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Seasonal and Interannual Variability of Water Exchange in the Strait of Istanbul

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Abstract

Temperature and salinity distribution and volume fluxes through the Strait of Istanbul were analyzed using the long-term monthly time series of temperature-salinity (1996-2010) and current profiles (1999-2010), collected from both ends of the strait. While the annual cycle of the upper layer temperature, with the minima in February and maxima in August, reflects the influence of air temperature with a near monthly phase shift, the annual cycle of the upper layer salinity, with the lowest values observed between April and September is mostly affected by the river discharge into the Western Black Sea. The seasonal variations of the lower layer temperature and salinity in the Strait of Istanbul are mostly influenced by flow blockages. Inversely proportional upper and lower layer volume fluxes indicate strong seasonal variations with the minimum and maximum values in April and October, respectively. The annual average upper and lower layer volume fluxes calculated from the high resolution dataset are 404 km^3y^{-1} and 250 km^3y^{-1} at the north end, and 430 km^3y^{-1} and 245 km^3y^{-1} at the south end of the strait, respectively.

Keywords: Temperature, salinity, volume fluxes, time series, Black Sea, Marmara Sea, Strait of Istanbul (Bosphorus Strait).

Introduction

The Strait of Istanbul (Bosphorus Strait) is a narrow (0.7-3.5 km), long (~31 km) and shallow (30-100 m) channel which enables water exchange between the Black Sea and the Sea of Marmara. Hydrodynamic conditions in the strait determine the characteristics of the water masses, which are also the boundary conditions for these two seas. As both the Black Sea and the Sea of Marmara, are semi-enclosed basins, they experience restricted water exchange. A hydraulic controlled maximal exchange flow system defined by Farmer and Armi (1986) carries two very different water masses in the strait. The upper layer (~18 psu) originates from the Black Sea, while the lower layer (~38 psu) flows from the Marmara Sea (Oğuz *et al.,* 1990; Özsoy *et al.,* 1998; Yüce, 1996). Flow exchange is mainly affected by the hydraulic conditions generated by the geometry of the strait. The northern and southern sills control the lower and upper layer flows causing maximal exchange and, they are occasionally impacted by extreme hydrological events (Oğuz *et al.,* 1990). On the other hand, Gregg *et al.* (1999) claim that the hydraulic control is somewhat quasi-steady. Additionally, Gregg and Özsoy (2002) have revealed that the exchange is also partially controlled by friction. In the strait of Istanbul, it is well known that the strong northerly winds occasionally cause the lower layer blockage during the high sea levels in the Black Sea, whereas the strong southerly winds cause the upper layer blockage (so-called Orkoz) during the low sea levels in the region (Alpar *et al.,* 1998, 1999; Latif *et al.,* 1991; Özsoy *et al.,* 1986).

The volume fluxes of each layer are estimated using different methods. At the northern exit of the strait, the upper layer volume flux is 600 km^3y^{-1} and the lower layer is 300 km^3y^{-1} based on the calculation of the steady state salt budget (Ünlüata *et al.,* 1990; Beşiktepe *et al.,* 1994). The other method is the calculation of the volume fluxes from the current velocity measured using ADCP. Jarosz *et al.* (2011a) calculated the volume fluxes from the mooring Acoustic Doppler Current Profiler (ADCP) and Conductivity-Temperature-Depth (CTD) data. At the north end of the strait it was found to 400 km^3y^{-1} for the upper layer and 300 km^3y^{-1} for the lower layer. Altıok *et al.* (2014) calculated the volume fluxes from the monthly measurements taken at the cross ADCP transect in the northern exit of the strait in the year 2003 to be 350 km^3y^{-1} for the upper layer and 299 km^3y^{-1} for the lower layer. These water masses passing through the strait are important for the hydrodynamics of the adjacent seas. The only connection between the Black Sea and the open seas is the water exchange via the Strait of Istanbul and the Marmara Sea and, the renewal time of the layers in these seas are mainly determined by the straits.

The volume fluxes of the layers in the strait play an important role in the calculation of the water and salt budget of the adjacent seas, besides being decisive for material exchange. The seasonal variation of the nutrients and organic carbon exchanged between the Black Sea and Marmara Sea is related both to the two layer flows of the Bosphorus and the chemical concentrations of the flows. The nutrient fluxes coming in from the Black Sea by the upper layer flow in winter is about at least two to three times greater than in the autumn due to changes in both the nutrient concentrations and volume fluxes (Polat & Tuğrul, 1995; Tuğrul *et al.,* 2002). Furthermore, the material exchange in the strait during the lower layer blockages causes a significant increase (20%) in the annual fluxes (Altıok *et al.,* 2014). Earlier studies indicate that the long-term measurements of the volume fluxes are essential for the calculation of the seasonal export rates of the nutrients and organic carbon in the straits.

The long-term changes in the temperature and salinity of the layers passing through the strait and their trends provide us with valuable information regarding the climatic investigation and dramatic changes in the ecosystem, such as mucilage (gelatinous aggregates) events in October 2007 in the Sea of Marmara (Aktan *et al.,* 2008; Tüfekçi *et al.,* 2010; Yılmaz, 2015). Danovaro *et al.* (2009) revealed a relationship between the climate-driven sea surface warming and mucilage occurrences in the Mediterranean Sea, including the Marmara Sea.

