Mediterranean Marine Science

Vol 3, No 1 (2002)

Nutrient exchange fluxes between the Aegean and Black Seas through the Marmara Sea

S. TUGRUL, T. BESIKTEPE, I. SALIHOGLU

doi: 10.12681/mms.256

Mediterranean Marine Science
Vol. 3/1, 2002, 33-42

Nutrient exchange fluxes between the Aegean and Black Seas through the Marmara Sea

S. TUĞRUL, Ş. T. BEŞİKTEPE and İ. SALİHOĞLU

Institute of Marine Sciences, Middle East Technical University (IMS-METU)
Erdemli, İçel 33731, TURKEY

e-mail: tugrul@ims.metu.edu.tr

Abstract

Long-term data obtained in the Turkish Strait System (TSS) including the Sea of Marmara, the Dardanelles and Bosphorus straits, during 1990-2000, have permitted us to calculate seasonal and annual fluxes of water and nutrients (nitrate, phosphate) exchanged between the Aegean and Black Seas through the TSS. Two-layer flow regimes in the TSS introduce the brackish waters of the Black Sea into the Aegean basin of the northeastern Mediterranean throughout the year. A counter flow in the TSS carries the salty Mediterranean water into the Black Sea via the Marmara deep basin. The annual volume influx from the Black Sea to the Marmara upper layer is nearly two-fold the salty water exported from the Marmara to the Black Sea via the Bosphorus underflow. The brackish Black Sea inflow is relatively rich in nitrate and phosphate in winter, decreasing to the lowest levels in late summer and autumn. Biologically labile nutrients of Black Sea origin are utilized in photosynthetic processes in the Marmara Sea and are partly exported to the Marmara lower layer. Eventually, the brackish Black Sea waters reach the Dardanelles Strait, with modified bio-chemical properties. On the other hand, the salty Mediterranean waters with low concentrations of nutrients enter the Marmara deep basin. During threir 6-7 year sojourn in the Marmara basin, the salty waters become enriched in nitrate (DIN) and phosphate (DIP), due to oxidation of planktonic particles sinking from the Marmara surface layer. The annual nutrient inputs from the Black Sea to the Marmara basin were estimated as $8.17 x 10^8$ moles of DIN and $4.25 x 10^7$ moles of DIP, which are much less than the importation from the Marmara lower layer via the Bosphorus undercurrent. The salty Aegean water introduces nearly $6.13 x 10^8$ moles of DIN and $2.79 x 10^7$ moles of DIP into the Marmara lower layer. The estimated DIP outflux from the Aegean Sea is nearly 2 times less than the importation from the Marmara Sea via the Dardanelles Strait.

Keywords: Black Sea, Aegean Sea, Marmara Sea, Water balance, Nutrient fluxes, Seasonal variations.

Introduction

The two-layer flow regimes in the Sea of Marmara connected to the adjacent seas via the Dardanelles and Bosphorus straits, permit water exchanges between the Black and the Aegean Seas throughout the year (GUNNERSON & ÖZTURGUT, 1974; GRASSHOFF, 1975; SOROKIN, 1983; BEŞİKTEPE *et al.,* 1993, BEŞİKTEPE *et al.,* 1994). The annual volume influx from Black Sea to the Marmara Sea is nearly twice the salty water outflux from the Marmara basin to the Black Sea via the Bosphorus undercurrent (ÜNLÜATA *et al.,* 1990; BEŞİKTEPE *et al.,* 1994). Cyclonic alongshore currents in the Black Sea carry the contaminated surface waters of the northwestern shelf as far as the Bosphorus region, with the modified hydro-chemical properties (POLAT & TUĞRUL, 1995). The brackish Black Sea inflow is further contaminated by land-based discharges in the Bosphorus region (ORHON *et al.,* 1994). Moreover, the salinity and nutrient contents of inflow slightly increase at the southern exit of the Bosphorus due to vertical mixing of the counter flows during the year. Concomitant photosynthetic processes in the Marmara upper layer, however, lead to consumption of biologically available nutrients and thus a net export of particulate nutrients to the lower layer. Eventually, the Black Sea inflow reaches the Dardanelles entrance, with modified nutrient concentrations (POLAT & TUĞRUL, 1995).

