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Influence of the extreme conditions on the water quality and material exchange flux in the Strait of Istanbul

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ABSTRACT

This study focuses on the influence of extreme hydrological events on the water quality of the Strait of Istanbul (Bosphorus), a stratified waterway, polluted by sewage outfalls and non-point sources. Monthly collected water quality parameters (nitrate + nitrite, ortho-phosphate, silicate, dissolved oxygen, total suspended solids, chlorophyll-a and fecal indicator bacteria (fecal coliform and enterococci)) were evaluated together with the hydrological data (salinity, temperature and current flow) for 1 year. Two blockage events, identified as extreme conditions, were detected during the study: a lower layer blockage in February 2003 and an upper layer blockage in October 2003.

During the lower layer blockage, the volume fluxes of the upper layer significantly increased to 28,140 $m^3\ s^{-1}$ and the lower layer almost stopped flowing (19 $m^3\ s^{-1}$). The dissolved oxidative nitrogen, ortho-phosphate and silicate inputs outflowing from the Black Sea were 117, 17.6, and 309 tons which were 3, 2, and 4 times the average daily fluxes respectively, in addition to enhancement of fecal indicator bacteria contamination in the sea surface flow.

During the upper layer blockage, the volume flux of the upper layer was 3837 $m^3\ s^{-1}$ and the counter flow reached 24,985 $m^3\ s^{-1}$ at the northern exit of the Strait of Istanbul resulting in 2.7 fold increase in the mean bottom flow. The daily exports of nutrients, total suspended solid and dissolved oxygen by the lower layer flow increased by at least 2 fold compared to the mass fluxes estimated from the seasonal/annual means of volume flux and concentrations. On the other hand, fecal indicator bacteria flux by the lower layer inflow to the Black Sea decreased by at least 2 fold compared to the mean daily flux. These results show that the material exchange between the Marmara and the Black seas becomes more important during blockage events.

1. Introduction

The Strait of Istanbul is a narrow (0.7–3.5 km), long (~31 km) and shallow (30–100 m) channel and connects the Black Sea with the Marmara Sea. The strait has a hydraulic controlled “maximal exchange” (Farmer and Armi, 1986) flow system and is occasionally impacted by extreme hydrological events. The northern and southern sills control the lower and upper layer flows causing maximal exchange where the upper layer (~18) flows from the Black Sea and the lower layer with ~38 flows in the opposite direction from the Marmara Sea (Oğuz et al., 1990; Özsoy et al., 1998; Yüce, 1996). The average upper layer volume flux is estimated as 600 $km^3\ year^{-1}$ and 300 $km^3\ year^{-1}$ in the lower layer (Beşiktepe et al., 1994; Ünlüata et al., 1990). The volume fluxes of each layer are variable due to changes in the atmospheric conditions and the sea level (Oğuz et al., 1990; Özsoy et al., 1998). Recently, Jarosz et al. (2011a) reported that the flow variability in the strait is related to the bottom pressure difference and the atmospheric forcing on the synoptic time scale (2–10 days). Moreover, it is well known that strong northerly winds occasionally cause lower layer blockage during high sea levels in the Black Sea, whereas strong southerly winds cause upper layer blockage during low sea level in the region (Alpar et al., 1998, 1999; Latif et al., 1991; Özsoy et al., 1986). Both blockages with the extreme volume fluxes for the counter flow in the strait last for only a few days but significantly alter exchanges of materials between the adjacent seas.

Although these hydrological events last for only a few days, they may cause long-term impacts on the ecosystem. The Strait of Istanbul is an ecologically important transition zone as the strait provides material exchange between the Black Sea and the Marmara Sea. The upper layer originating from the Black Sea is the main source of nutrients and organic matters for the Marmara Sea and these inputs play an important role on the Marmara Sea ecosystem (Polat and Tuğrul,

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1995; Polat et al., 1998; Tuğrul and Polat, 1995). The counter flow at the lower layer originates from the Mediterranean Sea and has low concentrations of nutrients and is almost saturated with oxygen during its entry through the Strait of Çanakkale (Dardanelles) (Fig. 1). This water is enriched in nutrients while losing the dissolved oxygen during their residency for almost seven years in the Marmara Sea (Beşiktepe et al., 1994; Ünlüata et al., 1990). Nutrient poor waters were enriched 10 fold during their passage from the Dardanelles to the Bosphorus (Tuğrul, 1993). This chemically modified lower layer waters leave the Marmara basin through the Strait of Istanbul (Baştürk et al., 1990; Tuğrul, 1993) and flow into the anoxic deep waters of the Black Sea. The salty Mediterreanean water with low oxygen content in the lower layer of the Marmara Sea is enriched in oxygen by downward entrainment of the upper layer waters through the halocline in the strait. The Mediterreanean water exit from the Bosphorus continued to be enriched in oxygen while spreading and diluting in the shelf. This water is mixed with cold intermediate water (CIW) directly and its temperature also decreased, and it is observed as cold anomalies in the subhalocline (Özsoy et al., 2001). Konovalov et al. (2003) suggested that the Strait of Istanbul plume waters were laterally injected into the suboxic and anoxic layers of the Black Sea and played an important role in the oxidizing of Mn(II) to Mn(III,IV), which then oxidized H_2S and finally caused an increase of MnO_2 and S_8 formation in the southwestern Black Sea. The oxygenation of the lower layer flow is not only important for the chemical reactions occurring within the strait, but also for the changes in the Black Sea chemistry.

In addition to the chemical changes during its passage, the lower layer also receives pollutants from the Strait of Istanbul. Istanbul is one of the most populated metropolises in the Black Sea region with a population of over 13.5 million people (TÜİK, 2014). The two-layer exchange flow in the Strait of Istanbul plays an important role in the removal of wastewaters discharged by the city of Istanbul. Today, more than 75% of domestic and industrial primary or secondary treated effluents are disposed directly into the Bosphorus lower layer and the strait-Marmara Sea junction via sewage outfalls with a daily capacity of 1,671,060 m^3 day^{-1} (Okuş et al., 2008).

Although there are many studies on the hydrology of this unique system, a comprehensive evaluation of the changes in the water quality during extreme hydrological events is currently not available in the literature. The purpose of this study is to understand the changes in the water quality and estimate the material exchange between the Marmara Sea and the Black Sea during both hydrological events, namely the blockages in the upper and the lower layers. The monthly data evaluated in this study is a part of long term water quality monitoring project (1996–2010) by the support of Istanbul Water and Sewerage Administration (ISKI). In order to make comparison of the material exchange between annual conditions and blockages events, it has been preferred a yearly cycle which included two types of extreme conditions. The year 2003 provides a unique opportunity as monthly observation including of these blockages in the same year. The lower layer blockages were observed rarely in February, March and April in 1998, 2003, 2004 and 2006. The observations of the upper layer blockages at the southern section of the strait are common in fall and winter months almost every year. Monthly variations in physical, chemical and biological data were analyzed, and annual material exchange flux estimations were compared to an upper layer blockage in autumn and a lower layer blockage in winter. The monthly changes of the water quality parameters will be discussed briefly, followed by an evaluation of hydrological conditions in two different types of blockages and material exchange estimations during these events.

2. Materials and methods

2.1. Samplings

Field surveys were conducted by R/V ARAR of Istanbul University, Institute of Marine Science and Management (IMSM-IU) in 2003. The conductivity, temperature, depth (CTD) and acoustic Doppler current

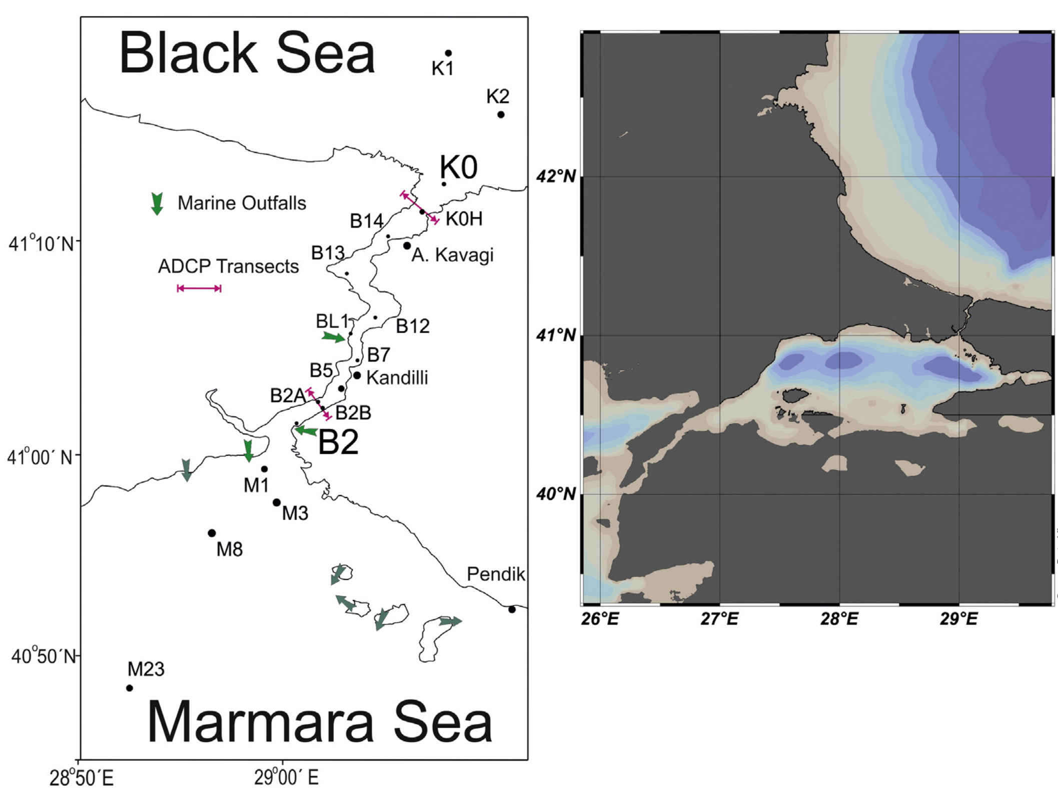

Fig. 1. Sampling locations in the Strait of Istanbul in 2003. Lines with double-sided arrows indicate the ADCP transects, dots indicate the stations of the CTD and ADCP, chemical, bacteriological, and chlorophyll-a samplings. Arrows indicate sewages discharges.