The warm and salty Mediterranean water exiting from the Bosphorus gets mixed with the Cold Intermediate Water (CIW) while spreading and diluting on the shelf. Its temperature decreases and this is observed as the cold anomalies in the subhalocline (Özsoy *et al.,* 2001). These waters are laterally injected into the suboxic and anoxic layers of the Black Sea and play an important role in the redox potential of the chemistry of the Black Sea. Dorofeyev *et al.,* (2012) claim the presence of a relationship in the interannual variability between the salinity in the permanent halocline in the Black Sea and the salinity of the Marmara Sea-water outflow through the Bosphorus. Tsimplis *et al.* (2004) imply that a salinity increase below 50 m in the Black Sea can be related to the positive salinity trend in the Mediterranean Sea.

Ginzburg *et al.* (2004) reported that the sea surface temperature (SST) in the Black Sea showed a positive trend with 0.09 $^{o}Cy^{-1}$ between 1982 and 2000. To measure this trend, both *in situ* and weekly satellite data were used. They also reported that SST anomalies were related to the El Nino and La Nina periods.

The main objective of this study is to investigate the temperature, salinity and volume flux variations in the Strait of Istanbul. The results of an investigation on the seasonal and interannual variability of the sea water layers in the Strait of Istanbul using temperature, salinity and volume fluxes based on a statistical analysis of the 14-year data set (1996-2010) from CTD and the 10-year data set (1999-2010) from ADCP measurements are presented. The high-resolution data analyzed in this study are very useful in determining the water mass structure and renewal characteristics in the adjacent Black and the Marmara Seas.

Methods

The CTD and ADCP data used in this study were collected from the north and south ends of the Strait of Istanbul (Fig. 1) on board the R/V ARAR operated by Istanbul University, Institute of Marine Sciences and Management (IMSM-IU). Monthly measurements at both ends of the strait were completed on the same day with an approximately 3-4 hour time lag in between. Monthly CTD data were collected between February 1996 and January 2010 using the Seabird SBE911 system and the Seabird SBE25 Sealogger. Seasonal drift and differences between the two instruments at the same stations were limited to 0.03 °C for temperature, and 0.014 psu for salinity (Altıok, 2001). Data quality of the temperature and salinity was assessed manually after each cruise and poor quality data were eliminated. For the time series analysis of temperature and salinity, a specific depth for each layer was designated, instead of using the layer averages. Layer averages of temperature and salinity do not reflect the exact properties of the respective water masses caused by the seasonal variabilities in the stratification and hydrographical dynamics of the strait. For example, the upper layer averages of temperature are skewed by the seasonal occurrence and layer thickness of the CIW. For the upper layer time series, temperature and salinity at 5 m depth were chosen as good indicators to monitor the seasonal variations in the upper layer waters coming from the Black Sea. For the lower layer time series, a 67 m depth (4 m above the bottom) at station K0 (north end), and a 37 m depth (3 m above the bottom) at station B2 (south end) were chosen to monitor the Mediterranean water inflow through the strait. Throughout this article, temperature and salinity data are represented with subscripts of T and S corresponding to depth in meters.

The Acoustic Doppler Current Profiler (ADCP) data were recorded by RDI DR-BBADCP 150 kHz between June 1999 and January 2010. The volume fluxes were calculated using the ADCP cross-shore transects at each end of the Strait of Istanbul (Fig. 1). Bottom tracking was used as the vessel-velocity reference. The resolution of the ADCP transects was 2 m in the vertical and ~50 m in horizontal. Current speed and direction data quality were assessed to remove the low quality data and the missing values were replaced by linear interpolation. No-slip lateral and bottom boundary conditions were used for the interpolation. Currents measured at the first vertical bin were assumed as constant throughout the vessel draft and blanking distance (0-8 m). Although this assumption may result in an underestimation of the surface current speeds, especially during stormy conditions, the resulting error in the volume flux is considered negligible considering the length of the time series. At each transect, the current velocity data were aligned according to the normal (north axis) of the transect direction. The alignment was approximately 60°at the south, and 45° at the north of the strait. 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 volume fluxes of the layers were calculated according to this interface.

Monthly air pressure and temperature data measured at the Florya and Kumköy meteorological stations (Fig.

1) between 1997 and 2010 were obtained from the Turkish State Meteorological Service.

Results and Discussions

The time series of the temperature, salinity and volume fluxes of the water masses passing through the Strait of Istanbul were examined at both ends of the strait. The characteristics of the upper layer waters coming from the Black Sea were influenced by the oceanographic and atmospheric conditions in the Western Black Sea. The properties of the lower layer waters were also variable temporally and spatially according to the hydrodynamic conditions prevalent in the strait. In order to indicate these effects on the properties of the layers, their time series at both ends of the strait were given together with the air temperature and pressure.

Monthly Variations in the Temperature, Salinity and Volume Flux

Upper Layer Temperature and Salinity

The time series of the monthly T_5 and S_5 at the K0 and B2 stations indicates the seasonal and interannual variations and their long-term trends (Figs. 2a, b). The temperature values in the strait hovered in the range of 2.3-27.0 °C at K0 and 2.7-25.7 °C at B2 during the 14-year period. The seasonal and interannual variations of T_5 reflected the air temperature in the Kumköy and Florya meteorological stations (Fig. 3b). For example, the minimum air temperature in both meteorological stations and the T_5 in the K0 and B2 stations were observed in February 2003. Similarly, the maximum air temperature and T_5 values were observed for the years 2001, 2002 and 2006. Besides these interannual changes, which are in keeping with the air temperatures, it was observed that sudden changes in the time series were due to the oceanographic conditions in the strait and adjoining seas. The T_5 decreased abruptly at K0 in July 1998 and in June 2003. In July 1998, cold water patches were found in the vicinity of the strait (Altıok *et al.,* 2012) as the anticyclonic eddy formations caused an increase in the CIW at the Black Sea exit (Sur *et al.,* 1997). A similar feature was observed in June 2003. Although variations in the T_5 at the K0 and B2 stations were usually parallel to each other, huge differences were observed during some months, especially in July 2007, July 2008 and August 2008. The CIW coming from the Black Sea with the upper layer in the strait causes a decrease in the upper layer temperature at the southern exit of the strait in the summer months (Altıok *et al.,* 2012). The hydrodynamic conditions in the strait were the main drivers for the differences in temperature in both these stations. On the other hand, the higher temperature and salinity values which were observed in the upper layer in March 2006 were due to the flow blockages and the resultant mixing with the lower layer waters in the southern part of the strait (B2).