On the other hand, the salty Mediterranean water at the Dardanelles southern entrance possesses almost saturated levels of dissolved oxygen but low values of nitrate and phosphate concentrations. The Dardanelles undercurrent introduces salty water into the Marmara basin, with seasonally varying volume fluxes (GRASSHOFF, 1975; SOROKIN, 1983). During their 6-7 year sojourn in the Marmara basin, these salty waters become very poor in dissolved oxygen, dropping to suboxic levels of 30-50 μM, with concomitant increases in the nitrate and reactive phosphate concentrations due to aerobic oxidation of POM snowing from the productive upper layer waters of Black Sea origin (POLAT *et al.,* 1998).

Until late 80's, the principal chemical oceanography of the two-layer flow regimes in the Sea of Marmara, Dardanelles and Bosphorus straits, had been poorly understood due to the scarcity of systematic data. Recent studies have addressed the critical role of the Black Sea input for the Marmara ecosystem (POLAT, 1995; TUĞRUL & POLAT, 1995, POLAT & TUĞRUL, 1996). In this report, based on long-term hydro-chemical data obtained by the METU-Marine Sciences Institute since 1986, we have calculated seasonal fluxes of water and nutrient exchanged between the Aegean and Marmara Seas via the Dardanelles Strait and between the Black and Marmara Seas via the Bosphorus Strait.

Materials and Methods

Oceanographic cruises have been carried out in the Turkish Strait System (Marmara Sea, Bosphorus and Dardanelles Straits) on a seasonal basis starting from 1986 by IMS-METU using R/V BILIM, within the context of a multi-year observational programme supported by different authorities (BEŞİKTEPE *et al.,* 1994). A typical station network established during these field campaigns is shown in Figure 1. Basic ecosystem variables, including temperature, salinity, nutrients and plankton data have been collected within the framework of this program. Stations selected for representing the hydro-chemical properties of the exchange flows in the entrance of the straits are noted over this figure. Their coordinates are as follows: 29.0147E and 41.0317N for St. B-2; 29.1228E and 41.2153N for B-15 in the Bosphorus; 26.7617E and 40.4383N for D-1; 26.2300E and 40.0283N for D-6 in the Dardanelles Strait.

Water samples were collected with a 12-bottle Rosette system attached to a Sea-Bird Model CTD probe. Dissolved oxygen concentrations were determined by following the conventional Winkler method. Nutrient measurements were carried out using a multi-channel Technicon AII Model auto-analyser.

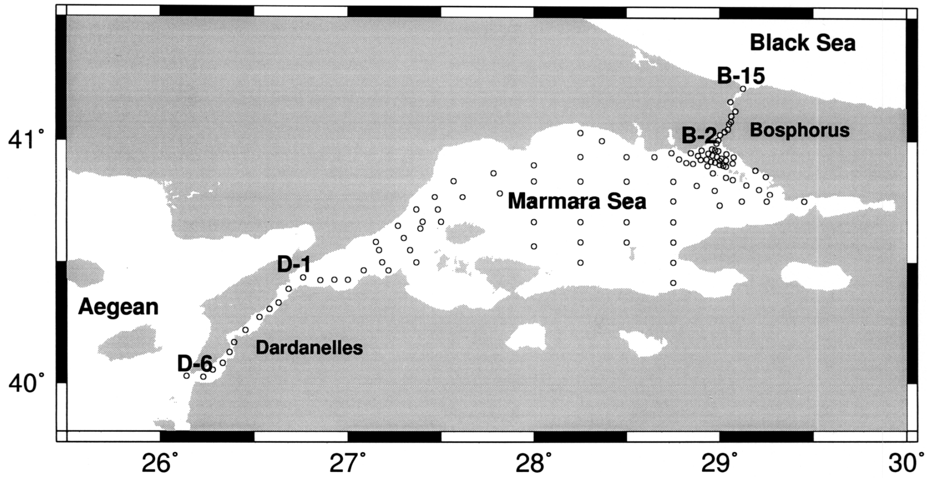


Fig. 1: Typical station network in the Marmara Sea and the positions of stations selected in the straits for flux estimates.

Results

Water Budget and Steady-State Fluxes: Water budget calculations given in the present study follow the methodology given in BEŞİKTEPE *et al.,* 1994. Here we will give a brief summary of the methodology. The upper and lower layer boundaries of the counter flows at the straits entrances have been defined based on the following salinity calculations: the upper layer extends down to depths where the salinity values $S_1^* = S_s + 0.2(S_b - S_s)$ and the lower layer starts at depths where $S_2^* = S_b - 0.2(S_b - S_s)$, where S_s stands for surface water salinity (average within the first 5m) and Sb is the bottom layer salinity (average within 5 m from the salinity maximum depth of each cast). The salinity values $S < S_1^*$ and $S > S_2^*$ were then averaged to compute average upper- and lower-layer salinities S_1 and S_2, respectively.