profiler (ADCP) data were measured at 17 stations along the Bosphorus Strait (Fig. 1). The positioning of the research vessel was determined by differential global positioning system (DGPS). Temperature, salinity and depth data were obtained by a SeaBird SBE-9/11 CTD probe system.

Current velocity data was collected by ADCP (RDI BBADCP, 150 kHz) mounted on the research vessel, using bottom track method. The average time of recording current velocity was a minimum of 5 minutes at each station. Atmospheric pressure, wind speed and direction data were obtained on hourly basis from Boğaziçi University, Kandilli Observatory and Earthquake Research Institute. Sea level measurements in Pendik and Anadolukavagi (Fig. 1) were obtained from the Office of Navigation, Hydrography and Oceanography (ONHO).

Water samples were collected at selected depths by a 5 L-bottle Rosette system (General Oceanics) coupled with a CTD probe. Nutrients of dissolved oxidative nitrogen (nitrate + nitrite NO_3+NO_2–N), ortho-phosphate (PO_4–P), silicate (SiO_2–Si), dissolved oxygen (DO), chlorophyll-a (Chl-a), total suspended solids (TSS) and fecal coliform (FC) were collected monthly. In addition to these parameters, *Enterococci* spp. (Ent) data were also collected from surface, interface (the depth correspondent to 30 salinity) and bottom depths. FC has been the national criteria indicator for monitoring the influence of sewage pollution. Recent literature has shown that *Enterococci* spp. are better correlated with human health outcomes than fecal coliform bacteria in sewage polluted marine waters (Wade et al., 2003) and many countries has replaced their marine pollution standards with fecal coliform bacteria. In this study, we collected data for both FC and Ent as indicators for sewage pollution.

DO, FC and Ent analyses were performed onboard, immediately upon collection of the samples. Nutrient and TSS samples were kept at −20 °C until further analysis at the land-based laboratory.

March salinity data of K0, November SiO_2–Si data of B2 and K0, and July PO_4–P data of B2 and K0 are not available. Values below detection limit for PO_4–P were corrected to the analytical detection limit (0.024 μM). Other parameters did not show any values below their method detection limits.

2.2. Sampling analysis

2.2.1. Analysis of chemical parameters

Samples for nutrients (NO_3+NO_2–N, PO_4–P and SiO_2–Si) were collected into high-density polyethylene (HDPE) bottles that were pre-washed with 5% HCl acid and rinsed with deionized water. Upon transport to the land-based laboratory at −20 °C, these samples were analyzed by Bran-Luebbe autoanalyzer (SPX, Germany). Nitrogenous nutrients (NO_3+NO_2–N) were analyzed by Cadmium Reduction Method 4500–NO_3^- E (APHA, 1999). PO_4–P analyses were performed using Ascorbic Acid Method 4500-P A (APHA, 1999). Silicate analysis was performed using Ammonium Molybdate Method 4500–SiO_2 D (APHA, 1999). All results were calculated from their respective standard curves and reported as μM.

DO analysis was performed by Winkler Method (APHA, 1999) onboard and reported as μM. TSS were filtered through pre-weighed 47 mm GF/C filters (Whatman, USA), and reported as μg L^{-1} (APHA, 1999). Chl-a concentrations were detected by acetone extraction method (Parsons et al., 1984) and reported as μg L^{-1}.

2.2.2. Analysis of fecal indicator bacteria

All samples collected for fecal indicator bacteria (FIB) were processed aseptically onboard within 6 h upon collection using Membrane Filtration Method 9222 (APHA, 1999). Subsamples with triplicate dilutions were filtered on sterile 0.45 μm cellulose nitrate membrane filters (Sartorius, Germany) using a sterile vacuum filtering set. For FC enumeration, filters were incubated for 24 h at 44.5 ± 0.1 °C on m-FC medium (Sartorius, Germany). Blue colonies were accepted as FC. For the enumeration of Ent, filters were incubated on Azid medium (Sartorius, Germany) at 37 ± 0.1 °C for 48 h. Dark brown colonies were accepted as Ent. All results of fecal indicator bacteria were calculated as CFU 100 mL^{-1}.

2.3. Flux calculations

The volume fluxes were calculated using ADCP cross-shore transects at each end of the Strait of Istanbul (Fig. 1). Missing or bad data in the transect were completed with linear interpolation method. No slip boundary condition is used for interpolation at bottom depth and sides. For the unmeasured surface currents, it is assumed that the velocity profile is constant at the upper layer (betweeen 0 and 8 m).

In order to calculate depth-averaged of water quality parameters for the layers, the separation of the layers was first determined using current velocity profiles for each station. The interface depth between the upper and the lower layers was defined according to the depth at which the current direction changed and the current velocity was zero. The depth-averaged of all parameters was calculated according to this interface depth. These values were further used to calculate the material fluxes by multiplying them by volume fluxes for each month. Annual fluxes are the sum of 12 months ($Q_c = C_iQ_i$, $i = 1{,}12$, Q_i: volume flux, C_i: concentration of related parameters, Q_c: annual flux of the parameters).

3. Results and discussion

In this section, monthly water quality data variability of two exits of the strait is discussed briefly and then, annual mean concentrations and material exchange fluxes are given. The hydrological conditions, their impact on the water quality and material exchange estimations during two blockages will be analyzed at Sections 3.2 and 3.3 separately. The Black Sea exit has been referred as K0 and the Marmara Sea exit as B2 from this point on (Fig. 1).

3.1. Monthly variations in salinity and water quality data at the two exits of the Strait of Istanbul

The salinity profiles of the water masses in the northern (K0) and the southern (B2) exits of the strait showed monthly variations in the two-layered structure (Figs. 2a and 3a). The upper and lower layers at K0 were separated by a thin interface at approximately 50 m depth. The interface at the southern exit was much closer to the surface at B2 (25 m). The flows were under the hydraulic control by the sills at the two ends of the strait and the contraction (Oğuz et al., 1990). The thickness and depth of interface varied each month according to atmospheric and oceanographic conditions (Özsoy et al., 1998). The upper layer salinity fluctuated from 16.5 to 18.0 at K0 throughout the year because of different water masses carrying by the Rim Current to the vicinity of the Bosphorus (Sur et al., 1994). The mixing between the two layers towards the south caused an increase in the upper layer salinity to 17.020.0 at B2 except in October 2003. In October 2003, the upper layer salinity was observed as 23.5 indicating an upper layer blockage in the strait. However, the lower layer salinity decreased from south to north of the strait. The salinity ranged slightly from 37 to 38.5 at B2 whereas the maximum salinity was 36.8 at K0 except for February. In February 2003, due to blocking of the lower layer, which will further be discussed thoroughly in the following section, the salinity was 17.1–17.4 in the water column at K0.