The monthly time series of the T_5 at the northern exit of the strait revealed a positive linear trend of about 0.07 °Cy^{-1} (Fig. 2a). This value is close to the findings of Ginzburg *et al.,* (2004), who estimated a value of 0.08 °Cy^{-1} for the western Black Sea region during 1982 and 2000. The T5 increased during the 14-year period by about 0.98 °C in the northern exit of the strait. At the southern exit of the strait, however, the positive linear trend was two times greater than that of the northern exit of the strait. The trend was 0.15 °Cy^{-1} at B2, indicating that the temperature increased in the 14-year period by about 2.1 °C (Fig. 2a). This upward trend might have been caused by the variability of the CIW along the strait and a mixing between the layers.

The ranges of the monthly S5 at the K0 and B2 stations were 14.03-18.62 psu and 15.88-23.67 psu, respectively (Fig. 2b). The difference between these value rang-

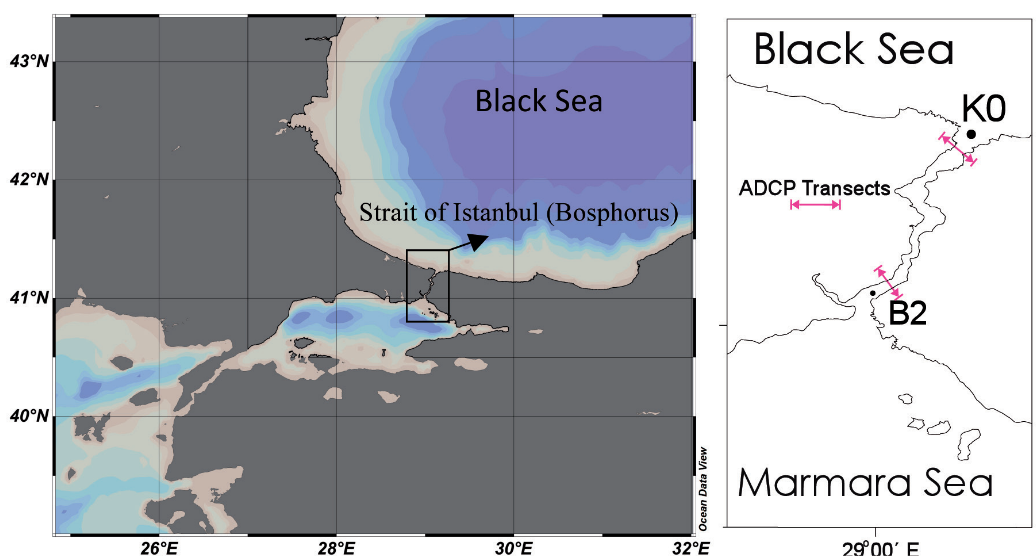

Fig. 1: Location of the Strait of Istanbul (left) and locations of the CTD stations and ADCP transects (right).

es indicates the distinct influences of the dynamics of the Black Sea and Marmara Sea on the upper layer salinity. Low salinity (<17.5 psu) waters were influenced by the Danube River (Sur *et al.,* 1994). In the summer months, the S_5 values at K0 were usually lower than 17.0 psu. The minimum K0 salinity values, namely 14.03, 14.59 and 15.02 psu were observed during July 2006, July 1999 and May 2002, respectively. In the southern exit of the strait, relatively higher salinity values were driven by the upper layer flow blockages resulting from the strong southerly winds, which were observed during the low air pressure conditions during the autumn and winter months (Fig 3a). Recently, the relationship between the southerly winds and low atmospheric pressure was examined in the Sea of Marmara by Book *et al.* (2014). The highest B2 salinity values were observed in December 1999, January 2000, October 2003, January 2004 and March 2006. The upper layer salinity was always higher at the B2 station compared with the K0 due to the mixing along the strait (Ünlüata *et al.,* 1990; Oğuz *et al.,* 1990).

The monthly S_5 at the K0 station (Fig. 2b) features a negative trend of around 0.01 psu y^{-1}, indicating that the upper layer salinity decreased during the 14-year period by about 0.14 psu. The trend in the upper layer salinity at B2 was -0.02 psu y^{-1} indicated that a greater degree of freshening occurred at the southern exit of the strait compared with the northern counterpart.