The flux computations are based on the Knudsen relations expressing the steady-state mass budgets. For each compartment of the system displayed in Figure 2, water and salt conservation are stated as follows;

$$Q_{1o} + Q_d = Q_{1i} + Q_f + Q_u$$
$$Q_{2o} + Q_u = Q_{2i} + Q_d$$
$$S_{1o}\,Q_{1o} + S_1\,Q_d = S_{1i}\,Q_{1i} + S_2 Q_u$$
$$S_{2o}Q_{2o} + S_2 Q_u = S_{2i}Q_{2i} + S_1 Q_d$$

The influx and outflux for the upper layer are Q_{1i}, Q_{1o} and those for the lower layer are Q_{2i}, Q_{2o}. The fluxes entrained in the upper and lower layers are Q_u, Q_d, respectively. They can be determined from the above equations if the net fresh water inflow $Q_f = Q_p + Q_r - Q_e$ (where Q_p, Q_r and Q_e are the precipitation, runoff and evaporation fluxes) is specified at the surface, and the salinities S_{1i}, S_{1o}, S_{2i}, S_{2o}, S_1, S_2 are specified at the two ends of each compartment and for each layer. It should be noted that this system is indeterminate in each separate compartment, because it involves six unknowns and four equations. The system is closed at the Black Sea with setting $Q_{1i}=0$ and $Q_{2o}=0$ because the Bosphorus is the only connection of the Black Sea to the world oceans. The flux estimates derived from the above equations for the Sea of Marmara greatly depend on the annual and seasonal estimates of net freshwater input to the Black Sea.

In the Black Sea, the contributions of precipitation and river runoff are of equal magnitude (300 and 320 km^3/yr respectively), totalling a fresh water input about twice as large as the loss by evaporation (350 km^3/yr) (ÜNLÜATA *et al.,* 1990). The Danube River with an annual water discharge of about 210

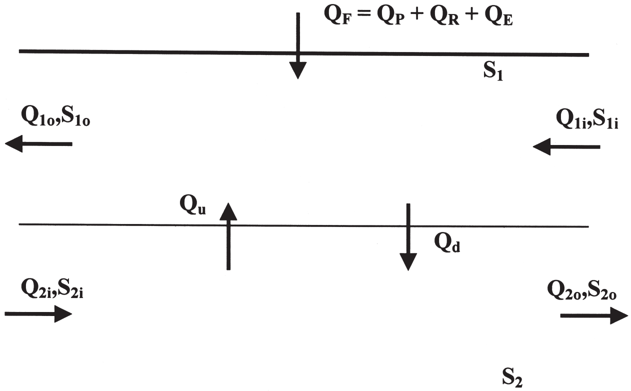
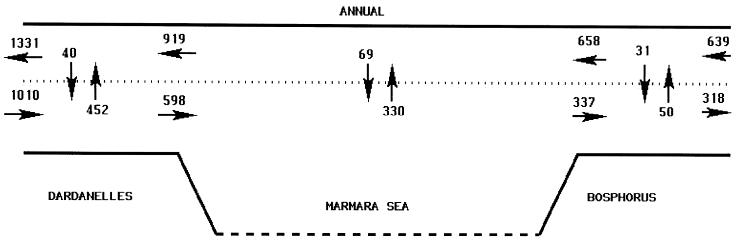


Fig. 2: Simplified two-layer fluxes in the Sea of Marmara.

