Chemical exchange between the Mediterranean and the Black Sea via the Turkish straits

by

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ABSTRACT

Water exchanges between the Mediterranean and the Black Sea occur via the Turkish straits – the Dardanelles and the Bosphorus – and the intersecting basin, the Sea of Marmara. Based on long term chemical data from both exits of the straits we have determined the annual means of the nutrient and organic carbon contents of the exchange flows. We found that the Black Sea surface outflow looses much of its phosphorus and nitrogen on its way to the Dardanelles Strait. On the other hand, the salty Mediterranean water which enters the Marmara deep basin with low nutrient concentrations becomes enriched at least 5-9 fold with nutrients before reaching the Black Sea, through inputs of Marmara Sea surface waters. The Black Sea outflow contains 212 μM of total organic carbon (on average), principally in dissolved form, nearly three times that of the salty Mediterranean inflow via the Turkish straits. From our estimations every year the salty Mediterranean inflow introduces about 0.19 x 10^4 tons of TP, 0.31 x 10^5 tons of TN and 0.41 x 10^6 tons of TOC to the Sea of Marmara via the Dardanelles. Although nearly 50 % of the nutrient-enriched inflow of salty water is returned back to the Aegean basin by the surface counterflow as a result of vertical mixing, the remaining flow reaches the Black Sea with an increased nutrient load – annually 0.90 x 10^4 tons of TP and 0.51 x 10^4 tons of TN – whereas its TOC load drops to 0.24 x 10^6 tons. Comparison of the annual chemical fluxes in the Turkish straits reveals that the TP exported from the Black Sea is compensated by the influx from the Marmara Sea. However, the export of TN and TOC from the Marmara Sea to the south is at least 4-5 times larger than the importation from the Mediterranean.

RÉSUMÉ

C'est au travers des détroits turcs – Bosphore et Dardanelles – et de la mer de Marmara que se produisent les échanges de masses d'eau entre la Méditerranée et la mer Noire. A partir de données recueillies sur le long terme, nous avons déterminé les moyennes annuelles de nutriments et de carbone organique contenus dans ces flux. Nos analyses indiquent que les eaux de surface s'écoulant de la mer Noire perdent une grande partie de leur teneur en phosphore et azote lors de leur transport vers les Dardanelles. Par contre, les eaux salées de Méditerranée qui pénètrent dans le bassin profond de Marmara avec de faibles concentrations de nutriments connaissent un accroissement notable (5 à 9 fois) en P et N avant d'atteindre la mer Noire. Les masses d'eau s'écoulant de la mer Noire contiennent 212 μM de carbone organique (en moyenne) principalement sous forme d'éléments dissous, soit environ trois fois plus que l'apport provenant de Méditerranée. D'après nos estimations, chaque année les flux salés de Méditerranée introduisent en mer de Marmara 0.19×10^4 tonnes de TP, 0.31×10^5 tonnes de TN et 0.41×10^6 tonnes de TOC via les Dardanelles. Bien que près de la moitié de ces masses d'eau salée retourne à la mer Egée sous l'effet d'un contre-courant de surface, le flux restant atteint la mer Noire avec une charge en nutriments accrue – annuellement 0.90×10^4 tonnes de TP et 0.51×10^4 tonnes de TN – tandis que sa charge en TOC tombe à 0.24×10^6 tonnes. L'analyse des flux chimiques annuels dans les détroits turcs révèle que le total du phosphore exporté à partir de la mer Noire est compensé par les apports de la mer de Marmara. Par contre, le flux d'azote et de carbone organique s'écoulant de la mer de Marmara vers le Sud est 4 à 5 fois plus élevé que celui provenant de Méditerranée.

INTRODUCTION

The Mediterranean is connected to the Black Sea through the so-called Turkish Straits System (TSS) comprising the Sea of Marmara, the Dardanelles and Bosphorus straits (Figure 1). The large fresh water input to the Black Sea causes a net outflux of water through the TSS via the Bosphorus surface current, whereas, throughout the year, the counter flow in the Turkish straits introduces salty Mediterranean water as far as the Black Sea basin (GUNNERSON and ÖZTURGUT, 1974; SOROKIN, 1983; BESIKTEPE *et al.*, 1993; OGUZ and ROZMAN, 1991). The flow regimes established in the Turkish straits due to the large density difference between the adjacent seas result in the formation of distinctly different two-layer ecosystems in both the Marmara and Black seas (SOROKIN, 1983; BASTÜRK *et al.*, 1990; TUGRUL, 1993; POLAT and TUGRUL, 1995; POLAT, 1995).

Water and salinity balances for the Black Sea reveal that the brackish water outflux from the Black Sea through the Bosphorus is nearly twice the salty water inflow from the Mediterranean via the Sea of Marmara (GRASSHOFF, 1975; SOROKIN, 1983). DEUSER (1971) and FONSELIUS (1974) were the first to use water fluxes and chemical data to calculate the organic carbon and phosphorus fluxes in the Black Sea. Their estimates are however open to question. First, their water exchange fluxes were probably underestimated by about 50% (see ÜNLÜATA *et al.*, 1990; BESIKTEPE, 1991). Secondly, during recent decades the chemical properties of the counterflows in the Turkish straits have been modified by large discharges of land-based

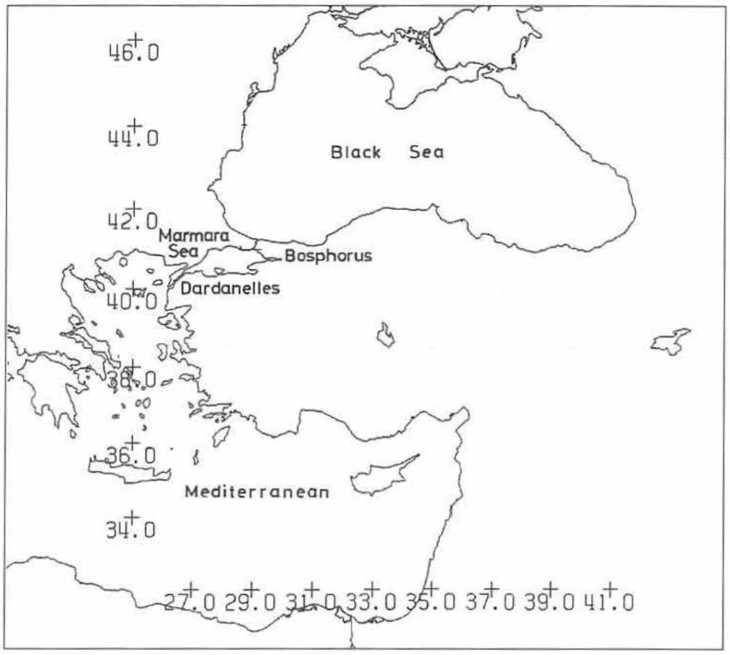


Figure 1 – The crucial location of Turkish straits, Dardanelles and Bosphorus, between the Mediterranean and the Black Sea.

chemicals to the adjacent seas (MEE, 1992; ORHON *et al.*, 1994; TUGRUL and POLAT, in press). Thus, the north-western Black Sea coastal waters, transported towards the Bosphorus region by alongshore currents (SUR *et al.*, 1994), are drastically polluted by large inputs of nutrients and organic matter via riverine and wastewater discharges (BOLOGA, 1985; MEE, 1992).