The low salinity values in the lower layer of K0 indicated that there was strong mixing between the layers along the strait throughout the year because of the entrainment. The interface structure was also an indication of mixing; the thick and/or step structure of the interface originated from mixing. For instance in April 2003, the lower layer was very thin, and the interface was very thick and had a stepwise structure at the south of the strait at B2. This water mixed while traveling to the north and was diluted to 31 at the Black Sea exit with a sharp

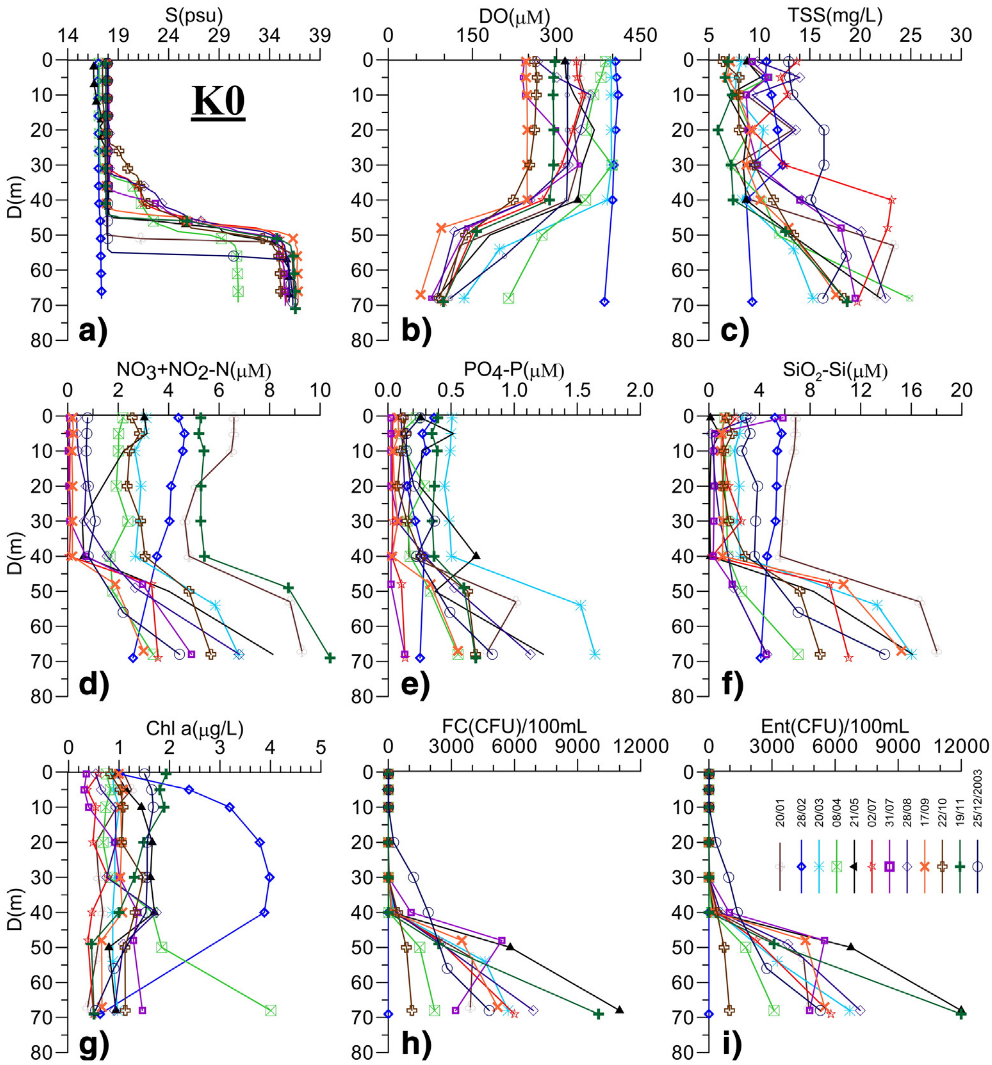

Fig. 2. 2003 annual profiles of a) salinity, b) DO, C) TSS, d) NO_3+NO_2–N, e) PO_4–P, f) SiO_2–Si, g) Chl-a, h) FC, and i) Ent profiles in the northern section of the Strait of Istanbul at the station K0.

interface. Overall, a persistent two layered flow structure was observed in all months except in February at K0.

Similarly, the chemical and microbiological components of the system also showed two-layer stratification (Figs. 2b–i and 3b–i) in all these sampling events except in February at K0. The upper layer DO concentrations varied seasonally depending on the water temperature. In the cold season (February, March and April) the upper layer DO concentrations reached up to 400 μM at the either exits of the strait, whereas in warmer period (July, August and September) the concentrations decreased to 250 μM (Figs. 2b and 3b). On the contrary, the lower layer DO concentrations ranged from 50 to 150 μM. The mixing between the layers flowing in the opposite direction while passing through the strait also modified the oxygen content of these layers. For example, the DO concentration was the highest at the deep waters of K0 (215 μM at the depth of 68 m) in April. Low salinity (30.8) explained intense mixing between the layers. The minimum DO concentration (58 μM at the depth of 67 m) was observed in September, when the salinity was high (36.8).

The two-layered stratification in the strait could also be seen clearly from the profiles of the other water quality parameters (nutrients, TSS, Chl-a, and FIB) at the both exits of the strait except for February at K0. The lower layer concentrations of the water quality parameters were greater than the upper layer both at B2 and K0 due to different water mass in the strait. The values of these parameters in the upper layer of the station K0 substantially showed the characteristics of the Black Sea upper layer.

Concentrations of NO_3+NO_2–N, PO_4–P, and SiO_2–Si were in the range of 0.05–6.6 μM, <0.02–0.5 μM and 0.06–6.86 in the upper layer of K0, respectively. NO_3+NO_2 and SiO_2 had the highest concentrations in January, February and November and this increase was concluded as the impact of winter conditions and low photosynthetic activity. NO_3+NO_2–N concentrations were also high in relatively warmer months such as April, May and October. The salinity values were lower than 17.5 in these months, which indicates that the Danube River influenced the water found in the area. Earlier studies in this region has showed that, the northwestern Black Sea shelf waters with low salinity reached the vicinity of the strait in about 1–2 months (Sur et al., 1994), carrying high amounts of nutrients (Polat and Tuğrul, 1995). In addition, relatively high salinity (>17.5) and nutrient conditions in the upper layer at K0 were attributed to vertical mixing in the NW shelf and Rim current. In early autumn, anticyclonic eddies were observed on the right side of the Rim Current in the western Black Sea (Sur and Ilyin, 1997). Therefore, upwelling associated with these eddies leads to increase salinity and nutrients of the surface waters in the region.

The nutrient and TSS content of the upper layer coming from the Black Sea increase in some months due to the runoff material originated from non-point sources (Okuş et al., 2002a). In addition, nutrient and

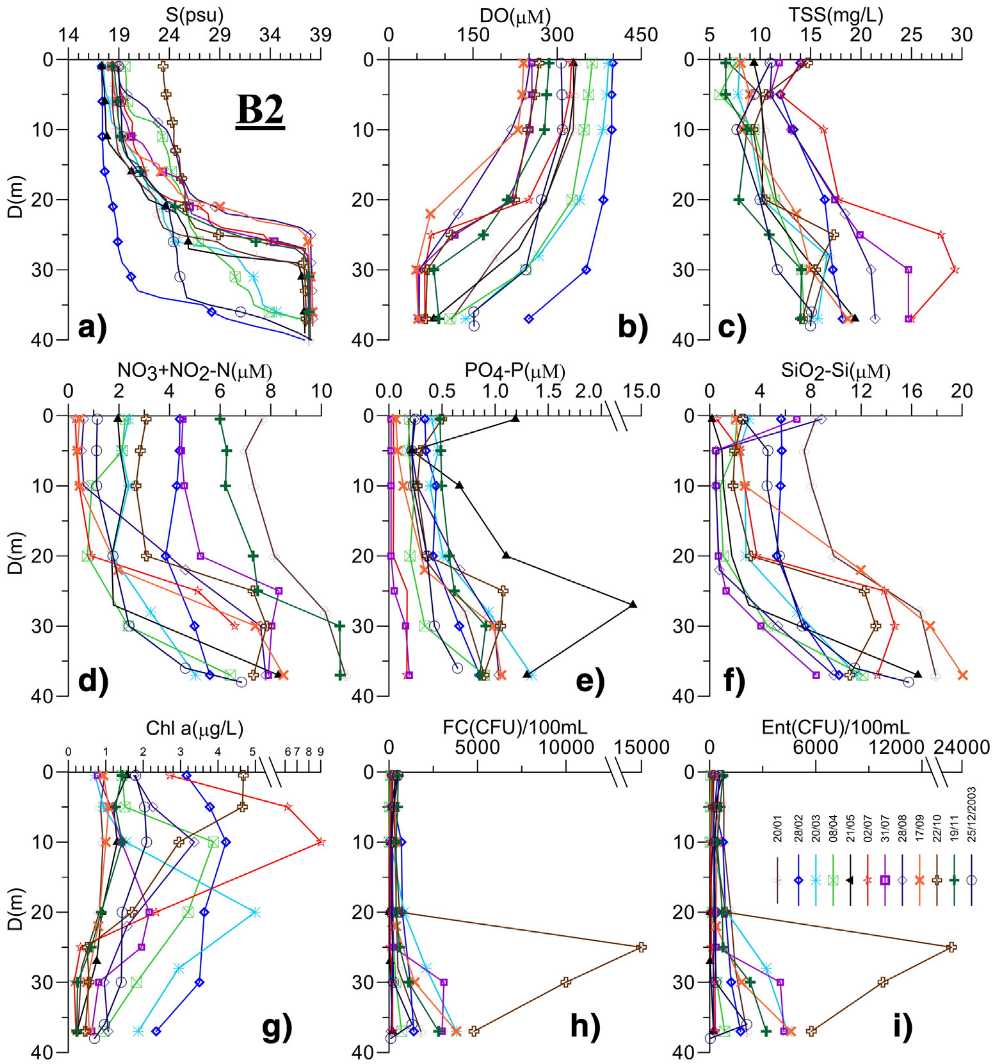

Fig. 3. 2003 annual profiles of a) salinity, b) DO, C) TSS, d) $NO_3 + NO_2$–N, e) PO_4–P, f) SiO_2–Si, g) Chl-a, h) FC, and i) Ent profiles in the southern section of the Strait of Istanbul at the station B2.