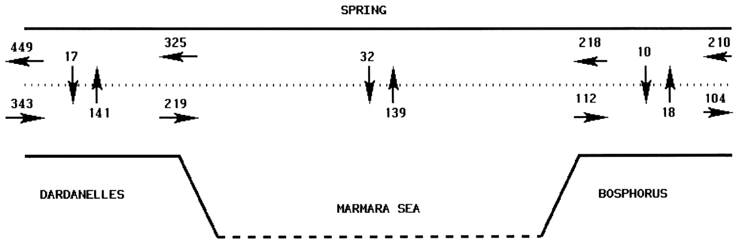
km^3/yr provides nearly 70% of the total runoff to the Black Sea. In this report, monthly volume fluxes of the Danube given in COCIASU *et al.,* (1997) were used to estimate the seasonal and annual fluxes of the net freshwater input to the Black Sea, assuming that the Danube discharge corresponds to nearly 60% of the net freshwater input (320 km^3/year) to the Black Sea basin. Thus, the seasonal variation of the net freshwater influx is as follows: 77 km^3 in winter, 105 km^3 in spring, 82 km^3 summer and 56 km^3 in autumn. The annual and seasonal volume fluxes computed using the above approach and 14-year hydrological data in the Sea of Marmara and the Straits are depicted in Figure 3. These new fluxes are comparable with our previous computations using 4 years of data (BEŞİKTEPE, *et al.,* 1994). The most notable difference between the two computations has appeared in the exchanges between upper and lower layers, decreasing in the new computation. The seasonal volume fluxes depicted in Figure 3 for the TSS have been estimated for the first time. The range of the seasonal variability depends on the rate of the brackish Black Sea inflow to the Marmara Sea. Accordingly, the volume fluxes between the compartments of the TSS appear to increase in the spring and drop to minimum levels in the autumn.

Layer-averaged concentrations of nitrate and phosphate in the exchange flows of the Bosphorus and Dardanelles straits were estimated from nutrient profiles obtained at the straits entrances, based on the boundaries of the counter-flows at the same locations (POLAT & TUĞRUL, 1995). Seasonal average values of nutrient concentrations for the upper and lower layer flows in the exchange flows of the two straits were derived from the monthly measurements. Water masses exchanged between the adjacent seas via the straits were calculated from the water and salt balances of the Marmara Sea, based on data obtained in the TSS since 1986. The new volume fluxes calculated on the seasonal basis have permitted us to estimate nutrient fluxes in the straits.

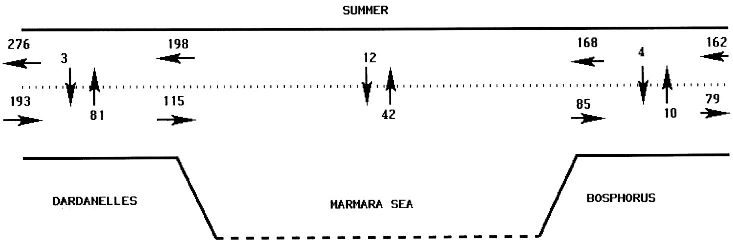
Nutrient Content of the Black Sea Water in the Straits: Typical profiles in Figure 4 demonstrate that nitrate+nitrite (DIN) and dissolved inorganic phosphate (DIP) concentrations in the brackish Black Sea inflow vary slightly with depth but markedly with season, depending on removal and input rates. Layer-averaged DIN and DIP concentrations in the summer-early autumn months are always very low (DIN=0.05-0.2 μM; DIP=0.02-0.1 μM); but they markedly increase to peak values of 4.5-7 μM for DIN and 0.2-0.4 μM for DIP in early winter months. Drastic winter increases indicate that the nutrient-enriched northwestern shelf waters reach as far as the Bosphorus region

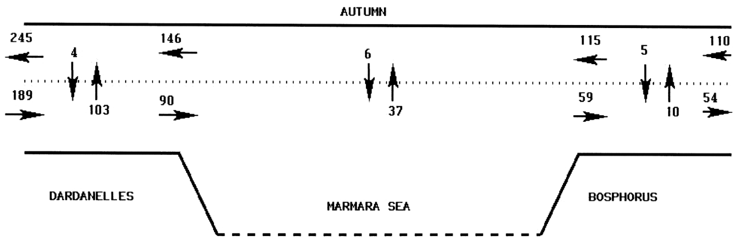


b)



c)





e)

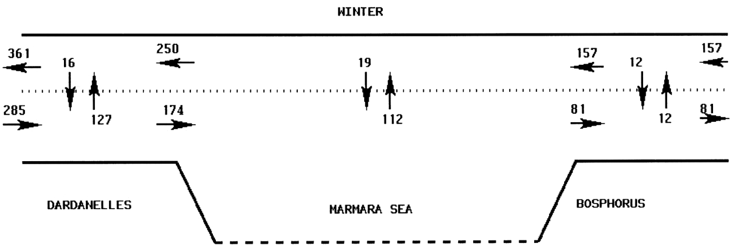


Fig. 3: Seasonal and annual volume fluxes (km3/season) across the compartments of the Sea of Marmara and straits. a) annual, b) spring, c) summer, d) autumn, e) winter.