The polluted Black Sea surface inflow, before spreading into the Marmara upper layer, is further contaminated by the waste discharged into the Bosphorus from the city of Istanbul by the numerous industries and the 6 million population (ORHON *et al.*, 1994). In addition vertical mixing provides nutrient input from the Marmara lower layer, especially in the Marmara-Bosphorus Junction region (BASTÜRK *et al.*, 1990; POLAT and TUGRUL, 1995). Reversely, throughout the Marmara basin, some of the labile chemicals in the Black Sea inflow are naturally exported to the lower layer in the form of biogenic organic matter until the Aegean basin of the Mediterranean is reached via the Dardanelles Strait (BASTÜRK *et al.*, 1990; POLAT, 1995).

By contrast, the salty Mediterranean water entering the Sea of Marmara possesses low concentrations of inorganic nutrients but is saturated with dissolved oxygen (BASTÜRK *et al.*, 1990). During its 6-7 year stay in the deep Marmara basins, before it reaches the Black Sea or is returned to the Aegean Sea by the Marmara surface outflow through the Dardanelles, this salty Mediterranean water becomes enriched about 10 fold in inorganic nutrients – with a concomitant decrease (down to 30-50 μM) in its dissolved oxygen content due to continuous snows of biogenic particulates from the productive surface layer throughout the year (BASTÜRK *et al.*, 1990).

Long-term measurements from the Turkish straits and the adjacent seas are therefore of critical importance not only for deriving chemical balances but also for the development of ecosystem and water quality models as well as for the improved understanding of the oceanography of the Turkish waters. With these goals, a national oceanographic monitoring and research programme has been conducted by the Institute of Marine Sciences of the Middle East Technical University (IMS-METU) throughout the TSS since 1986. In the present paper, systematic data collected at both exits of the two straits are discussed so as to characterize the hydrochemical properties of the exchanging waters of the Mediterranean and the Black Sea.

A detailed evaluation of the hydrochemical properties of the counter-flows in the Bosphorus has been given elsewhere by POLAT and TUGRUL (1995). This paper summarizes the principal findings and includes more recent measurements from the Bosphorus region. Since no systematic data from the Dardanelles Strait have been published before, we have examined long-term hydrochemical data obtained by the IMS-METU group in this region. First, the boundaries of the counterflows were deduced from the hydrographic and current measurements; then, the seasonalities in the depth-averaged concentrations of different forms of nutrients and organic carbon were examined to estimate the annual means of the exchange flows in the Turkish straits. Based on the mean concentrations and using new volume fluxes, we have estimated the annual fluxes of total phosphorus (TP), total nitrogen (TN) and total organic carbon (TOC) exchanged between the Mediterranean and the Black Sea via the Turkish Straits System.

MATERIALS AND METHODS

During the cruises of the R/V *Bilim* in the Sea of Marmara between 1986 and 1994, nutrient and organic carbon samples were collected at the southern and northern entrances of the Bosphorus and the Dardanelles. Phosphate and nitrate+nitrite concentrations were determined by a Technicon model multichannel auto-analyzer, slightly modified from the operating manual, closely following the methods given in STRICKLAND and PARSONS (1972). Water samples for particulate organic carbon (POC), nitrogen (PON) and phosphorus (PP) determinations were filtered through pre-ignited GF/F filters under low vacuum.

The PON and POC contents of the filters pretreated with HCl fumes were determined quantitatively by a Carlo Erba Model 1108 CHN analyzer. Particulate phosphorus collected on filters was measured as described in the Hawaii Ocean Time-Series Programme: Field and Laboratory Protocols (September, 1990). Briefly, filters were combusted at 450-500°C for 3 hours in order to oxidize organic phosphorus compounds to the inorganic form. The filters were then extracted with 0.5 N HCl at 90°C for 1.5 hour. After adjusting the pH to 8.0 and the final volume to 20 ml, the concentrations were determined colorimetrically by the ortho-phosphate method. Dissolved organic carbon (DOC) concentrations in the water samples were determined either by the persulphate-UV oxidation (WET) method using a Technicon model colorimeter (between 1987 and 1989) or by the high temperature catalytic oxidation (HTCO) technique using a Shimadzu model TOC-500 (or TOC-5000) instrument (between 1991 and 1994). Details of the methods have been described by POLAT (1989) and TUGRUL (1993). The instrument blank, of crucial importance in obtaining reliable DOC data from various WET and HTCO methods, was thoroughly discussed by POLAT and TUGRUL (1995): for reasons mentioned in that work, Technicon data have been corrected by adding a value of 20 μM throughout this paper.

HYDROCHEMICAL PROPERTIES OF THE COUNTERFLOWS IN THE BOSPHORUS AND DARDANELLES STRAITS

Vertical Profiles and Boundaries

The typical salinity profiles and velocity vectors displayed in Figure 2 allow us to deduce the boundaries of the counterflows in both straits exits. The brackish waters of the Black Sea at the northern entrance of the Bosphorus Strait, which have a vertically uniform salinity (isohaline feature) down to 45-50 m, flow into the Bosphorus toward the Marmara Sea. Below the surface current, a counterflow introduces diluted Mediterranean waters from the Marmara basin to the Black Sea under normal meteorological and hydrological conditions in the adjacent seas. The thickness of the Bosphorus surface flow decreases steadily from north to south and becomes as thin as 10-15 m at the southern exit before it eventually spreads into the Marmara surface layer. The counterflow in the strait is separated by a sharp interface coinciding with the upper halocline where water flows are relatively small.