TSS input to the upper layer through the mixing of sewage polluted lower layers at the southern part of the strait (Okuş et al., 2002b; Polat and Tuğrul, 1995).

Overall, nutrient and TSS concentrations at the lower layer were higher than those of the upper layer along the strait. High nutrient and TSS content in the lower layer were related to the influence of the wastewater introduced via marine outfall systems and the waters coming from the Marmara Sea. The sinking of particulate matter from the productive upper layer causes to increase in nutrient and TSS of the lower layer of the Marmara Sea (Tuğrul and Polat, 1995).

The Chl-a profiles at the northern section (Fig. 2g) indicate that the upper layer concentrations were in the range of 0.2–4.0 μg L^{-1} with the higher concentration observed in February and November. Indeed, in the Black Sea, Chl-a concentrations show two maxima (winter/spring and fall) in surface layer and reach up to 2.25 μg L^{-1} in February/March (Chu et al., 2005). Monthly changes in Chl-a concentrations (Fig. 3g) were higher at least two-folds at B2 upper layer (0.6–9.0 μg L^{-1}) with the highest concentration that was detected at B2 in June (9.0 μg L^{-1}). The reason of this increase of Chl-a may consider nutrient enrichment in the upper layer water passing through the strait.

The lower layer Chl-a at the both exit of the strait remained constant over the year because of the insufficient light in the lower layer. High Chl-a values in the lower layer could be considered as indication of vertical mixing in the strait. Two profiles had significantly different from other Chl-a profiles at the station K0: February and April. The February results corresponded to the lower layer blockage and will further be examined in the following section. The second highest chlorophyll *a* in the lower layer was detected in April. The lower layer DO concentrations were extremely high (215 μM) whereas the salinity was significantly low (30.8 at 68 m), which indicated an intense mixing between the two layers. The lower layer Chl-a concentration reached 4 μg L^{-1}, indicating that the productive upper layer mixed with the lower layer at this sampling event.

In order to better show the influence of the wastewater on the strait water quality, we also tested these waters for the occurrence of FIB (Figs. 2h–i and 3h–i). To our knowledge, this is the first study that compares the FIB concentrations in the Black Sea and the Marmara Sea exits of the strait as an indicator for sewage pollution. FIB profiles indicate that there is dramatical increase in lower layer in the strait. The upper layer bacteriological pollution increased towards the south. FC and Ent concentrations were less than 100 CFU/100 mL in K0 and, were less than 1000 CFU/100 mL in B2 upper layer during the all sampling period. High values of FIB in the surface water along the strait are mainly caused by non-point sources of the pollution.

The lower layer FC and Ent concentrations at the south (B2) reached a maximum 4.5×10^3 CFU/100 mL (except for October). The concentrations at the lower layer of K0 increased to a maximum of 1.2×10^4 CFU 100 mL^{-1}. FIB content of the lower layer increased in the south-north direction due to the amount of sewage via outfalls along the strait (Figs. 2h, i and 3h, i). This primary (and at some points secondary) treated domestic wastewater was released into the lower layer through sewage outfalls (see Fig. 1) along the strait and caused high concentrations of FIB at the lower layer. In April, FIB concentrations were the lowest at both B2 and K0. As mentioned above, high DO, TSS, Chl-a concentrations and low salinity were detected in this sampling event. Smaller numbers of FIB also support the occurrence of mixing in April and low FIB concentrations were attributed to a dilution effect via mixing of less contaminated upper layer with the sewage impacted lower layer. Our results also showed that FIB concentrations increased when the lower layer mixing was at its minimum. Current velocities, wind direction, temperature, Wastewater Treatment Plants (WWTPs) performances, and non-point sources also influence the bacteriological water quality along the strait.

In order to show in detail, the vertical and longitudinal FIB distribution along the Bosphorus was given as an example of observed a two layer flow system pronounced in July 2003 (Fig. 4). High FIB concentrations (>2000 CFU/100 mL) were usually found in interface and bottom depth throughout the strait. In Fig. 4, the arrows show the current directions along the strait. The current direction changes in depth where the salinity reaches up approximately 30 which is indicated with the bold contour (Fig. 4). The upper layer FIB concentrations increase from north to south whereas they increase south to north in the lower layer.

Our monthly monitoring of the strait system also allowed for the detection of two extreme events during the study period. Upper or lower layer blockage in the Strait of Istanbul has been well-documented via hydrological data in the earlier studies (Alpar et al., 1998, 1999; Jarosz et al., 2011a; Latif et al., 1991; Özsoy et al., 1986). In this study, these extreme conditions were analyzed together with an extensive set of water quality parameters to better assess the impact of extreme hydrological events on the strait ecosystem.

3.2. Material exchange flux in the Strait of Istanbul

The volume flux of the upper layer originated from the Black Sea was calculated as 11,098 $m^3\ s^{-1}$ (350 $km^3\ year^{-1}$), whereas the counterflow from the Marmara Sea was 9481 m^3/s (299 $km^3/year$) at the northern exit of the strait (Table 1). Our results for the upper layer volume flux were lower than the estimations of Beşiktepe et al. (1994) who calculated volume fluxes from salt budget requirement for steady state conditions as 600 $km^3\ year^{-1}$ and 300 $km^3\ year^{-1}$ for the upper and lower layers at the north end of the strait, respectively. Since our results were based on in-situ measurements throughout a year, these may not necessarily be identical with these of a long-term salt budget hypothesis. Our estimation of the volume flux was based on combined in-situ measurements of monthly ADCP transects and CTD data throughout a year. Recently, Jarosz et al. (2011b) reported that estimated flux from mooring ADCP and CTD data at the two ends of the strait was 400 $km^3\ year^{-1}$ for upper layer and 300 $km^3\ year^{-1}$ for lower layer which is also not in accordance with the salt budget requirement. The similarities between the volume flux results also indicated the importance of the methodological overlap between two studies. Additionally, it was concluded that the exchange flux variability was also related to sea level variations, net water budgets and atmospheric pressure variations in the adjacent basins (Özsoy et al., 1998). Therefore, our study presented a better resolution of the budget estimation which comprised the measurements of different conditions over the period of a year. In the southern exit of the Strait, the upper and lower layer volume fluxes were 12,779 $m^3\ s^{-1}$ (403 $km^3\ year^{-1}$) and 8720 $m^3\ s^{-1}$ (275 $km^3\ year^{-1}$) respectively.

The upper layer waters coming from the Black Sea had lower oxygen content when it reached the Marmara Sea compared to its value at the northern entrance. On the other hand, in the northern exit of the strait, the mean concentration of DO increased to 173.9 μM, and its annual flux was 507 $\times$ 10^8 moles (Table 1). The amount of dissolved oxygen content of this water is important for suboxic and anoxic layers of the Black Sea to increase of MnO_2 and S_8 formation (Konovalov et al., 2003). Inversely, the TSS content of the upper layer increased as it flowed toward the southern exit of the strait. The reason for this situation is not only the vertical mixing of the counterflows through the halocline in the strait, but also pollution from point and non-point sources in the strait. The increasing of TSS fluxes from north to south for the upper layer was much greater than for the lower layer, although there is discharge to the lower layer. Annual Chl-a concentrations were calculated slightly high in the upper layer at the southern exit of the strait where there was suitable conditions for the phytoplankton abundance.

Mean annual concentrations of dissolved oxidative nitrogen, orthophosphate and silicate were estimated at least two times higher at lower layer than the upper layer at the southern exit of the Strait (B2). Similar trends were also estimated on the mean annual concentrations of NO_3+NO_2–N and PO_4–P and SiO_2–Si values between layers at the northern exit (K0) (Table 1). Estimated annual flux of dissolved

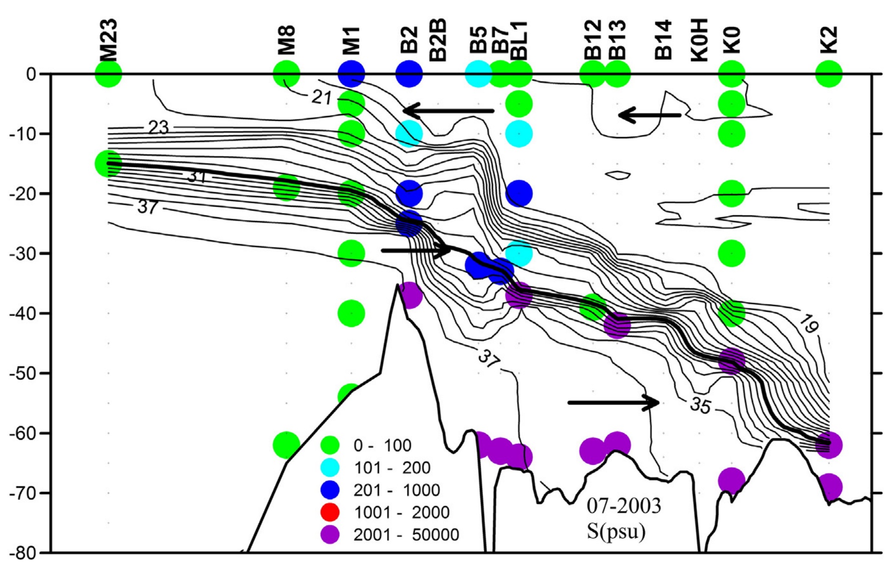

Fig. 4. FC (CFU 100 mL^{-1}) distribution superimposed with salinity transect in the Strait of Istanbul in July 2003 (for interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

Table 1
Annual depth averaged concentrations and calculated fluxes.

