sea level difference across the Bosphorus varies in time with a mean of 33 cm and standard deviation of 13 cm. In other words, the mean range of :Δh is [20-46] cm. Secondly, the mean NFWI to the Black Sea is positive so that the portion of the Fig. 17a that is of interest here is the region where Q1>Q2, that is to the right of the intersections of Q1 and Q2 curves.

Now, in Q1>Q2 region, the minimum volume flux for the upper layer is 400 km^3/yr, corresponding to the intersection of Q1 and Q2 curves. This value is nearly equal to the Bosphorus out-flows reported in Table 1. But the corresponding lower layer flow is almost twice the inflows given in the same table. In fact, all the estimates, including the present one, in Table 1 imply a Q1/Q2 ratio approximately equal to two (since this ratio must be equal to the salinity ratio of the two layers). The Δh value where this ratio is satisfied is 31 cm, with Q1=570 km^3/yr and Q2=285 km^3/yr, implying a NFWI=285 km^3/yr which is remarkably close to that found by using the estimates of Ozturgut.

Oğuz *et. al.* (1989) results (Fig. 17b) lead to similar values; Q1/Q2=2 is satisfied where NFWI=300 km^3/yr with Δh=27cm.

This does not prove, however, that Özturgut's rainfall value is correct but rather that possible combination of errors incurred in evaporation and precipitation estimates can yield to underestimated values of NFWI. For example, consider the rainfall and run-off estimates from the Entsiklopedia Okean Atmosfera (1983) given in Table 1. If instead of using 354 km^3/yr for the evaporation, a value of 254 km^3, as carefully computed by Kochikov (1961) is employed, the resulting NFWI would have been 300 km^3/yr!

We point out in passing that the differences in the estimates of the net fresh water input also affect fluxes across the halocline of the Black Sea. With the present estimates, the upward and the downward fluxes are 1133 and 821 km^3/yr, respectively (Fig. 6). Using Merz's (in Möller, 1928) data, Fonselius (1974) reports an upward flux of 700 km^3/yr and a downward flux of 500 km^3/yr.

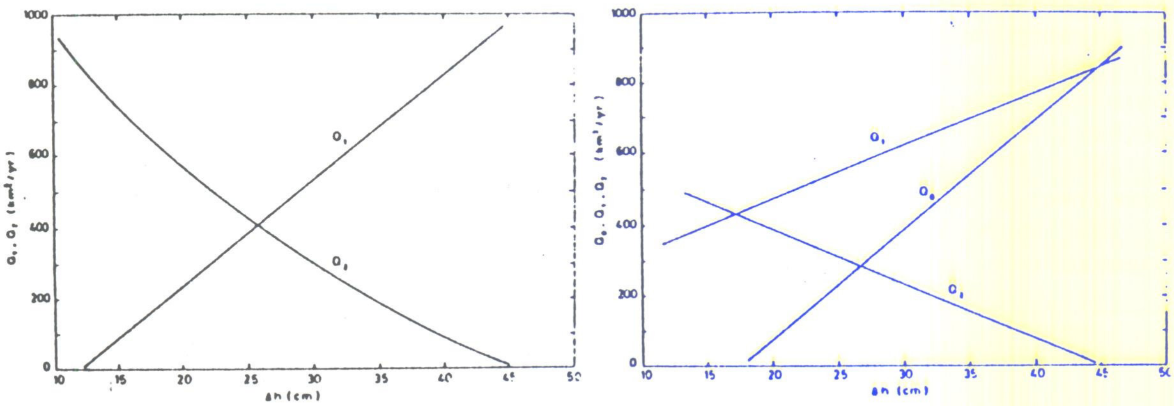

Figure 17a,b. Variations of upper and lower layer flows (Q_1, Q_2) as a function of the sea surface difference across the Bosphorus computed by (a) Sümer and Bakioğlu (1981) (on the left), (b) Oğuz et al. (1989) (on the right).

TABLE 1. ESTIMATES OF THE BLACK SEA BUDGET (km3/yr)

	RAIN FALL	RUN_OFF	EVAPO_RATION	NET FRESH WATER INPUT	BOSP. INFLOW Q2	INFLOW FROM AZOV	TOTAL INFLOW	BOSP. OUT_FLOW Q1	OUTFLOW TO AZOV	TOTAL OUT_FLOW
MERZ	231	328	354	205	193	–	398	398	–	398
ZENKEVICH (1947)	145	320	319	146	202	–	348	348	–	348
NEUMANN AND ROSEMAN (1954)	240	428	462	206	193	–	399	398		398
CASPERS (1957)	234	320	354	200	–	–	–	–	–	–
LEONOV (1960)	230	309	365	174	193	95	462	392	70	462
BRUKVICH (1960)	225	350	350	255	175	–	430	400	–	400
SOLYANKIN (1963)	119	346	332	133	176	53	362	340	32	372
OKEANOGRAFICESKAIA ENTSIKLOPEDIA (1966)	–	400	–	–	202	–	–	398	59	–
TIXERONT (1970)	181	400	392	189	211	–	400	400	–	400
OZTURGUT (1971)	300	352	353	299	249		548	548		548
SERPOIANU (1973)	120	336	340	116	123	53	292	260	32	292
PORA AND OROS(1974)	254	294	301	247	229	38	514	485	29	514
ENTSIKLOPEDIA OKEAN_ATMOSFERA (1983)	234	320	354	200	188	–	388	388	–	388
BONDAR (1986)	119	364	332	151	202	50	403	371	32	403
PRESENT STUDY	300	352	353	300	312	–	612	612	–	612

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