Upper Layer Volume Fluxes

The time series of the monthly upper layer volume fluxes at the K0 and B2 stations exhibited a wide range of variability (Fig. 2c). The range of the volume fluxes were 45-38, 560 m^3 s^{-1} at the southern section of the strait, and 149-33, 313 m^3 s^{-1} at the northern section of the strait. When the minimum value is close to zero (<10 km^3 y^{-1} or 330 m^3 s^{-1} which is negligible), it is assumed that the upper layer flow is blocked. In the southern section of the strait, the upper layer flow blockage was observed more frequently. The October 2003 case had been investigated earlier along with the nutrient and bacteria fluxes by Altıok *et al.,* (2014). The upper layer flow blockages in the southern section of the strait also occurred in October 2002 and March 2006. In March 2006, the upper layer blockage was observed in the northern exit of the strait as well, and the corresponding volume flux was the overall minimum for this section. In October 2002, the S_5 did not reach the higher salinity values, indicating no blockage event in the southern section of the strait but its volume flux was at its lowest level. As observed in October 2003 (Altıok *et al.,* 2014) the upper and lower layers with the thick interface flowed in the same direction during the upper layer blockage. In this event, the upper layer salinity is not higher in the northern section of the strait but the volume flux of the upper layer is very low (10 km^3 y^{-1}). Instantaneous measurements made during blockage episodes that lasted five days indicate that these values are variable (Jarosz *et al.,* 2011b). For this reason, the frequency of the upper layer blockages can be determined by considering both the S_5 and volume flux values.

The maximum value of the upper layer volume flux was 33,310 m^3 s^{-1} (1,050 km^3 y^{-1}) at the K0 station and 38,560 m^3 s^{-1} (1,216 km^3 y^{-1}) at B2, in April 2006 (Fig. 2c). In general, the higher flux values were observed during the lower layer blockage during the spring and winter months (December, February, March and April). The upper layer volume flux is typically very high in the late spring and early summer months (May, June and July).

The monthly time series of the upper layer volume fluxes at both ends of the strait (Fig. 2c) showed a negative linear trend of about 280 $m^3s^{-1}y^{-1}$ (9 km^3y^{-1}) at K0, and 400 $m^3s^{-1}y^{-1}$ (13 km^3y^{-1}) at B2. The upper layer volume fluxes decreased over the 10-year period by about 90-130 km^3. This decrease could be related to the climatic changes in precipitation, river runoff and evaporation of the Black Sea.

Lower Layer Temperature and Salinity

The time series of the monthly temperature and salinity of 67 m depth at the K0 station and 37 m depth at the B2 station reveal minor variations with sudden peaks and their long-term trends (Figs. 4 a, b). During the 14 year-period the temperature values in the strait were in the range of 2.9-16.5 °C and 6.2-16.7 °C, while the monthly salinity range was 17.4-37.7 psu and 17.8-38.5 psu, at the lower layer of the K0 and B2 stations, respectively. The lower layer, characterized by warm and saline waters, exhibits slight variations for most part of the year (Figs. 4 a, b). However, the temperature and salinity values indicate sudden peaks during the blockage events.

The temperature values of the lower layer at both ends of the strait were close to each other with just a few exceptions. During some months due to the presence of the cold intermediate layer in the northern section of the strait, the T_{67} values were lower than those of the T_{37}. When the cold layer was absent in the strait, the T_{67} values were slightly higher than those of the T_{37} because of being in direct contact with the overlying warm upper layer (Altıok *et al.,* 2012), as observed in October 2001, 2006, September and October 2007.

The salinity of the lower layer at the southern exit of the strait was greater by nearly 2 psu at the northern exit of the strait. However, during some months the less saline lower layer could be observed at the southern exit of the strait. This feature is related to the upper layer blockage. When the upper layer blockage begins at the southern exit of the strait it produces the thicker lower layer and increases the vertical mixing between the layers. The lower layer salinity decreases while the upper layer salinity increases due to the vertical mixing and intrusion of the upper layer of water into the strait from the Marmara Sea (Altıok *et al.,* 2014). The lower layer salinity continues to decrease at the northern exit of the strait during the upper layer blockage. The lower salinity values (<34 psu) indicate intense mixing due to the upper layer blockage in the strait.