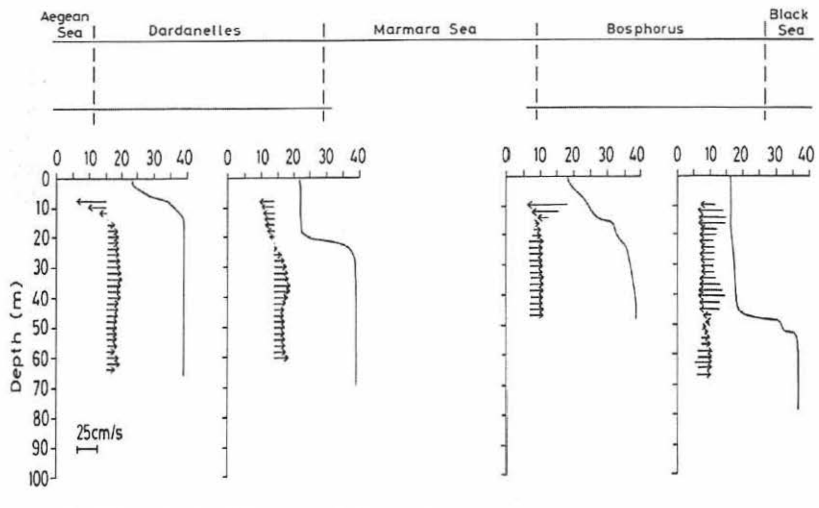
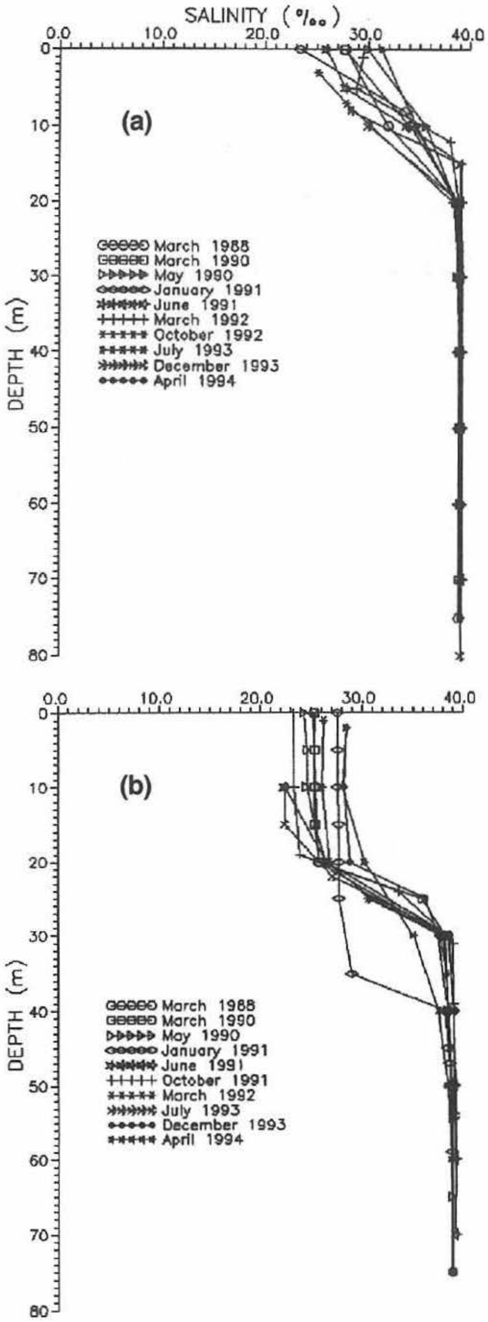


Figure 2 – The typical salinity and velocity profiles at the northern and southern exits of the Bosphorus and Dardanelles straits (adapted from LATIF *et al.*, 1992).

The seasonal and spatial variations of the two-layer feature in the Bosphorus region have been evaluated by ÜNLÜATA *et al.* (1990), OGUZ and ROZMAN (1991) and LATIF *et al.* (1991). Intense vertical mixing of the counterflows in the strait, especially near the southern exit, causes a net increase of at least 2-3 ppt in the salinity of the Bosphorus surface flow before reaching the Marmara basin.

Figure 3 – Salinity profiles at the southern (a) and northern (b) entrances of the Dardanelles Strait.



Similar processes also occur in the Dardanelles Strait. As shown in Fig. 3, the Dardanelles surface flow is much thinner and more saline at the southern extremity of the strait. The brackish surface layer of the Marmara Sea at the northern entrance of the Dardanelles Strait has a vertically uniform salinity (isohaline feature) down to 20 m in summer, although, in winter, the surface layer becomes thicker and at least 2-4 ppt more saline due to intense mixing in the Marmara basin (OGUZ and SUR, 1989). The counterflows in the strait are separated by a sharp interface, 3-5 m thick, as in the Bosphorus Strait, below which the salty Mediterranean water flows toward the Marmara Sea. The halocline waters also flow toward the Aegean Sea but with lower velocities. The salinity of the Aegean outflow is not influenced significantly by vertical mixing in the Dardanelles; it enters the strait with a seasonally and vertically constant salinity of nearly 39.0 ppt and is diluted only slightly by the surface counterflow in the strait. Thus, throughout the year the Mediterranean water eventually reaches the western Marmara basin with a salinity of 38.6-38.9 ppt.

Systematic hydrochemical data obtained at both exits of the Bosphorus and Dardanelles straits have been examined extensively to define the ranges of seasonal variation in the nutrient and organic carbon concentrations of the exchange flows. Time series obtained at the two exits of the Bosphorus between 1986-1994 have been evaluated very recently by POLAT and TUGRUL (1995), and TUGRUL and POLAT (in press). They demonstrate that the nutrient and organic carbon concentrations change slightly with depth in both the upper and lower layer waters, permitting the determination of the ranges of seasonal variation in the depth-averaged chemical concentrations of the counterflows at the Bosphorus exits. The seasonality appears much more pronounced in the Black Sea outflow than in the inorganic nutrient-enriched salty outflow from the Marmara lower layer via the Bosphorus counterflow.

Until recently, the chemical oceanography of the two-layer flow regimes in the Dardanelles remained poorly understood due to the scarcity of systematic measurements. With this in mind, long-term data obtained by the IMS-METU between 1986-1994 have been examined extensively by POLAT (1995). Typical hydrochemical profiles are displayed in Figs. 4 and 5. They illustrate that the salty Mediterranean water enters the Marmara basin with low nitrogen and organic carbon concentrations. As shown in Fig. 4a, during the April-September period, the inorganic nutrient profiles show a uniform distribution down the entire water column of the strait exit to the Aegean Sea. The winter nitrate concentrations of

Figure 4 – NO_3 profiles at the southern (a) and northern (b) entrances of the Dardanelles Strait.