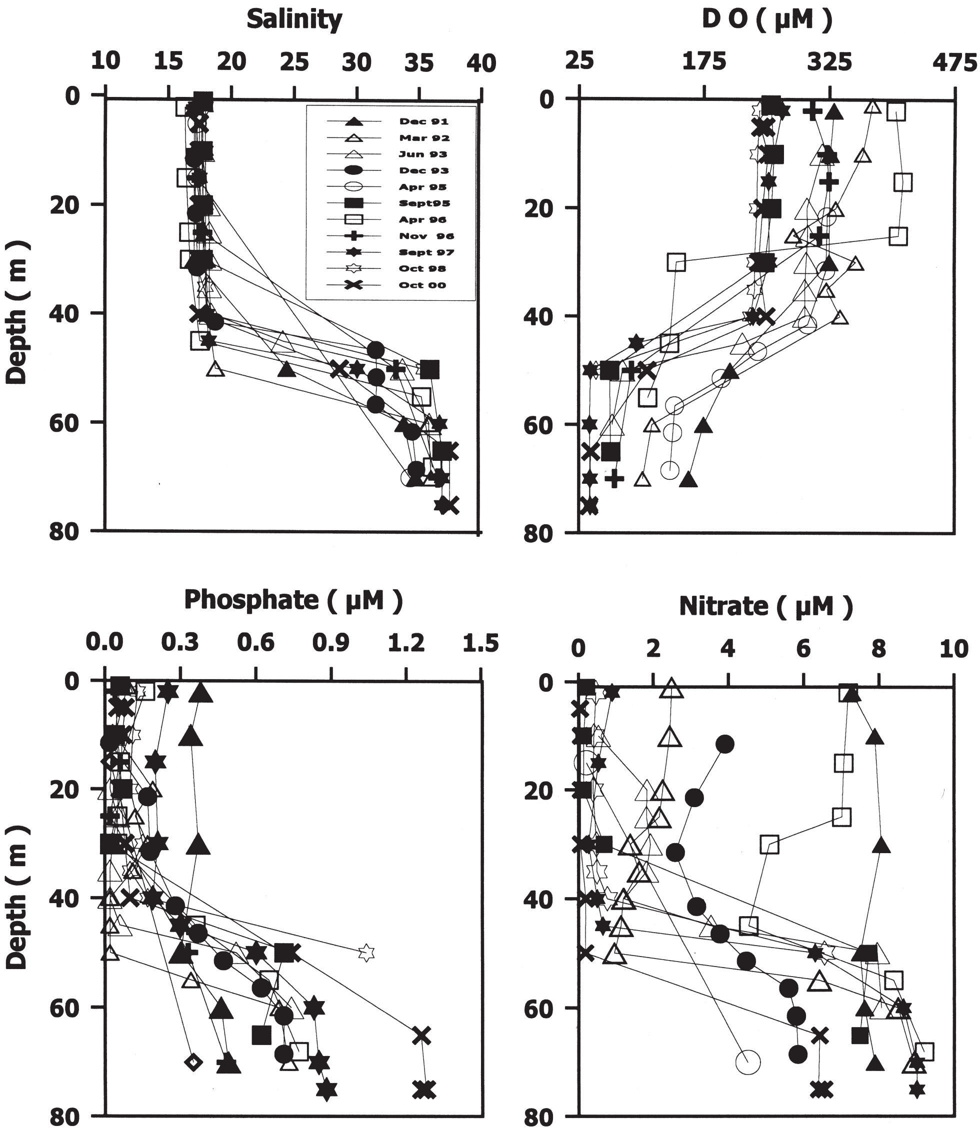


Fig. 4: Selected profiles of salinity, dissolved oxygen, nitrate+nitrite and reactive phosphate in the Bosphorus - Black Sea entrance.

when their consumptions descend in winter months (Cociasu *et al.,* 1996, 1997; POLAT & TUĞRUL, 1995). In the Marmara Sea, the nutrient components of the Black Sea inflow are partly modified by various physical and photosynthetic processes until the Dardanelles Strait is reached. Accordingly, the DIN and DIP in the Marmara upper layer water at the Dardanelles entrance display less pronounced seasonal variations.