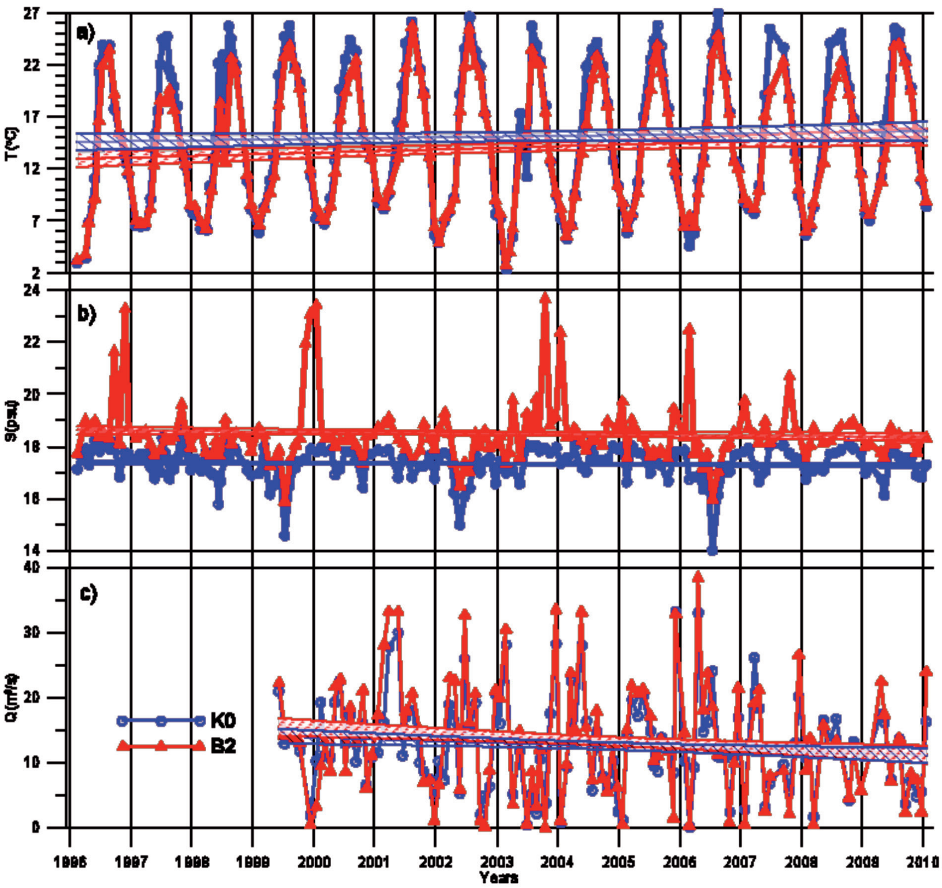

Fig. 2: Time series of a) temperature and b) salinity at 5 m depth, and c) upper layer volume fluxes at stations B2 (red, triangles) and K0 (blue, circles). Straight lines indicate respective linear trends and 60% confidence level in data.

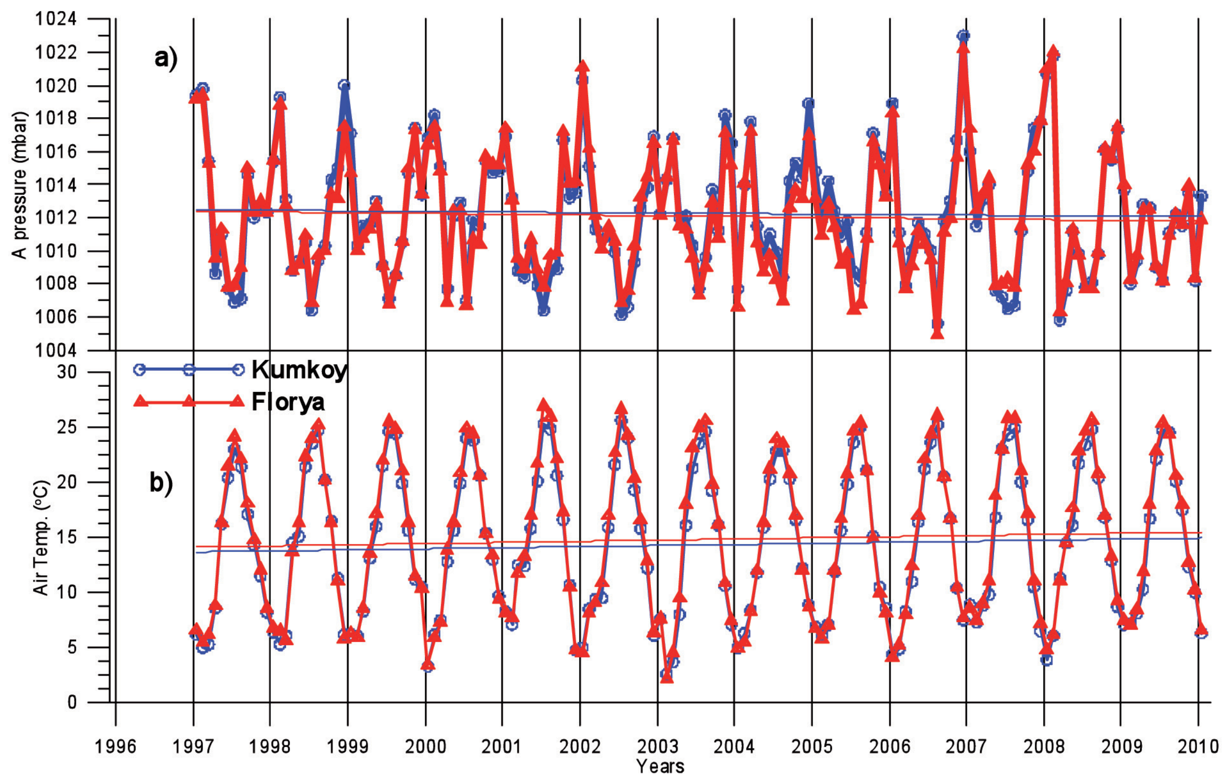

Fig. 3: a) Atmospheric pressure and b) air temperature at Florya (red, triangles) and Kumköy (blue, circles).