		Average 2003			
		North		South	
Concentrations/values		Upper	Lower	Upper	Lower
	T (°C)	11.41 ± 6.1	12.62 ± 3.9	12.70 ± 5.9	13.90 ± 2.2
	S	17.95 ± 0.4	30.97 ± 5.6	21.30 ± 1.7	34.53 ± 3.3
	DO (μM)	325.5 ± 49.2	173.9 ± 89.7	290.6 ± 60.6	143.6 ± 70.3
	TSS (mg L^{-1})	9.93 ± 2.4	16.22 ± 3.2	10.96 ± 2.5	17.11 ± 3.8
	Chl-a (μg L^{-1})	1.17 ± 0.6	1.13 ± 0.8	2.34 ± 1.6	1.13 ± 0.8
	NO_3+NO_2–N (μM)	2.11 ± 0.2	4.70 ± 2.5	2.65 ± 2.4	6.09 ± 2.7
	PO_4–P (μM)	0.21 ± 0.2	0.58 ± 0.4	0.32 ± 0.2	0.89 ± 0.6
	SiO_2–Si (μM)	2.19 ± 1.9	8.62 ± 5.4	3.70 ± 2.7	10.21 ± 5.0
	Ent (CFU 100 mL^{-1})	104 ± 265	4071 ± 2702	399 ± 286	2205 ± 2630
Annual fluxes	Q (km^3)	350	299	403	275
	DO (X10^8 moles)	1151	507	1205	357
	TSS (kg)	3660	4895	4482	4828
	Chl-a (g)	539	345	750	295
	NO_3+NO_2–N (X10^8 moles)	9.62	11.35	13.78	15.83
	PO_4–P (X10^7 moles)	8.68	13.25	15.86	19.78
	SiO_2–Si (X10^8 moles)	10.15	17.25	18.86	24.36
	Ent (X10^8 CFU 100 mL^{-1})	782	9748	2241	8180

oxidative nitrogen and dissolved inorganic phosphorus from inflow of Black Sea, which constitutes the upper layer of K0, was significantly lower than the annual flux of B2 upper layer which outflow to the Marmara Sea. Compared to the upper layer values, lower layer estimated annual flux was higher from inflow of Marmara Sea which gradually decreased along the strait and outflow to the Black Sea by the bottom layer of K0. Thus, estimation of annual flux of those nutrients shows an increasing trend vertically from upper layer to bottom layer in both exits, while decreasing trends were observed from south to north direction for both layers.

NO_3+NO_2–N and PO_4–P annual mean concentrations results showed similar vertical and horizontal trends according to reported in previous studies with slightly higher estimations than these previous studies. In the northern section of the strait, Polat and Tuğrul (1995) and Tugrul et al. (2002) calculated the upper layer NO_3+NO_2–N concentrations as 1.6 and 1.3 μM, respectively (Table 2). Their calculated ortho-phosphate annual mean concentrations are 0.2 and 0.1 μM, respectively. On the other hand, in this study fluxes were lower than their estimations due to different volume fluxes calculation which based on experimental results.

Tugrul et al. (2002) reported that the NO_3+NO_2–N and PO_4–P concentrations were the lowest in the summer and the early autumn, markedly increasing during early winter. They concluded that the nutrient enriched northeastern shelf waters reached the Bosphorus region during the winter when the biological consumption was low (Tugrul et al., 2002). Additionally, descending biological consumption rates in the Black Sea during winter had also been reported in the other studies (Cociasu et al., 1996; Okuş et al., 2002b, 2008; Polat and Tuğrul, 1995). In this study, the highest NO_3+NO_2–N and PO_4–P concentrations in upper layer were detected in winter (January and February), spring (March, April and May) and autumn (November).

The differences between the results of this study and the previous studies in annual mean concentrations values were mainly caused by changes in the water quality over time and sampling frequency. Earlier studies were based on seasonal sampling over time, whereas our study focuses on monthly monitoring over a 1 year period. In the 1990s there were very few sewage outfall systems in the region. In the 2000s, more than 75% of the domestic and industrial wastewaters generated within the Istanbul Metropolitan Area were connected to the sewage outfall systems with primary treatment which was already defined as the largest contributor of pollution in the basin (Okuş et al., 2008). Thus, the results of this study indicated that values of the dissolved oxidative nitrogen and dissolved inorganic phosphorus multiplied at the lower layer due to enrichment of the inputs by the constructed of several sewage outfall systems in a decade.

The material transport completely depends on the variability and bioavailability of the parameter. Thus, we investigated the differences of water quality parameters by evaluating the nutrients and FIB variability in terms of material transport. Enterococci are known to be a better indicator of sewage intrusion to marine waters (U.S. EPA, 2012). At the upper layer of K0, FIB concentrations were either low or 100 CFU 100 mL^{-1} below the detection limit. The upper layer Ent flux was estimated 782×10^8 CFU 100 mL^{-1} at K0. The Black Sea originated waters entering the strait were influenced by the point and non-point sources during their travel to the south and the Ent flux was estimated as 2241×10^8 CFU 100 mL^{-1} at B2. The lower layer flux at K0 on the other hand was at least 10 times higher than the upper layer flux at the same point, showing the impact of marine outfalls on the lower layer water quality (Table 1). Although the Ent fluxes do not provide useful results due to their short decay rate (days) in the marine environment, estimation of Ent fluxes demonstrated the presence of sewage load at both ends of the strait and its distribution between layers during the blockage events.

Table 2
Comparison of the upper and lower layer NO_3+NO_2–N and PO_4–P with previous studies. Data retrieved from *a* Okuş et al. (2002b), *b* Tugrul et al. (2002), *c* Polat and Tuğrul (1995). Polat and Tuğrul (1995) recorded units in tons $year^{-1}$ and converted moles. (N_{fluxes} (0.18 t $year^{-1}$, and 0.48 t $year^{-1} \times 10^5$), P_{fluxes} (0.34 t $year^{-1}$, and 1.11 t $year^{-1} \times 10^4$) in Polat and Tuğrul (1995) for influxes and outfluxes.)

Layers	Parameters	This study	*a*	*b*	*c*
Upper layer (K0)	NO_3+NO_2–N (μM)	2.11	1.0	1.29	1.00
	NO_3+NO_2–N (×10^8 moles)	9.62		8.17	12.85
	PO_4–P (μM)	0.21	0.2	0.07	0.18
	PO_4–P (×10^7 moles)	8.68		4.02	10.98
Lower layer (B2)	NO_3+NO_2–N (μM)	6.09	5.4	9.70	9.50
	NO_3+NO_2–N (×10^8 moles)	15.83		27.82	34.27
	PO_4–P (μM)	0.89	0.7	0.97	1.01
	PO_4–P (×10^7 moles)	19.78		27.918	35.84

3.3. The salinity, currents and bacteria distribution along the strait during lower layer blockage

In the Strait of Istanbul, the weather is affected by cyclonic systems especially in winter months. The dominant winds are northerly with a frequency of 60% from May to October with southerly winds occurring only at a frequency of 20%. The sea level is affected by winds in the region. In general, onshore winds cause a rise in the sea level, whereas offshore winds lower the sea level (Alpar and Yüce, 1998). Fig. 5a presents the relationship between wind speed and direction, atmospheric