Nutrient Content of the Salty Mediterranean Inflow in the Straits: Nutrient profiles in Figure 5 show that the salty water in the Dardanelles entrance contains low concentrations of nutrients, varying seasonally between 0.47-1.62 µM for DIN and 0.03-0.05

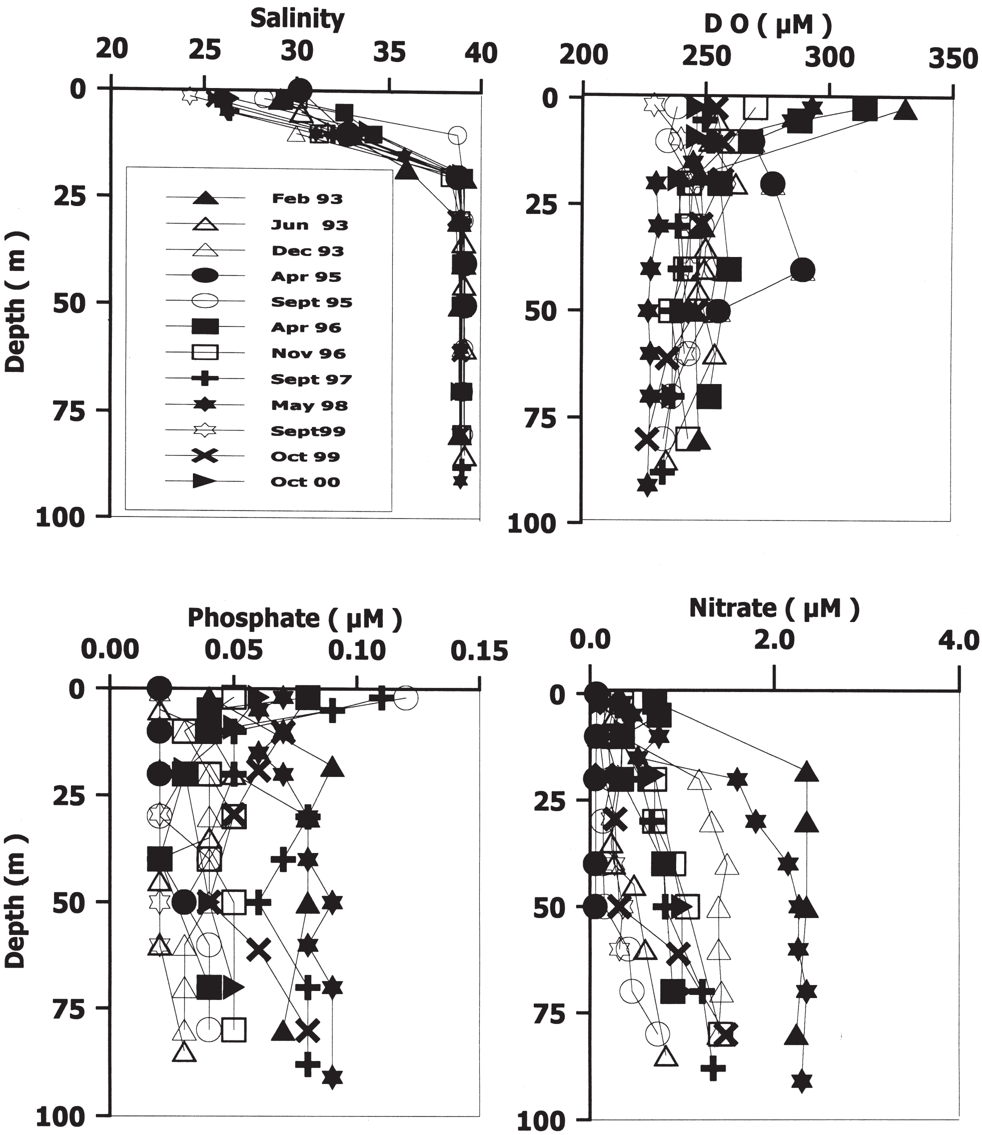


Fig. 5: Selected profiles of salinity, dissolved oxygen, nitrate+nitrite and reactive phosphate in the Dardanelles - Aegean Sea entrance.

μM for DIP. The winter average of DIN for the salty Dardanelles underflow exceeds that of the Marmara surface water at the Dardanelles entrance. The salty water is known to become be enriched in DIN and DIP by about 10-fold but the molar ratio of DIN/DIP drops from about 20 to levels of 8-10 in the Marmara basin as it reaches the Bosphorus entrance. This ratio is nearly invariant in the Bosphorus underflow during the year.

Discussion

Nutrient Fluxes in the Bosphorus and Dardanelles Straits: The seasonal volume fluxes and associated nutrient concentrations

Table 1
Seasonal & Annual Nitrate Fluxes in the Bosphorus and Dardanelles Straits.