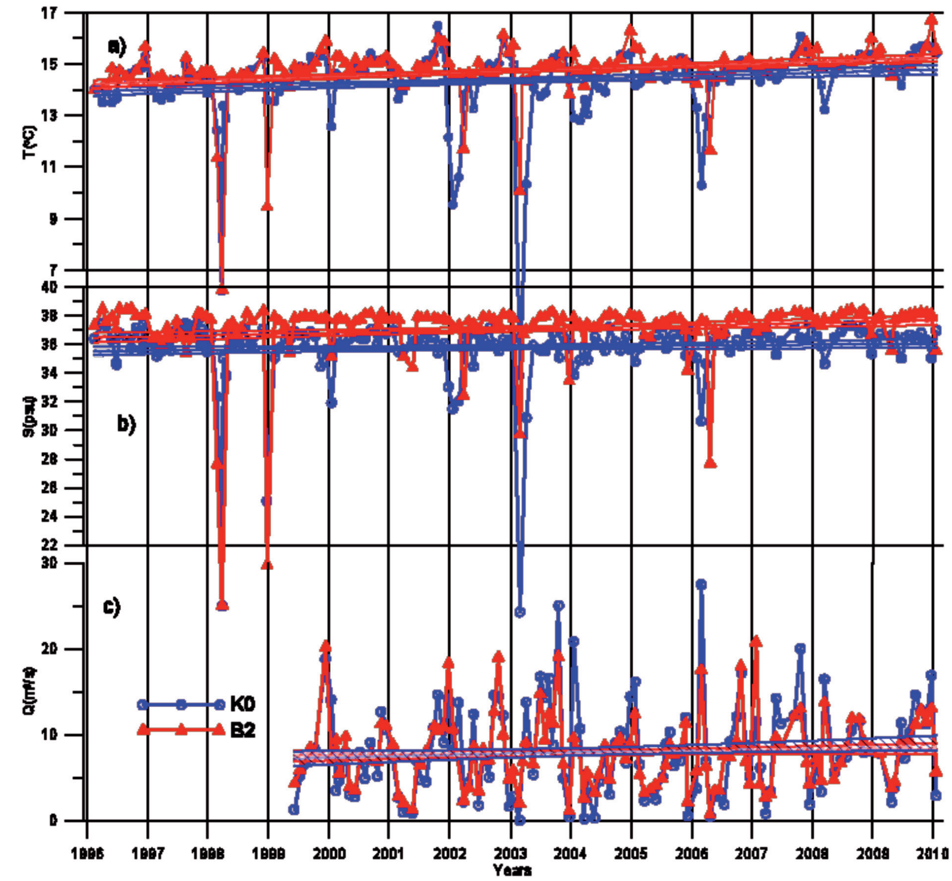

Fig. 4: The time series of a) temperature, b) salinity at 67 m depth for station K0 (blue, circles) and at 37 m depth for station B2 (red, triangles), and c) lower layer volume fluxes at both stations. Straight lines indicate respective linear trends and 60% confidence level in data.

On the other hand, during the complete lower layer blockage as seen in March 1998, December 1998 and February 2003, the S_{67} showed the same value as the Black Sea upper layer water salinity, which was less than 18.5 psu.

The monthly time series of the T_{67} and S_{67} at the northern exit of the strait showed a positive trend of about 0.06 °Cy^{-1} and 0.04 psu y^{-1}, respectively. In the southern exit of the strait, the lower layer temperature and salinity trends were 0.07 °Cy^{-1} and 0.09 psu y^{-1}. The temperature trends in the lower layer were less than in the upper layer. On the other hand, unlike the upper layer the salinity trends were positive in the lower layer (Fig. 2c).

Lower Layer Volume Fluxes

The ranges of the monthly lower layer volume fluxes at the K0 and B2 stations were 19 m^3 s^{-1} -27460 m^{3}s^{-1} (0.6-866 km^{3}y^{-1}) and 638-2,0750 m^{3}s^{-1} (20-654 km^{3}y^{-1}), respectively. The low values (<1000 m^{3}s^{-1}) of the lower layer volume fluxes indicate lower layer blockage or near blockage, while the higher volume fluxes (>13,000 m^{3}s^{-1}) of the lower layer indicate the upper layer blockage. In fact, the maximum values of the volume fluxes at the two ends of the strait were observed in March 2006 when the upper layer volume fluxes were very low at the two ends of the strait. During the upper layer blockage, the volume fluxes of the lower layer were greater than 13,000 m^{3}s^{-1} (~400 km^{3}y^{-1}) and/or the S_{67} values were less than 34 psu in January 2000, December 2001 and January 2002, as well as February 2002, April 2003 and March 2006. The upper layer blockage caused the thicker and much more diluted lower layer outflow to the Black Sea. Altıok *et al.* (2014) claim that during the blockage events the material exchange between the Marmara Sea and the Black Sea was two to three times higher than the annual average.

A complete lower layer blockage occurred during March and December 1998, but unfortunately the ADCP current was not measured at that time. During those periods, the S_{67} and S_{37} values (<20 psu) were very low. The other lower layer blockage occurred only at the northern exit of the strait in February 2003. The details of this blockage are given in the study by Altıok *et al.* (2014). The S_{67} was about 17.8 psu and the lower layer volume flux was 19 m^3 s^{-1}. The dates of the diminished volume flux (<1000 m^{3}s^{-1} 30 km^{3}y^{-1}) were March 2001, 2004, 2007, and April 2006, May 2002, 2004, December 2003 and 2005. In all of these dates, the S_{67} and T_{67} values reflected the Mediterranean water, that is, they showed salinity values greater than 35 psu and temperature values ranging between 13.5-15 °C.

The time series of the lower layer volume fluxes of the two ends of the strait showed a positive trend while the time series of the upper layer volume fluxes trend were negative (Fig. 2.c). For the northern exit of the strait the trend was 170 $m^3s^{-1}y^{-1}$ (5 km^3), whereas for the southern exit it was 80 $m^3s^{-1}y^{-1}$ (3 km^3). These trend calculations seem to be consistent with each other. The upper layer volume flux trend is greater than the lower layer due to several factors of influence causing changes in the volume flux, such as river runoff, rainfall, evaporation and winds in the Black Sea.

Seasonal Variations in the Monthly Mean Temperature and Salinity of the Layers

In this study, such long-term data obtained from the monthly measurements, including the occurrence of any kind of hydrological event in the strait enable more accurate calculations of the annual cycle of temperature and salinity for the layers. For each month, the mean monthly temperature and salinity values for the layers at both ends of the strait were calculated and analyzed statistically (Tables 1, 2, 3 & 4). As evident from Fig. 5, all the parameters reveal a different annual cycle.