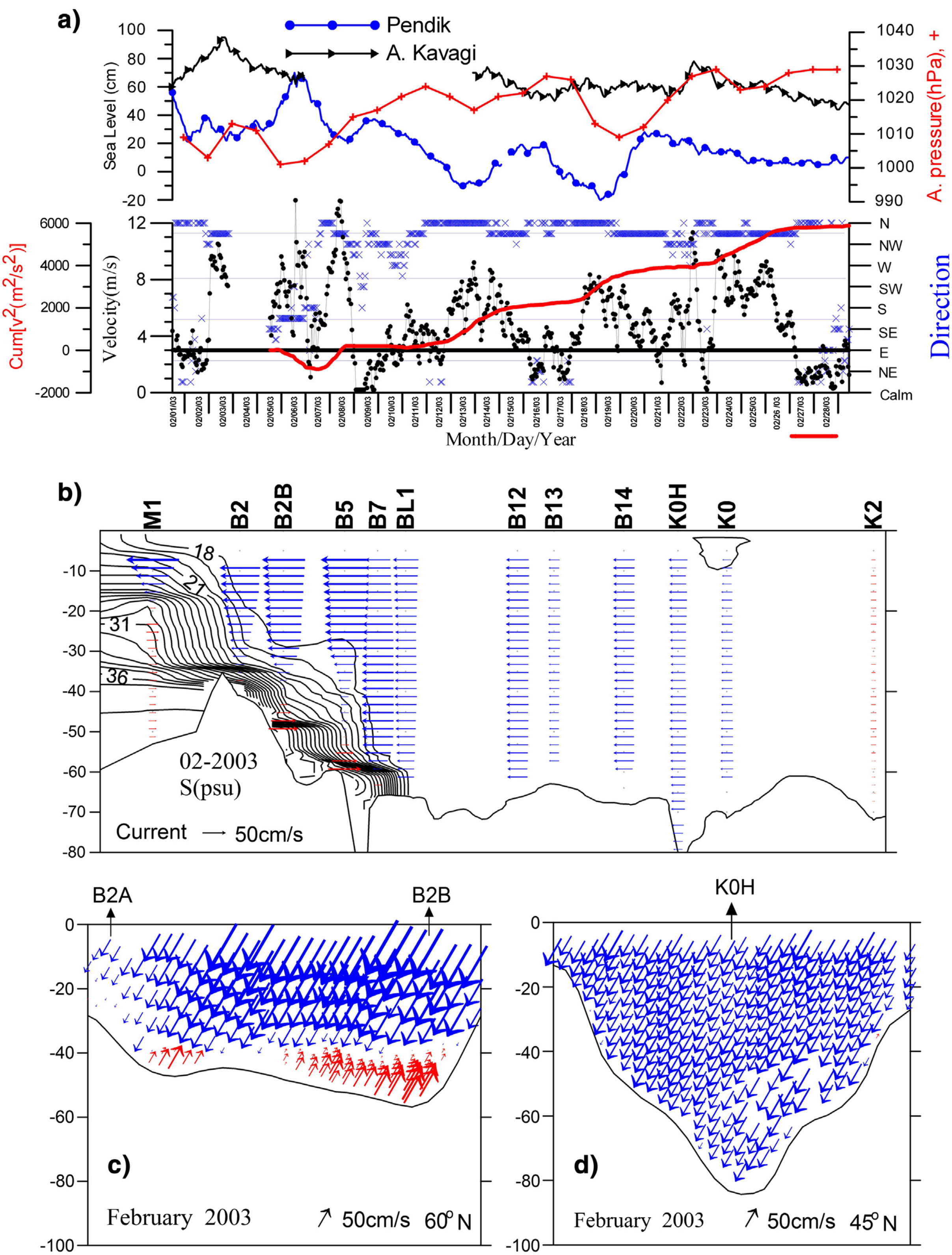

Fig. 5. a) Sea level, atmospheric pressure, cumulative wind stress, wind speed (m s^{-1}) and direction (degree) at 10 m from Kandilli in February 2003 (red line indicates cruise date); b) salinity and current transects in the Strait of Istanbul; c) north and d) south cross line ADCP transects in February 2003 during the lower layer blockage.

pressure and sea level observations (please refer to Fig. 1 for the locations of meteorological stations). When the northerly winds were strong, the sea level in northern part was high, and in the south the sea level was low. If the southerly winds were dominant, the sea level was almost close to each other in both stations. Mean sea level differences between the Black Sea and the Sea of Marmara ranged from 20 to 40 cm (Ünlüata et al., 1990).

In February 2003, the northerly winds were dominant and high atmospheric pressure represented a typical winter condition. The cruise date in this month was on the 27th and 28th of February 2003 after strong northerly winds (5–9 m s^{-1}). According to the cumulative square of wind component along the strait axis, the effect of the northeasterly winds showed positive values (Fig. 5a). This clearly indicates the effect of the wind stress on the sea level changes rather than the only its speed and direction. Although the wind speed was low, sea level differences between the north and the south were still high due to dominant northerly winds for extended periods of time.

ADCP/salinity transect (Fig. 5b) showed that current vectors aligned with the channel orientation and overlaid with the salinity transects. Therefore, waters originating from the Black Sea were dominant throughout the water column from the surface to the bottom at the north of the strait. The lower layer flow was trapped at the south of the strait with only several meters thickness at B7 bottom (Fig. 1). The upper layer flow speed increased from 50 cm s^{-1} to 100 cm s^{-1} along its movement in the strait.

During this event, the north of the strait was completely covered by Black Sea upper layer water. The salinity of this water mass was about 17 and the temperature was 2.5 °C. The data collection was performed right after the winds slowed down and therefore a slight lower layer intrusion was observed at the south. These results were supported by the current flow data; the cross-shore ADCP transects data (Fig. 5c and d) indicated that there was only one layer flowing to the south in the northern exit of the strait, whereas a two layer stratification was detected in the southern exit of the strait. Jarosz et al. (2011a) observed lower layer blockages in the northern section of the strait that lasted for several days. However, their data was only limited to 6 months (from September 2008 to February 2009) and did not show any blockages in the southern section of the strait.

In the southern part of the strait, a two-layered flow system was detected (Fig. 5d) and the lower layer current (50 cm s^{-1}) was observed below 40 m depth. The upper layer was very thick and rather fast compared with the lower layer. The current speed was higher than 150 cm s^{-1} throughout the water column.

During the lower layer blockage, there are no sewage effects in the lower layer at the northern part of the strait (Fig. 6). FC and Ent concentrations at the lower layer of K0 were the most significant parameter indicating the blockage (Fig. 2h, i). The most northern point that FC could be detected during the event was B7 (2.4×10^3 CFU 100 mL^{-1}) at the lower layer. The salinity and current data also supported these findings and indicated that there was lower layer intrusion at B7. This result is particularly important to show that FIB can be used as tracers to understand rapid changes in water quality during hydrographical events.

3.4. Material transport during lower layer blockages

The calculated volume flux of the upper layer was 28,140 m^3 s^{-1} (68×10^9 m^3 $month^{-1}$ or 2.43×10^9 m^3 day^{-1}) with a temperature of 2.53 °C and with a salinity of 17.13 in the northern section (Table 3). There was no outflow to the Black Sea during lower layer blockages. The upper layer volume flux was 30,446 m^3 s^{-1} (74×10^9 m^3 $month^{-1}$ or 2.63×10^9 m^3 day^{-1}), 18.89 and 3.62 °C (Table 3), whereas the lower layer volume flux was 1989 m^3 s^{-1} (5×10^9 m^3 $month^{-1}$ or 0.17×10^9 m^3 day^{-1}), 34.97 and 13.48 °C, in the southern section of the strait. The upper layer volume fluxes at both sections of the strait and the lower layer at the Black Sea exit were the extreme values according to average volume flux values of the layers. The upper layer volume fluxes during the lower layer blockage were approximately 2.5 times greater than the annual flux estimations. This value is, however, lower than the maximum estimation of Jarosz et al. (2011b) calculated from mooring ADCP observations for upper layer flux as 1200 km^3 $year^{-1}$ (100×10^9 m^3 $month^{-1}$) during lower layer blockages. Its values can demonstrate that extremities may depend on interannual oceanographic and atmospheric conditions.

The upper layer NO_3+NO_2–N (2.5×10^8 moles $month^{-1}$), PO_4–P (1.7×10^7 moles $month^{-1}$) and, SiO_2–Si (3.3×10^8 moles $month^{-1}$) inputs were 26, 20 and 23% of the annual NO_3+NO_2–N, PO_4–P and, SiO_2–Si fluxes respectively at the northern exit of the Strait of Istanbul. In other words, their daily inputs outflowing from the Black Sea were 117, 17.6, 309 t day^{-1} which were 3, 2, and 4 times the average daily fluxes (Table 3).

Mixing was another important factor for nutrient enrichment of the Black Sea originated waters during their travel towards the south along the strait. Nutrient concentrations increased significantly and their fluxes reached to 3.2×10^8 moles $month^{-1}$ for NO_3+NO_2–N, 3.3×10^7 moles $month^{-1}$ for PO_4–P, 4.3×10^8 moles $month^{-1}$, and for SiO_2–Si, at the southern section of the strait due to the occurrence of mixing.