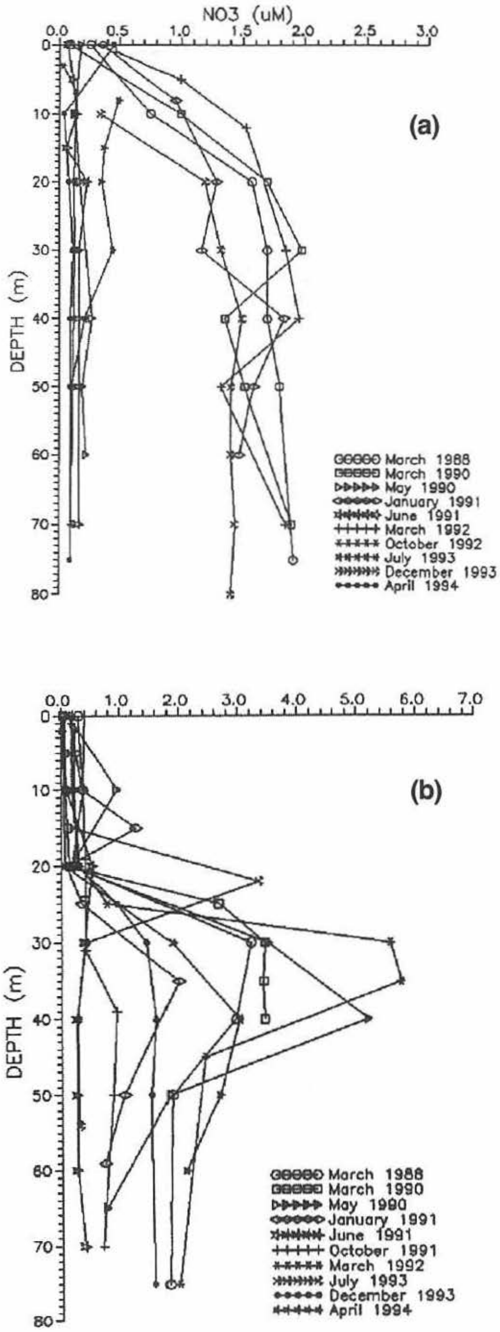
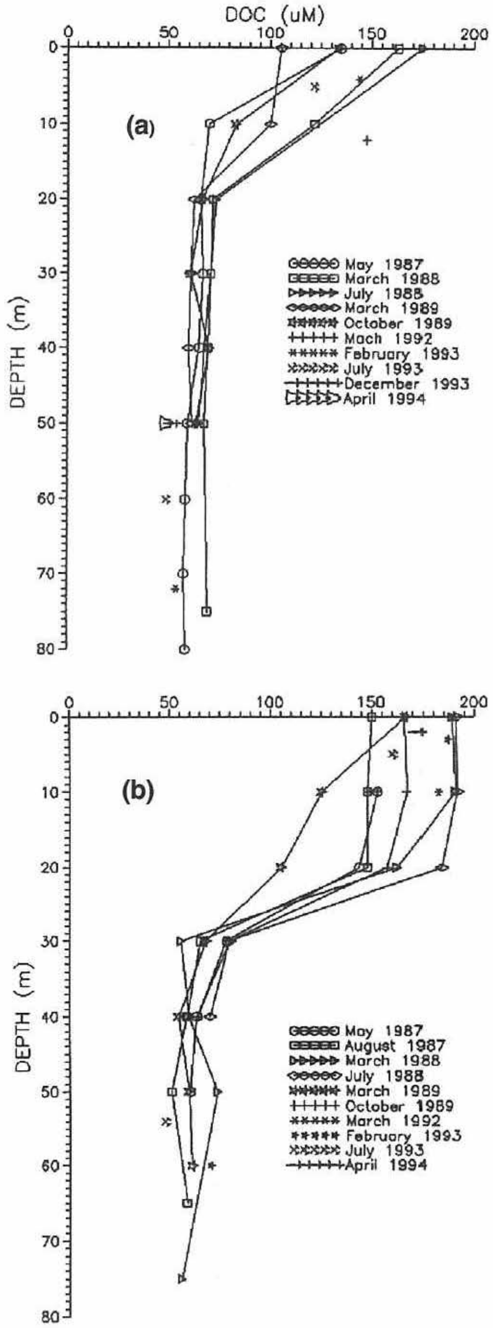


Figure 5 – DOC profiles at the southern (a) and northern (b) entrances of the Dardanelles Strait.



the salty Aegean water exceed that in the surface layer occupied by the less saline waters (of Black Sea origin) at the Aegean-Dardanelles Junction. The large seasonality observed in the nitrate concentrations of the salty waters results in the formation of a seasonal nitracline within the thin interface separating the counterflows at the southern entrance of the strait.

These chemical features differ notably from the profiles obtained at the north-eastern exit to the Marmara basin (see Figure 4b) due to mixing of the nutrient-poor Aegean inflow with the nutrient-enriched, older water mass in the Marmara lower layer. For example, nutrient maxima are generally formed within the upper subhalocline, though with seasonally varying peak values. This is the result of the intrusion of the nutrient-poor, salty Aegean waters below the nutrient-enriched subhalocline waters in the Marmara-Dardanelles Junction. However, when the salty water flows in from the Aegean Sea strongly enough to occupy the whole lower layer in the strait, chemical profiles may become vertically uniform as at the southern exit. Due to the large difference between the DOC contents of the Marmara surface water and the salty Aegean inflow to the Marmara basin, DOC profiles always show a DOC gradient layer coinciding with the permanent halocline (see Figure 5).