BOSPHORUS					DARDANELLES		
Flow type (layer)	**Season**	**Volume flux ($*10^9$ m^3)**	**NO3 conc. ($mmol/m^3$)**	**NO3 flux $*10^8$moles**	**Volume ($10^9 m^3$)**	**NO3 conc. ($mmol/m^3$)**	**NO3 flux $*10^8$ mol**
Upper	Spring	200	1.32	2.64	307	0.2	0.61
Upper	summer	158	0.42	0.66	194	0.12	0.23
Upper	Autumn	105	0.22	0.23	142	0.3	0.42
Upper	Winter	145	3.2	4.64	234	0.36	0.84
Upper	**Annual**	**608**	**1.29**	**8.17**	**877**	**0.24**	**2.1**
Lower	Spring	94	9.17	8.62	202	1.14	2.3
Lower	summer	76	10.46	7.95	112	0.47	0.52
Lower	Autumn	49	9.34	4.58	87	0.88	0.76
Lower	Winter	68	9.81	6.67	158	1.62	2.55
Lower	**Annual**	**287**	**9.7**	**27.8**	**559**	**1.03**	**6.13**

Table 2
Seasonal & Annual Phosphate Fluxes in the Bosphorus and Dardanelles Straits.

BOSPHORUS					DARDANELLES		
Flow type (layer)	**Season**	**Volume flux ($*10^9$ m^3)**	**PO4 conc. ($mmol/m^3$)**	**PO4 flux $*10^7$moles**	**Volume ($10^9 m^3$)**	**PO4 conc. ($mmol/m^3$)**	**PO4 flux $*10^7$ mol**
Upper	Spring	200	0.05	1.00	307	0.06	1.84
Upper	summer	158	0.03	0.47	194	0.03	0.58
Upper	Autumn	105	0.05	0.52	142	0.05	0.71
Upper	Winter	145	0.14	2.03	234	0.09	2.10
Upper	**Annual**	**608**	**0.07**	**4.25**	**877**	**0.06**	**5.26**
Lower	Spring	94	0.92	8.65	202	0.05	1.01
Lower	summer	76	0.99	7.52	112	0.03	0.34
Lower	Autumn	49	0.91	4.46	87	0.05	0.43
Lower	Winter	68	1.07	7.27	158	0.05	0.79
Lower	**Annual**	**287**	**0.97**	**27.84**	**559**	**0.05**	**2.79**

compiled in Table 1 and 2 have been used to estimate seasonal DIN and DIP fluxes in the Straits. Volume fluxes given in these tables are the net fluxes coming into the Marmara Sea. Hence, the entrained amounts of fluxes from upper or lower layers are extracted. Comparison of the seasonal chemical fluxes reveals that the DIN fluxes in the straits vary markedly with season, due to changes in both the DIN concentrations and volume fluxes. The winter DIN input from the Black Sea to the Marmara basin is about 4.64 x 10^8 moles, 20 times the influx in the autumn. A similar but less pronounced seasonality appears in the Marmara DIN input to the Aegean Sea via the Dardanelles. On the annual basis, the Black Sea influx to the Marmara Sea is about 4 times greater than the DIN outflux to the Aegean basin via the Dardanelles, indicating that a large fraction of the DIN input from the Black Sea is converted to particulate and dissolved organic nitrogen compounds by photosynthetic activity in the Marmara Sea. DIN loads carried by the Bosphorus and Dardanelles undercurrents to the adjacent seas, however, display a contrary view. On the annual basis, the Aegean DIN input (6.13 x 10^8 moles) to the Marmara lower layer is much less than the outflux (27.8 x 10^8 moles) to the Black Sea through the Bosphorus. In other words, the observed large stock in the Marmara deep basin is provided by particle snows (21.7 x 10^8 moles of nitrogen/year in the form of labile PON) from the productive Marmara surface layer waters.

Seasonal variations in the DIP fluxes via the exchange flows in the Straits are less pronounced than in the estimates for DIN (Table 1). The Black Sea DIP input to the Marmara basin increases nearly 4 times from autumn to winter (2.03×10^7 mol-P). A similar seasonality can be realized from the DIP input to the Aegean Sea via the Dardanelles Strait. On an annual basis, the Black Sea DIP input to the Marmara basin is comparable with the DIP outflux from the Marmara upper layer via the Dardanelles. On the other hand, the annual DIP outflux (27.84×10^7 mol-P) from the Marmara lower layer to the Black Sea via the Bosphorus is about 10-fold the input (2.79×10^7 mol-P/year) from the Aegean Sea.