During the lower layer blockage, no FIB could be detected at the north at both layers (Table 1). On the other hand, the Ent flux was 3 times higher than the annual averages of the upper layer at the southern strait. However, the FIB at M20 was not different from other sampling

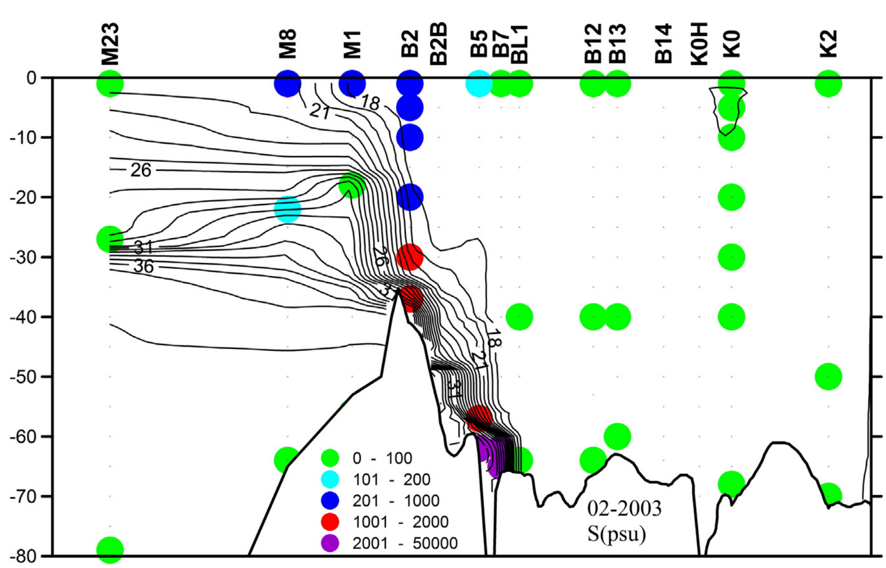

Fig. 6. FC (CFU 100 mL^{-1}) distribution superimposed with salinity transect in the Strait of Istanbul in February 2003 (for interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

Table 3
Depth averaged concentrations and calculated fluxes for lower layer blockage.

		February 2003			
		North		South	
		Upper	Lower	Upper	Lower
Concentrations/ values	*T* (°C)	2.53		3.62	13.48
	S	17.13		18.89	34.97
	DO (μM)	399.7		384.8	249.4
	TSS (mg L^{-1})	10.3		14.8	18.2
	Chl-a (μg L^{-1})	2.9		3.7	2.3
	NO_3+NO_2–N (μM)	3.7		4.3	5.6
	PO_4–P (μM)	0.3		0.4	0.9
	SiO_2–Si (μM)	4.9		5.9	10.3
	Ent (CFU 100 mL^{-1})	1		778	1750
Fluxes/month	*Q* ($m^3 \times 10^9$ $month^{-1}$)	68	0	74	5
	DO ($\times 10^8$ moles $month^{-1}$)	272	0	283	12
	TSS (kg $month^{-1}$)	700	0	1092	88
	Chl-a (g $month^{-1}$)	198	0	276	11
	NO_3+NO_2–N ($\times 10^8$ moles $month^{-1}$)	2.5	0.0	3.2	0.3
	PO_4–P ($\times 10^7$ moles $month^{-1}$)	1.7	0.0	3.3	0.4
	SiO_2–Si ($\times 10^8$ moles $month^{-1}$)	3.3	0.0	4.3	0.5
	Ent ($\times 10^8$ $month^{-1}$)	1	0	573	84

events (unpublished data). The 3 days of delay between the data collection from M20 and occurrence of blockage itself might have caused this result. It is well known in the literature that, FIB can only survive in the marine environment for up to 3 days (Noble and Weisberg, 2005). Therefore, FIB data may not be a good indicator for representing at least 3 day old waters that were impacted by the blockage and transported to Marmara Sea.

In the southern section of the strait, FIB concentration of the lower layer was less than the annual average and therefore the FIB flux was very low (84 CFU 100 $mL^{-1} \times 10^8$) during this event.

3.5. The salinity, currents and bacteria distribution along the strait during upper layer blockage (Orkoz)

The upper layer blockage occurred on the 22nd of October, when the strong southerly winds (4 m s^{-1}) were dominant (Fig. 7a). Daily mean atmospheric pressure was low during the southerly winds. The cumulative wind effect was negative, which means the southerly winds had a continuous influence. Unfortunately, sea level data were unavailable during the measurement day in north, but the sea level increased due to strong southerly winds in south. The next day, as the southerly winds continued, the sea level differences between the north and south were balanced and finally on the third day, the southern part sea level was higher than the northern part (Fig. 7a).

The ADCP/salinity transects showed mixing between the layers (Fig. 7a). The surface salinity varied significantly from north to south along the strait (particularly between B12 and B7). The upper layer salinity was greater than 23 in the southern section whereas the salinity at the northern section was 18. The lower layer was very thick; its salinity was greater than 37 in the southern section whereas the salinity was less than 35 in the northern section.

Although salinity transects showed a two-layered structure in the strait, according to the current vectors, the counterflow was interrupted and the entire system was flowing to the Black Sea in the southern section. There was very weak upper layer flow to the Marmara Sea in the northern section. The duration of this type of blockage can last for hours to days at different parts of the strait during upper layer blockage. Jarosz et al. (2011a) showed that the blockage lasted for about a day in the northern part of the strait while it took 5.5 days in the southern part of the strait. In another study, a complete reversal of the upper layer flow was recorded in April 2000, lasted for 2 days (Gerdes, 2002).

Although there was a salinity gradient throughout the water column, the cross-shore ADCP transects data (Fig. 7c) showed that the upper layer was blocked in the southern exit of the Strait. The lower layer flow reached its maximum velocity with 1.0 and 1.3 m s^{-1} at the depth of 33 and 43 m in the southern section respectively. In contrast, although there was a two-layered stratification in the northern exit of the Strait, the upper layer was very thin. The lower layer was faster in the northern section and the maximum velocity of the flow was 1.8 and 2.1 m s^{-1} at 49 and 67 m respectively at the middle of the northern transect. During the upper layer blockage, the lower layer current speed increased along the strait.

During the upper layer blockage, both layers flowed in the same direction from south to north. This caused an increase in mixing between the layers and the interface was thicker than normal conditions. The other result of this was an increase in current speed in the lower layer because of decreasing upper layer pressure. The upper layer waters ($S > 2$) coming from the Marmara Sea were observed in the middle of the strait (to the station B7). Two-layer stratification of water quality parameters at K0 (Fig. 2a–g) indicated that the upper layer blockage had not started yet in the northern section of the strait.

The maximum concentrations of FIB were found in the interface and bottom depth of the mid and south section of the strait (Fig. 8). In the northern section of the strait at both upper and lower layers FIB concentrations were lower than normal conditions. Although current vectors did not indicate any different layers, relatively lower FIB concentrations were observed in the surface waters along the strait (Fig. 8) because of the salinity interface. A possible explanation for this could be strong environmental changes (pressure and salinity) that these bacteria faced during the mixing of these two distinct waters, which may have caused this bacteria to enter viable but not culturable (VBNC) state (Oliver, 2000). The decrease of the lower layer FIB concentration in April may have been also caused by these extreme salinity changes within such short periods of time.

3.6. Material transport during upper layer blockages

The calculated volume flux of the upper layer was 3837 m^3 s^{-1} (10×10^9 m^3 $month^{-1}$, or 0.33×10^9 m^3 day^{-1}) with a temperature of 18.06 °C and with a salinity of 18.01 in the northern section. The lower layer exit to the Black Sea was 24,985 m^3 s^{-1} ($67 \times 10^9 m^3$ $month^{-1}$, or 2.16×10^9 m^3 day^{-1}, $T = 16.57$ °C, $S = 27.84$). This value was 2.7 times greater than average daily volume flux. The upper layer volume flux was only 45 m^3 s^{-1} (close to zero in unit m^3 $month^{-1}$) with an average salinity of 24.11 and an average temperature of 17.38 °C (Table 4) whereas the lower layer volume flux was 19,108 m^3 s^{-1} (51×10^9 m^3 $month^{-1}$, or 1.65×10^9 m^3 day^{-1}) having an average salinity of 32.35 and an average temperature of 15 cu in the southern section of the strait (Table 4).

The impact on the concentrations was significant at the southern part of the strait and all parameters measured were below detection limits (Table 4). On the other hand, K0 displayed two-layer stratification. The NO_3+NO_2–N, PO_4–P and SiO_2–Si outputs to the Black Sea by lower layer were 24, 23 and 15% of the annual fluxes respectively. In comparison for daily fluxes were 3, 2.9, and 2.5 times greater than average fluxes (N: 131/43.6 t day^{-1}, P: 32/11.2 t day^{-1}, Si: 337/133 t day^{-1}). For this layer the TSS and DO fluxes were also nearly 20% of the annual fluxes. DO input via the lower layer is important for the suboxic and anoxic layers of the Black Sea (Konovalov et al., 2003). The TSS outputs inflowing to the Black Sea were 29.6 kg which was 2.2 times the average daily flux. The daily Chl-a flux during this event was about 3 times higher than mean flux. Although Chl-a was detected with very low concentrations in the lower layer, the thicker interface located in upper depth (Fig. 8) caused to increase Chl-a flux which might be considered as an indicator of mixing.