Annual cycle of the Upper Layer Temperature and Salinity

The monthly mean upper layer temperatures of both the K0 and B2 stations indicates seasonal variations in the range of 6.1-24.7 °C (at K0) and 6.5-22.9 °C (at B2) with the minimum value observed in February and the maximum observed in August. The annual mean upper layer temperature may be expressed by one harmonic sinusoidal function as air temperatures in the Kumköy and Florya meteorological stations with a nearly monthly phase shift (Fig. 5.a). The temperature difference between the two ends of the strait is greater than nearly 2-4 °C from May to August due to the presence of the cold intermediate layer in the strait during the summer months, as reported in an earlier study by Altıok *et al.* (2012). This cold intermediate water also affects the mean temperature in July, indicating a small decrease and having a large standard deviation (Tables 1 & 2).

The annual cycles of the upper layer salinity at the two exits of the strait follow the same pattern. Their lower values are found from April to September. The annual variations of the upper layer salinity were in the range of 16.8-17.7 psu at the K0 station and 17.9-19.3 psu at B2. The minimum monthly mean salinity for the upper layer was observed in May at both the B2 and K0 stations, whereas its maximum was observed in January at station B2 and in November at station K0. The upper layer salinity of the K0 station reflects the South-Western Black Sea surface waters and, its monthly mean values (<17.5 psu) also indicate the Danubian influence in the area between April and August. The maximum standard deviation of the salinity was also observed in July when the less saline water was (<15.0 psu) observed. In the B2 station, the maximum salinity value and its standard deviation were observed in January when the upper layer blockage (Orkoz) event occurred frequently. The salinity of station B2 was always greater than that of station K0, by at least 0.65 psu. The highest difference was observed in January when the upper layer blockages are frequently observed (Tables 1 & 2).

Annual cycle of the Lower Layer Temperature and Salinity

The monthly mean lower layer temperature and salinity of the two ends of the strait indicate a similar annual cycle with the minimum values in February/March (Figs. 5c, d). The salinity value at the southern exit of the strait decreases from 37.14 psu (in January) to 35.1 psu

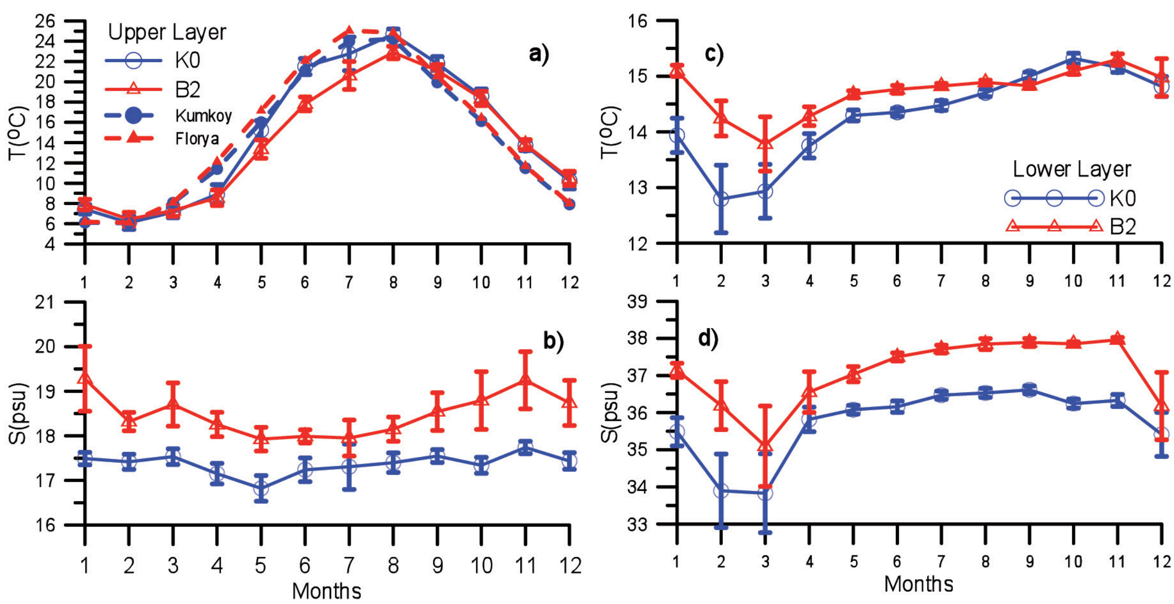

Fig. 5: The monthly mean annual cycle of upper and lower layers temperature and salinity (bars indicate standard deviations).

Table 1. Monthly Mean Upper Layer (at 5m) Temperature and Salinity at the Northern Exit of the Strait of Istanbul.

K0	Temperature (°C) at 5m				Salinity (psu) at 5m			
Months	T_a	T_{min}	T_{max}	**std**	S_a	S_{min}	S_{max}	**std**
1	7.42	4.94	8.76	1.17	17.49	16.75	17.97	0.35
2	6.10	2.34	8.18	1.68	17.42	16.64	17.94	0.43
3	7.13	4.60	9.59	1.34	17.53	16.76	18.02	0.44
4	8.91	3.40	11.25	2.35	17.15	16.18	18.00	0.58
5	15.23	11.07	19.19	2.37	16.82	15.00	18.25	0.72
6	21.50	17.56	25.45	1.98	17.24	15.79	18.04	0.67
7	22.76	11.24	26.62	4.15	17.31	14.03	18.35	1.27
8	24.70	21.49	26.96	1.29	17.40	16.14	18.01	0.55
9	21.81	17.75	23.79	1.70	17.55	17.01	18.16	0.36
10	18.57	15.39	21.59	1.80	17.34	16.42	18.07	0.45
11	13.71	12.30	16.83	1.23	17.74	16.92	18.62	0.35
12	10.23	5.66	12.97	2.01	17.44	16.57	17.94	0.47

Table 2. Monthly Mean Upper Layer (at 5m) Temperature and Salinity at the Southern Exit of the Strait of Istanbul.