Seasonal Variations of Chemical Concentrations

Based on the well-defined boundaries of the counterflows at the exits of the two straits and using long-term data from the strait exits, we have determined the depth-averaged chemical properties of the exchange flows in the Turkish straits. Figure 6a illustrates the drastic seasonal changes in the concentrations of phosphate and nitrate in the outflow from the Black Sea at the Bosphorus entrance. The nutrient concentrations increase at least tenfold from autumn to winter and then decrease again to trace levels in sum-

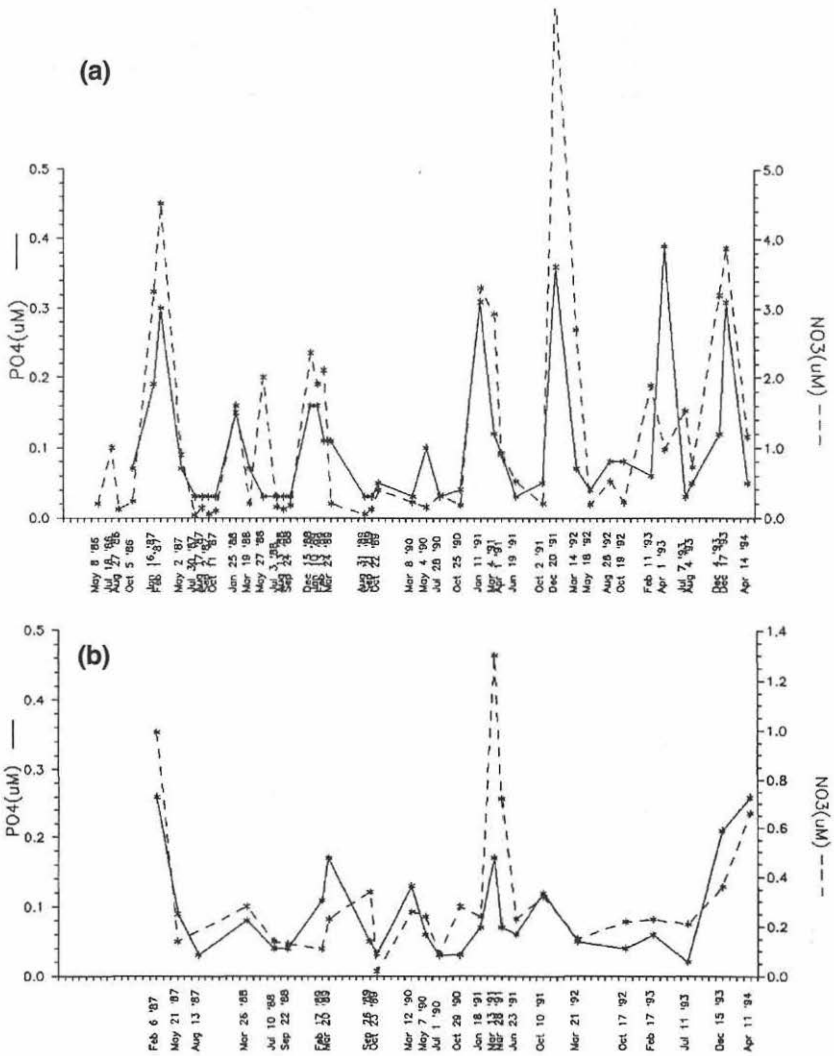


Figure 6 – Seasonal variations of PO_4-P and NO_3+NO_2-N (a) in the surface Black Sea outflow at the northern entrance of the Bosphorus Strait, (b) in the surface Marmara Sea outflow at the northern entrance of the Dardanelles Strait.

mer. This is mainly the result of remarkable seasonal fluctuations in the utililization rates of labile nutrients: this utilization diminishes dramatically in winter, accompanied by large riverine and industrial discharges to the coastal waters of the western Black Sea flowing toward the Bosphorus region as emphasized by Polat and Tugrul (1995).

Seasonal variations in the dissolved inorganic nutrient content of the Marmara surface outflow via the Dardanelles (see Figure 6b) are much less pronounced. The observed winter maxima were principally due to entrainment of the inorganic nutrient-enriched salty waters from the lower layer by intense vertical mixing with the western basin surface layer. In fact, the north-eastern Marmara surface layer also receives large nutrient inputs both from the Black Sea via the Bosphorus and from land-based sources in the Istanbul region (Polat, 1995; Tugrul and Polat, in press). Before the Marmara surface flow reaches the Dardanelles, its nutrient contents are modified to some extent by biomediated chemical processes and by the sinking of biodegradable particulate matter (Bastürk *et al.*, 1990; Polat, 1995). Accordingly, the ratios of nutrient species in the Marmara surface outflow differ from those in the Black Sea inflow to the Marmara Sea (Polat, 1995). Because of the limited external input to the western Marmara surface layer, the early winter (December-January) nutrient increase in the Marmara surface outflow is not as drastic as in the brackish inflow from the Black Sea (Polat and Tugrul, 1995).

The depth-averaged values of dissolved and particulate organic carbon (DOC, POC) and of the particulate fraction of nutrients (PON, PP) were also measured systematically. In the Black Sea outflow, particulate concentrations always increase markedly during the winter-early spring bloom. However, the DOC content of the outflow varies seasonally by only some 10% depending on the content of labile DOC in the input and on its decay rate in the western Black Sea surface waters. In the Marmara Sea, the concentrations of POC, PON and PP increase as well during the late winter-spring bloom (Polat, 1995). They reach occasionally peak values in early summer months due to a short-term bloom. The DOC contents of the Marmara surface outflow were found very similar to those of the Black Sea outflow.

The seasonal change in the chemical composition of the salty subsurface waters leaving the Aegean and Marmara basins via the Turkish straits is illustrated in Figure 7. The nutrient concentrations increase markedly from summer to winter, particularly at the Dardanelles entrance (see Figure 7a); the seasonality is much more pronounced in the nitrate content (0.1-2.4 μM), while phosphate concentrations range seasonally from between <0.02 to 0.08 μM, remaining close to the detection limit of the method (0.02 μM). The consistent winter increase is the result of the input from the deep layers by convective winter mixing in the open Aegean Sea (Küçüksezgin *et al.*, in press).

During the 1991-1994 period, the particulate concentrations in the Aegean inflow ranged seasonally from 0.04 to 0.70 μM for PON and from 0.01 to 0.04 μM for PP, whereas the POC values were in the range of 1.2-7.0 μM. The DOC concentration, varying slightly between 50-80 μM according to the season, is much larger than the POC content of the outflow (Tugrul, 1993; Polat and Tugrul, 1995).