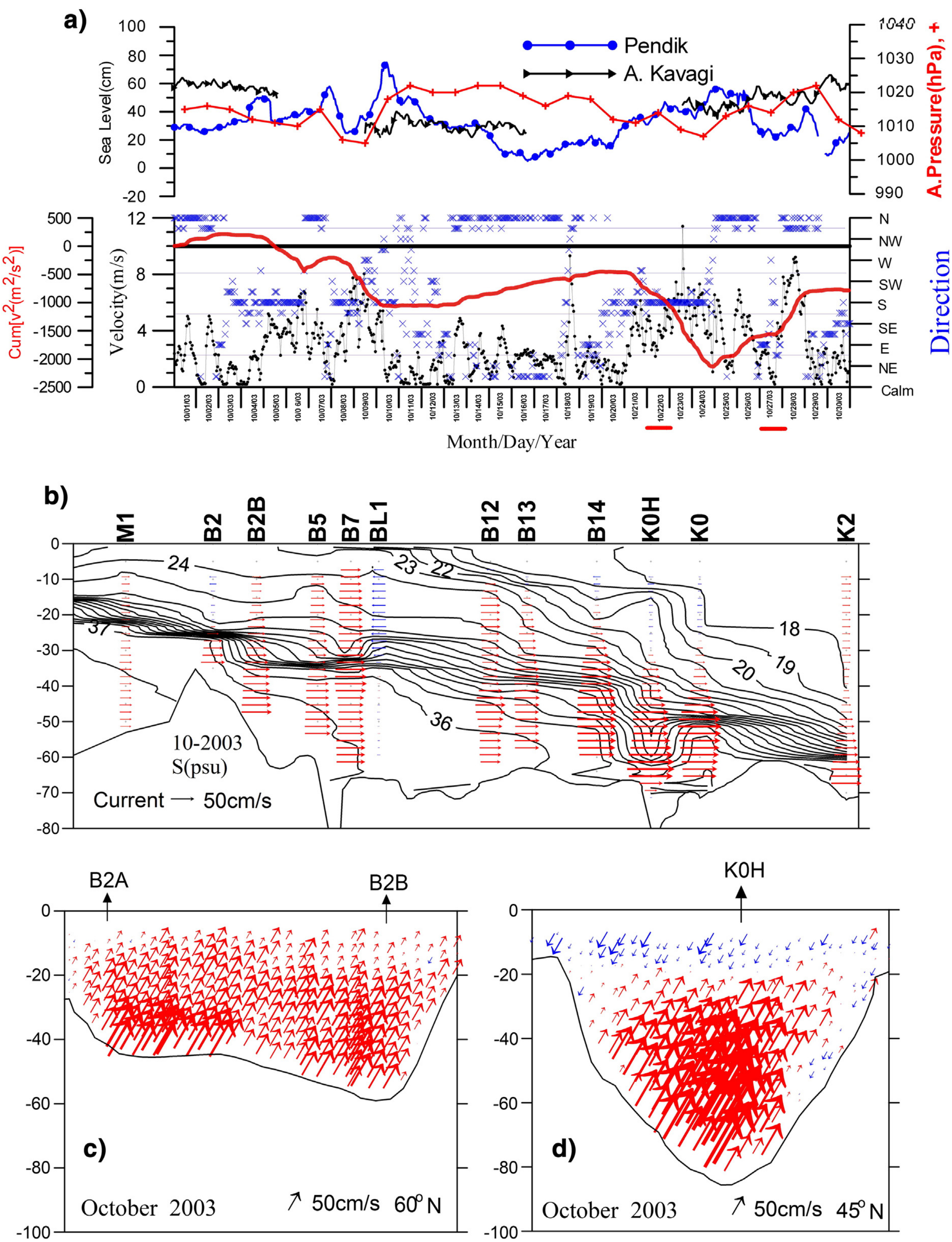

Fig. 7. a) Sea level, atmospheric pressure, cumulative wind stress, wind speed (m s^{-1}) and direction (degree) at 10 m from Kandilli in October 2003 (red line indicates cruise date); b) salinity and current transects in the Strait of Istanbul; c) north and d) south cross line ADCP transects in October 2003 during the upper layer blockage.

Contrarily, FIB flux was 5–7 fold higher (60%) in southern section whereas nearly 2 fold lower (5%) in northern section. The decrement of the FIB flux in south-north direction is mainly because of the low concentrations of the FIB in the northern section of the strait. The reason of the decrease may be linked to high current velocity and thick interface as described in Section 3.3.

4. Conclusion

This study puts together various sets of data on the quality of water masses passing through the Strait of Istanbul during a one year period with monthly interval including extreme conditions. The mean concentrations of water quality parameters and their annual fluxes of the layers

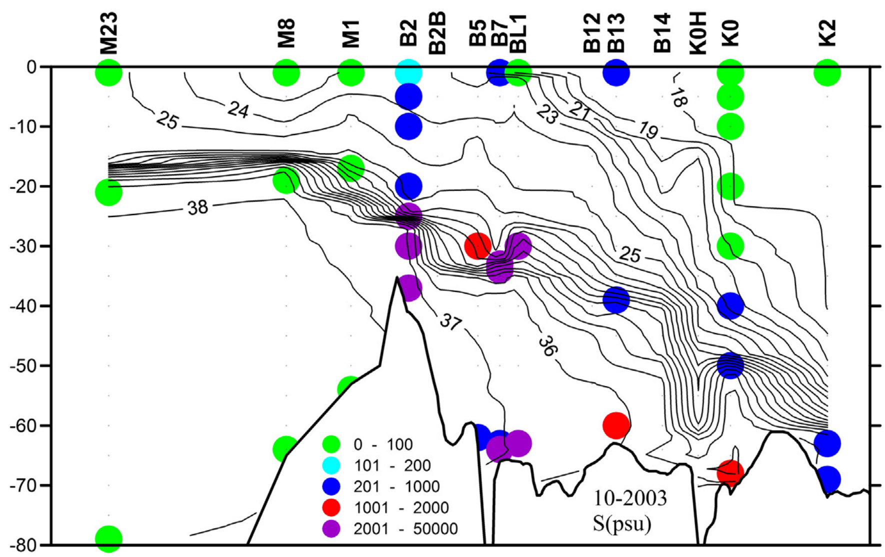

Fig. 8. FC (CFU 100 mL^{-1}) distribution superimposed with salinity transect in the Strait of Istanbul in October 2003 (for interpretation of the references to color in this figure legend, the reader is referred to the web version of the article).

were calculated in order to compare flux exchanges through the strait for the extreme conditions. The dissolved oxidative nitrogen, orthophosphate and silicate coming from the Black Sea were great seasonal changes. The lower layer concentrations however do not show significant seasonal change.

Over a 1 year period two types of blockage which can lead to severe changes in mainly volume fluxes and exchange of materials in the strait were recorded. These events were so strong that the volume fluxes were close to zero for one layer, or reached to its maximum for the other layer. The nutrients and FIB fluxes depending on volume flux increased according to annual rate. This study showed that the Black Sea carried a significant amount (20%) of the annual fluxes of nutrients, TSS and DO to the upper layer during the lower layer blockage. The FIB flux increases three times of the annual average of the upper layer at the same event. On the other hand, during the upper layer blockage, the material transport is at least 20% higher of the annual average by the lower layer to the Black Sea. The FIB flux 2 folds lower than the annual flux in the lower layer at the same event. It is to say that, those extreme events have an important contribution for the material fluxes between two seas via the Strait of İstanbul.

The data presented here proves that the material exchange between the Marmara and the Black seas becomes even more imprtant during bloackage events. Future studies require developing predictive models to help better manage the transport of pollutants in this two layered flow system. This study also showed that routine hydrographical measurements combined with water quality monitoring data is a powerful tool able to detect short-term changes, which may have serious impacts on the ecosystem health in long term.

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Table 4
Depth averaged concentrations and calculated fluxes for upper layer blockage.

		October 2003			
		North		South	
Concentrations/values		Upper	Lower	Upper	Lower
	T (°C)	18.06	16.57	17.38	15.92
	S	18.01	27.84	24.11	32.35
	DO (μM)	263.2	170.5	259.0	126.2
	TSS (mg L^{-1})	7.8	13.2	11.3	14.2
	Chl-a (μg L^{-1})	1.0	1.2	4.2	0.9
	NO_3+NO_2–N (μM)	2.5	4.2	2.9	6.2
	PO_4–P (μM)	0.1	0.5	0.3	0.8
	SiO_2–Si (μM)	1.4	5.4	2.1	9.5
	Ent (CFU 100 mL^{-1})	1	554	233	9275
Fluxes/month	Q (m^3) × 10^9 $month^{-1}$	10	67	0	51
	DO (×10^8 moles $month^{-1}$)	27	114	0	65
	TSS (kg $month^{-1}$)	80	887	1	725
	Chl-a (g $month^{-1}$)	11	83	1	45
	NO_3+NO_2–N (×10^8 moles $month^{-1}$)	0.3	2.8	0.0	3.1
	PO_4–P (×10^7 moles $month^{-1}$)	0.1	3.1	0.0	4.2
	SiO_2–Si (×10^8 moles $month^{-1}$)	0.1	3.6	0.0	4.9
	Ent (×10^8 CFU 100 mL^{-1} $month^{-1}$)	0	371	0	4747

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