In conclusion, estimates of DIN and DIP exchange fluxes in the straits indicate that there is net DIN and DIP export from the Marmara to the Black Sea via the Bosphorus undercurrent. The Marmara upper layer acts as a sink for DIN input from the Black Sea and a large fraction of labile nutrients is accumulated in the lower layer, with the nearly constant N/P ratio of about 8-10. Interestingly, the DIN input from the Aegean Sea to the Marmara basin exceeds the importation from the Marmara Sea via the Dardanelles Strait due to the upwelling of the deep water from the Aegean Sea.

Acknowledgements

This study was supported by the Turkish Scientific and Technical Research Council (TUBITAK) and the NATO Scientific Affairs Division within the framework of the Science for Peace Programme.

References

BASTURK, Ö., S. TUĞRUL, A. YİLMAZ & C. SAYDAM., 1990. Health of the Turkish Straits: Chemical and Environmental Aspects of the Sea of Marmara. METU-Institute of Marine Sciences, Tech. Rep., No.90/4, ERDEMLI, İÇEL, 69 pp.

BEŞİKTEPE, Ş., E. ÖZSOY & Ü. ÜNLÜATA., 1993. Filling of the Sea of Marmara by the Dardanelles Lower Layer Inflow, Deep-Sea Res., 40, 1815-1838.

BEŞİKTEPE, Ş, H. İ. SUR, E. ÖZSOY, M.A. LATIF, T. OĞUZ & Ü. ÜNLÜATA., 1994. The circulation and hydrography of the Marmara Sea, Prog. Oceanogr., 34, 285-334.

COCIASU, A., V. DIACONU, L. TEREN, I. NAE, L. POPA, L. DOROGAN & V. MALCIU., 1997. Nutrient stocks on the Western shelf of the Black Sea in the last three decades. In E. ÖZSOY & A. MIKAELYAN (eds), Sensitivity to change: Black Sea, Baltic and North Sea, NATO ASI Series, 49-63 Kluwer Academic Publishers.

GRASSHOFF, K., 1975. The hydrochemistry of landlocked basins and fjyords. In: Chemical oceanography. J.P.RILEY & SKIRROW, eds., Academic Press, New York, 456-597.

GUNNERSON, C. G. & E. ÖZTURGUT., 1974. The Bosphorus. In: The Black Sea- Geology, Chemistry and Biology. Amer. Assoc. Petrol. and Geologists, 20, 99-114.

ORHON, D., O. USLU, S. MERIÇ, İ. SALINOĞLU & A. FILIBALI., 1994. Wastewater Management for İstanbul: Basis for Treatment and Disposal. Environmental Pollution, 84, 167-178.

POLAT, S.Ç., 1995. Nutrient and organic carbon budgets in the Sea of Marmara: A progressive effort of the biogeochemical cycles of carbon, nitrogen and phosphorus. Ph. D. Thesis, METU-IMS, Erdemli, Turkey, 215 pp.

POLAT, Ç.S. & S. TUĞRUL., 1995. Nutrient and organic carbon exchanges between the Black and Marmara seas through the Bosphorus strait, Continental Shelf Res. 15(9):1115-1132.

POLAT, Ç. & S. TUĞRUL., 1996. Chemical exchange between the Mediterranean and Black Sea via the Turkish straits. CIESM Science Series No.2, Bull. de I'Institut Océanog., 17, 167-186.

POLAT, Ç. S. TUĞRUL, Y. Çoban, Ö. BAŞTÜRK & İ. SALIHOĞLU., 1998. Elemental composition of seston and nutrient dynamics in the Sea of Marmara. Hydrobiologia, 363, 157-167.

SOROKIN, YU. I., 1983. The Black Sea. In B.H. Ketchum (ed.), Estuaries and Enclosed Seas.

Ecosystem of the World. Elsevier, Amsterdam: 253-292.

TUĞRUL, S. & Ç. POLAT., 1995. Quantitative comparison of the influxes of nutrients and organic carbon into the Sea of Marmara both from anthropogenic sources and from the Black Sea. Water Science and Technology, 32, 115-121.

ÜNLÜATA, Ü., T. OĞUZ, M. A. LATIF & E. ÖZSOY., 1990. On the Physical Oceanography of the Turkish Straits, In: The Physical Oceanography of Sea Straits, L.J. Pratt (Ed.), NATO/ASI Series, 318, 26-60, Kluwer Academic Publishers, Dordrecht.