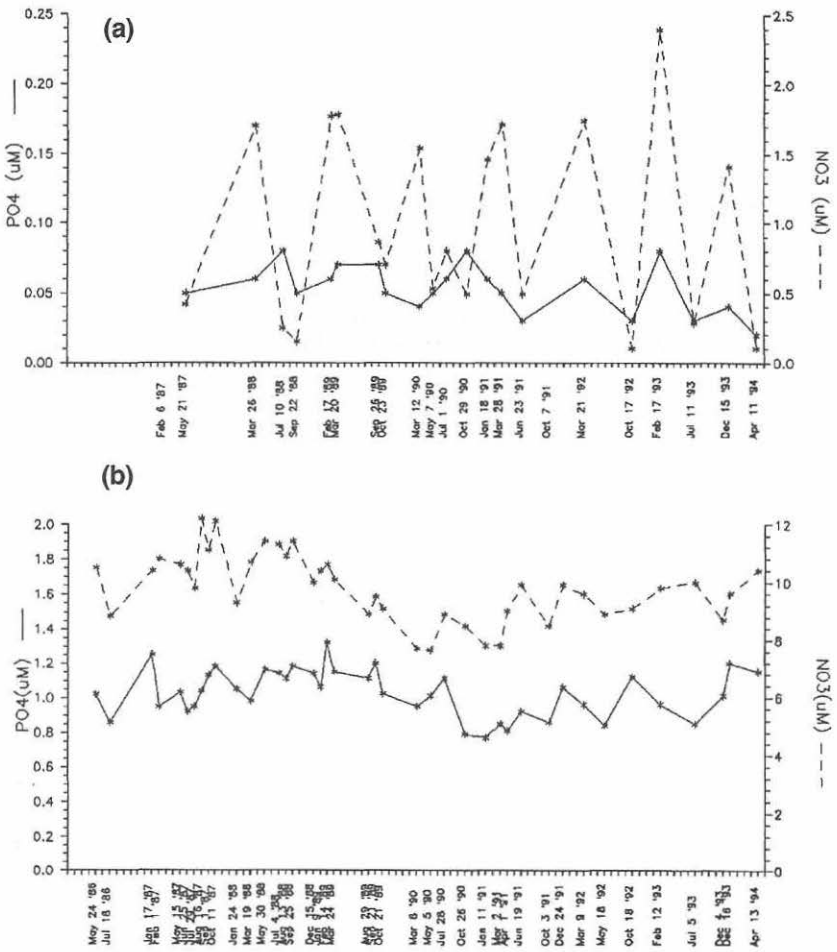


Figure 7 – Seasonal variations of PO_4-P and NO_3+NO_2-N (a) in the sub-surface Mediterranean inflow at the southern entrance of the Dardanelles Strait, (b) in the sub-surface Marmara outflow at the southern entrance of the Bosphorus Strait.

The salty Mediterranean waters in the Marmara basin are known to be enriched significantly in nutrients and impoverished in dissolved oxygen (BASTÜRK *et al.*, 1990; POLAT, 1995), whereas the total organic carbon content is hardly modified (TUGRUL, 1993). Data from the Bosphorus region demonstrate that the Mediterranean water leaves the Marmara deep basin with seasonally varying nutrient concentrations of 0.7-1.3 μM of phosphate and 7-12 μM of oxidized nitrogen (see Figure 7b), indicating a ten-fold enrichment. The salty Marmara outflow is poor however in particulate nutrients, being as low as 0.2-1.0 μM in PON and 0.03-0.07 μM in PP, whereas the POC content was observed to range from 2.0 to 11.0 μM during 1991-1994. These values are much lower than the inorganic nutrient and dissolved organic carbon (DOC = 58-83 μM) contents of the Marmara outflow via the Bosphorus Strait.

Annual Mean Concentrations

Table I lists the annual means of the various forms of nutrients and organic carbon concentrations in the exchanging waters of the two straits. The mean values of ammonia (NH_4^+) and dissolved organic nitrogen (DON) concentrations are based on limited data. The estimate of 0.5 μM NH_4^+ for the Black Sea outflow was derived from measurements obtained in the south-western Black Sea (SEN GUPTA, 1971; KIRIKOVA, 1986; SAPOZHNIKOV, 1990; CODISPOTI *et al.*, 1991; unpublished data of R/V. *D. Mendelyev* cruise 44 in July-September 1989). Based on limited ammonia data from the eastern Marmara Sea (FRIEDERICH *et al.*, 1990), an annual mean value of 0.2 μM may be assumed for the salty Marmara outflow via the Bosphorus, which is certainly much less than the nitrate content (9.6 μM) of the outflow. For the Dardanelles exchange flows, a mean value of 0.15 μM for ammonia was assumed for the Marmara surface outflow and of 0.1 μM for the salty Mediterranean outflow based on the limited data from the adjacent seas (FRIEDERICH *et al.*, 1990; KÜÇÜKSEZGIN *et al.*, in press; the unpublished data of the June-1994 R/V *Meteor* cruise to the north-eastern Mediterranean).

TABLE I

Annual means of nutrient and organic carbon concentrations (μM) in the surface (C1) and sub-surface (C2) flows

	BOSPHORUS		DARDANELLES	
	C_{b1}	C_{b2}	C_{d1}	C_{d2}
DIP	0.11	0.99	0.09	0.05
PP	0.15	0.05	0.21	0.02
DOP	0.30	0.06	0.14	0.05
TP	0.56	1.10	0.44	0.12
NH_4^+	0.50	0.20	0.15	0.10
N_{Ox}	1.31	9.60	0.33	1.03
DIN	1.81	9.80	0.48	1.13
PON	1.96	0.40	1.94	0.30
DON	18.00	3.70	13.00	3.00
TN	21.77	13.90	15.42	4.43
POC	17.0	4.7	20.0	3.6
DOC	195.0	72.6	166.0	64.3
TOC	212.0	77.3	186.0	67.9

Because of large riverine discharges into the north-western shelf waters, the Black Sea surface waters possess large concentrations of less labile dissolved organic compounds (MEYBECK, 1982; MEE, 1992), with maximum concentrations as high as 18-25 μM observed in polluted coastal waters (SOROKIN, 1983; VINOGRADOV, 1992). Since alongshore currents enable these DON-enriched surface waters to reach as far as the Bosphorus, a mean value of about 18.0 μM reported by SOROKIN (1983) for the coastal surface waters was presumed for the outflow via the Bosphorus. The DON content of the Mediterranean outflow at the Dardanelles entrance, derived from the published reports (COSTE *et al.*, 1988), is of the order of 3.0 μM.

The salty water is slightly diluted by the DON-rich brackish counterflow in the surface. Based on the initial salinity values at the southern entrance of both the Dardanelles and Bosphorus straits, a mean value of 3.7 μM was estimated by mixing the counterflows with their initial DON values and assuming that they vary only slightly with season. Similarly, the chemical properties of the brackish Black Sea inflow to the Marmara surface layer are further modified by vertical mixing with the salty, DON-poor Mediterranean water in the Marmara lower layer until the Dardanelles entrance is reached; thus, the annual average of the DON content of the Marmara surface outflow may be presumed to drop to 13 μM (POLAT, 1995).

A comparison of the annual mean concentrations of the various forms of nutrients and organic carbon in the exchanging water of the Turkish straits reveals that the Black Sea outflow reaches as far as the Aegean basin of the Mediterranean with large DON and DOC values due to their low decay rates, but with a net decrease in the mean nitrate value due to consumption in the Marmara basin. In the Black Sea outflow, the annual mean of TP (0.56 μM) is composed of comparable concentrations of DIP and PP whereas the DOP constitutes nearly 50% of the TP. Similarly, the labile nitrogen concentration of the outflow, including only dissolved inorganic+particulate organic components of TN, is about 3.8 μM on an annual basis, corresponding to merely 20% of the mean TN of 21.8 μM, the remainder being less labile DON mainly of riverine origin. The TOC content of the outflow is of the order of 210 μM, with an insignificant contribution from the particulate fraction.

The nutrient content of the salty Mediterranean water leaving the Marmara basin by the Bosphorus undercurrent (see Table I) behaves differently. The nitrate and reactive phosphate dominate the TN and TP content of the salty outflow. In fact, the Mediterranean water enters the Marmara basin with low nutrient concentrations, in the order of 0.12 μM for TP, 4.43 μM for TN and about 67.9 μM for TOC. During its 6-7 years sojourn in the basin, the Mediterranean water is enriched in inorganic nutrients by the particulate nutrient input from the surface and their subsequent decay to the inorganic form. TOC content however is influenced only slightly and is much lower than in the surface counterflow. The concentrations of particulate and dissolved organic nutrients in the Bosphorus underflow are lower than their initial values at the Dardanelles entrance because photosynthesis in the Marmara Sea is limited to the upper layer. Therefore, the DOP and PP concentrations of the Mediterranean water in the Bosphorus are very similar to those reported by COSTE *et al.* (1988) for the Mediterranean waters flowing out through the Gibraltar Strait.

Seasonal and interannual variations in the labile POC and (DIN+PON) contents of the surface outflows both from the Black and Marmara seas are likely to alter the annual means of the total nitrogen and organic carbon by no more than about 10% because they are dominated throughout the year by the less labile DOC and DON. The decrease in inorganic components of nutrients in the strait surface flows is partly compensated by an increase in the dissolved and particulate organic nutrients in the surface waters; accordingly the observed seasonality in the TP is of the order of 10% of the annual mean estimated for both of the Black Sea and Marmara surface outflows (POLAT, 1995).

WATER AND CHEMICAL EXCHANGE FLUXES THROUGH THE BOSPHORUS AND DARDANELLES STRAITS

The two-layer flow regimes in the Turkish straits are known to exhibit both short- and long-term changes, depending on the meteorological and hydrological conditions in the adjacent seas and the total fresh-water input to the Black Sea (ÜNLÜATA *et al.*, 1990; LATIF *et al.*, 1991; OGUZ and SUR, 1989; LATIF *et al.*, 1992; ÖZSOY *et al.*, 1992; BESIKTEPE *et al.*, 1994; ÖZSOY *et al.*, 1994). The outflow from the Black Sea increases during the spring-early summer period and decreases during the autumn-winter period; a similar seasonality is expected in the Marmara surface outflow via the Dardanelles Strait.

Earlier current measurements (GUNNERSON and ÖZTURGUT, 1974) and very recent Acoustic Doppler Current Profiler (ADCP) surveys (LATIF *et al.*, 1992; ÖZSOY *et al.*, 1994) in the Bosphorus demonstrate these dynamic changes. According to the limited ADCP data obtained by LATIF *et al.* (1992) and ÖZSOY *et al.* (1995), the upper flow generally ranges between 15 000 and 30 000 m^3s^{-1} during the spring period. Short-term changes in the counterflows may be significant in autumn and winter. For example, during the short-term blockage of the surface flow by strong southwesterly winds in December 1993, the salty water flowing from the Marmara Sea via the strait was observed to be as large as 20 000 m^3s^{-1}; then, the flow may drop to 1 000 m^3s^{-1} for some days or even become blocked for a short-period when the surface counterflow increases (ÖZSOY *et al.*, 1994).

It is impossible on the other hand to evaluate the seasonal and episodic water flows in the Dardanelles Strait. The only reliable flow data available for calculating the chemical fluxes are the annual volume fluxes estimated from the conservation of salt, assuming the system to be in a steady state and that there exists a net input of fresh water to the Black Sea. ÜNLÜATA and ÖZSOY (1986), using the net fresh water input to the Black Sea together with the 1985-1986 salinity data from the Turkish Straits System, estimated the water balance in the Sea of Marmara from the equations of conservation of mass. Later, ÜNLÜATA *et al.* (1990), BESIKTEPE (1991) and ÖZSOY *et al.* (1994) used more recent data from the Sea of Marmara to refine their calculations of the volume fluxes exchanged through the straits.

Chemical exchange fluxes estimated in this study are principally based on the steady state assumption that the water exchange fluxes and the chemical concentrations are constant on a yearly time scale. Therefore, based on the mean concentration values (Ci) given in Table I and on the volume fluxes provided in Figure 8a, we derived the annual loads of nutrients and organic carbon laterally exchanged through the Turkish straits (see Fig. 8b), using the equations given below :

I. Exchanges through the Bosphorus:

Surface Black Sea outflux (F_{b1}) = $Q_{bu} * C_{b1}$; $Q_{bu} = Q_{b1} - Q_{b1}'$

Sub-surface Marmara outflux (F_{b2}) = $Q_{bL} * C_{b2}$; $Q_{bL} = Q_{b2} - Q_{b2}'$

II. Exchanges through the Dardanelles:

Surface Marmara outflux (F_{d1}) = $Q_{du} * C_{d1}$; $Q_{du} = Q_{d1} - Q_{d1}'$

Sub-surface Aegean outflux (F_{d2}) = $Q_{dL} * C_{d2}$; $Q_{dL} = Q_{d2} - Q_{d2}'$

where Q_{bu}, Q_{bL}, Q_{du} and Q_{dL} are the net lateral volume fluxes exchanged between the adjacent seas after correction for the flux entrained by the counterflow.

In fact, both the volume fluxes and the total phosphorus, total nitrogen and total organic carbon concentrations of the exchanging waters vary seasonally by at least some 10% of the estimated means (POLAT and TUGRUL, 1995; POLAT, 1995). Apart from the natural seasonal fluctuations in the mass fluxes, daily volume fluxes in the straits are known to vary considerably. Chemical exchange fluxes were derived from instantaneous ADCP flow measurements in the straits and the accompanying total phosphorus and labile nitrogen (inorganic+particulate) concentrations. The short-term estimates displayed in Tables II and III are consistent with the rates computed from the annual fluxes displayed in Figure 8b. Nevertheless, during the blockage of either layer, the chemicals exported by the counterflow may very much exceed the values derived from the annual mean fluxes. In conclusion, the long-term measurements of water flows and chemical parameters carried out in the Turkish straits strongly suggest that the annual fluxes indicated in Figure 8b represent the orders of magnitude of chemicals exchanged between the adjacent seas. However, they should be used cautiously as seasonal rates of chemical exchanges in the Turkish straits.

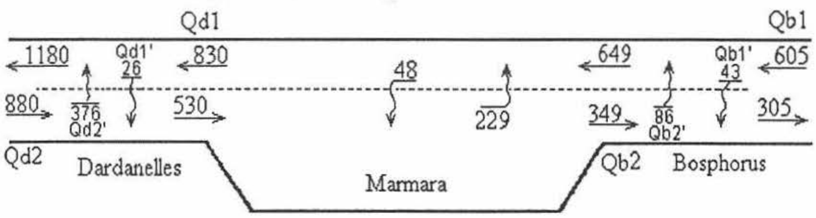


Figure 8a – Water fluxes (km^3y^{-1}) through the Turkish straits (after ÖZSOY *et al.*, 1995).

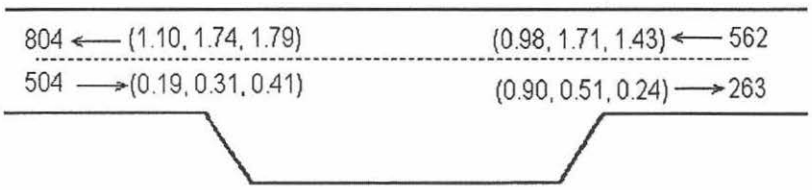


Figure 8b – Estimated annual exchanges of (TP, TN, TOC) through the Turkish straits (x 10^4 tons TP, x 10^5 tons TN, x 10^6 tons TOC).

TABLE II

Estimation of fluxes of water and total phosphorus through the Bosphorus Strait from specified ADCP data

	Surface			Sub-surface		
Date	Q_{b1}	C_{b1}	F_{b1}	Q_{b2}	C_{b2}	F_{b2}
Apr. 1, 91	25000	0.62	1.51	1000	0.90	0.09
Oct. 2, 91	4000	0.45	0.18	10000	0.93	0.90
Dec. 20, 91	17500	0.78	1.33	3000	1.18	0.35
Mar. 8, 92	47500	0.62	2.88	0	1.02	0.00
Mar. 14, 92	15000	0.59	0.86	4000	0.83	0.32
Aug. 28, 92	17000	0.52	0.86	5000	0.77	0.38
Aug. 31, 92	5000	0.51	0.25	10000	1.01	0.99
Feb. 11, 93	45000	0.56	2.45	0	0.99	0.00
Dec. 18, 93	0	0.52	0.00	20000	1.02	1.99

Q = (m^3s^{-1}), C = (μmole/L), F = (x10^4 tons P y^{-1} = 0.9765*Q*C)

While we find that the TP export (0.98 x 10^4 tons y^{-1}) from the Black Sea to the Marmara basin is nearly balanced by the importation from the Marmara lower layer by the Bosphorus counterflow, the TN and TOC outfluxes from the Black Sea (estimated as 1.71 x 10^5 and 1.43 x 10^6 tons y^{-1} respectively) are 3-5 times the input from the Marmara basin. The nutrient outflux from the Black Sea via the Bosphorus may be insignificant for the Black Sea system because it is much lower than the riverine inputs (MEE, 1992). However, it is of great importance for the nutrient balance in both the Marmara Sea and the Aegean basin of the Mediterranean. In the Marmara basin, the upper layer TP budget is principally determined by inputs from

TABLE III

Estimation of fluxes of water and labile nitrogen through the Bosphorus Strait from specified ADCP data

	Surface			Sub-surface		
Date	Q_{b1}	C_{b1}	F_{b1}	Q_{b2}	C_{b2}	F_{b2}
Apr. 1, 91	25000	3.7	0.41	1000	12.8	0.04
Oct. 2, 91	4000	2.0	0.04	10000	12.0	0.40
Dec. 20, 91	17500	9.0	0.70	3000	13.6	0.14
Mar. 8, 92	47500	5.5	1.15	0	12.1	0.00
Mar. 14, 92	15000	5.0	0.33	4000	11.6	0.15
Aug. 28, 92	17000	2.9	0.22	5000	11.6	0.19
Aug. 31, 92	5000	3.8	0.08	10000	12.5	0.42
Feb. 11, 93	45000	3.6	0.72	0	13.1	0.00
Dec. 18, 93	0	4.6	0.00	20000	12.5	1.17

Q = (m^3s^{-1}), C = (μmole/L), F = (x10^5 tons N y^{-1} = 0.4415*Q*C) both the Black Sea and the Marmara lower layer, whereas the land-based discharges are of secondary importance for the whole system on an annual basis (POLAT, 1995; TUGRUL and POLAT, in press).

On an annual basis, the chemicals exported from the Black Sea to the Marmara upper layer eventually reach as far as the Aegean basin of the Mediterranean via the Dardanelles surface flow, their dilution being compensated by the increase in the volume outflux from the Dardanelles. The TOC exported (1.79×10^4 tons y^{-1}) from the Marmara to the Aegean Sea is about 25% larger than the Black Sea outflux via the Bosphorus, whereas the TP and TN outfluxes by the two surface flows are very similar. It should be noted that the surface water outflow in the Dardanelles is nearly 50% larger than in the Bosphorus due to the entrainment of salty Mediterranean water into the surface flow in the Marmara basin. Comparison of the annual chemical fluxes in the Dardanelles reveals that the inputs from the Marmara Sea to the Mediterranean are at least 4-5 times the exports from the system via the strait undercurrent, indicating a net mass transfer from the Black Sea to the Mediterranean via the Turkish Straits System. The Black Sea inputs, comparable with those of riverine and atmospheric origins (COSTE *et al.*, 1988; BETHOUX *et al.*, 1992; MONTEGUT, 1993), but much lower than the Atlantic inflows to the Western Mediterranean, are expected to contribute to the net production and thus to the nutrient balances in the Aegean basin of the Eastern Mediterranean.

ACKNOWLEDGEMENTS

We gratefully thank the scientists of IMS-METU, the captain and the crews of R/V *Bilim* for their contributions to this study which has been thoroughly supported by the Turkish Scientific and Technical Research Council (TUBITAK) and the NATO Scientific Affairs Division within the framework of the Science for Stability Programme.

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