B2	Temperature (°C) at 5m				Salinity (psu) at 5m			
Months	T_a	T_{min}	T_{max}	**std**	S_a	S_{min}	S_{max}	**std**
1	7.89	4.96	9.22	1.31	19.28	17.40	23.40	1.82
2	6.45	2.71	8.65	1.70	18.32	17.36	19.26	0.52
3	7.30	3.97	9.93	1.44	18.70	17.72	22.48	1.21
4	8.56	3.74	10.75	1.93	18.25	17.26	19.77	0.68
5	13.36	9.12	17.50	2.26	17.93	16.48	18.97	0.67
6	17.82	16.28	21.85	1.72	17.99	17.36	18.72	0.37
7	20.62	12.62	25.41	3.44	17.95	15.88	19.25	1.01
8	22.89	19.60	25.67	1.54	18.15	17.05	19.82	0.68
9	21.12	17.63	22.42	1.47	18.54	17.83	21.63	1.06
10	18.36	15.47	21.37	1.75	18.79	17.34	23.68	1.62
11	13.82	12.49	16.69	1.23	19.25	17.76	23.28	1.60
12	10.47	6.44	13.00	1.77	18.74	17.80	23.07	1.26

(in March) when it reaches its lowest value, increasing in November to its highest value (37.96 psu) and decreasing once again in December, recording a mean value of 37.08 psu. It oscillated from 33.83 psu in March to 36.61 psu in September with a mean value of 35.74 psu at the northern exit of the strait. While the lower layer salinity in both stations increases rapidly from March to April, it increases more slowly between April and November. The decrease begins in December.

The monthly mean lower layer salinity of station B2 is always greater than that of station K0 due to mixing between the layers throughout the strait. The salinity differences between the two ends of the strait reflect the degree of mixing/entrainment in the strait on a seasonal scale. According to mean salinity difference (1.34 psu), the highest mixing occurs in January, February, October and November when its value is greater than the average (Tables 3 & 4).

In contrast to the upper layer temperature which has an annual cycle parallel with the air temperature, the lower layer temperature reveals a different cycle mostly having been affected by the hydrological conditions prevailing in the strait. The monthly mean lower layer temperature of both the stations, K0 and B2, were in the range of 12.80-15.32 °C (at K0) and 13.78-15.30 °C (at B2) with the lowest values and highest standard deviations being observed in February and March, respectively. Although their annual cycles are similar to the lower layer salinity variations the temperature at the B2 station is not higher than the temperature of the station K0 during the whole year. From April to August the differences between the two stations is less than 0.5 °C; in September and October the temperatures of station K0 is higher than that of station B2. As mentioned earlier the presence of the cold intermediate water during the summer months caused the upper and lower layer temperatures to decrease due to the mixing and entrainment along the strait.

The lower layer temperature and salinity decrease resulted from the lower layer blockage frequently observed in December, March and April. The blockages were potential factors influencing the seasonality of the lower layer temperature and salinity.

Table 3. Monthly Mean Lower Layer (at 67m) Temperature and Salinity at the Northern Exit of the Strait of Istanbul.

K0	Temperature (°C) at 67m				Salinity (psu) at 67m			
Months	T_a	T_{min}	T_{max}	std	S_a	S_{min}	S_{max}	std
1	13.94	9.54	15.41	1.54	35.48	31.51	37.02	1.90
2	12.80	2.92	14.81	3.04	33.89	17.35	36.71	4.96
3	12.93	6.19	14.74	2.42	33.83	17.79	37.08	5.30
4	13.75	10.34	14.72	1.09	35.82	30.88	37.50	1.66
5	14.30	13.26	15.10	0.49	36.08	34.47	36.63	0.59
6	14.35	13.66	14.94	0.36	36.16	34.60	37.02	0.77
7	14.47	13.75	14.97	0.43	36.47	35.52	37.31	0.55
8	14.70	14.26	15.32	0.34	36.53	35.50	37.45	0.61
9	15.00	14.35	15.61	0.37	36.61	35.76	37.37	0.53
10	15.32	14.52	16.47	0.49	36.24	35.10	37.15	0.61
11	15.16	14.48	16.03	0.47	36.33	34.49	37.70	0.81
12	14.82	12.16	15.65	0.90	35.41	25.11	37.53	2.96

Table 4. Monthly Mean Lower Layer (at 37m) Temperature and Salinity at the Southern Exit of the Strait of Istanbul.

B2	Temperature (°C) at 37m				Salinity (psu) at 37m			
Months	T_a	T_{min}	T_{max}	std	S_a	S_{min}	S_{max}	std
1	15.10	14.33	15.72	0.50	37.14	35.14	37.94	0.97
2	14.24	10.05	15.56	1.58	36.19	27.68	38.05	3.23
3	13.78	6.23	15.26	2.44	35.10	17.78	37.82	5.41
4	14.28	11.65	15.01	0.84	36.56	27.72	38.50	2.75
5	14.67	14.08	15.14	0.32	37.03	34.35	37.99	1.03
6	14.76	14.17	15.18	0.36	37.50	36.68	38.21	0.54
7	14.82	14.18	15.22	0.25	37.71	36.60	38.50	0.54
8	14.89	14.49	15.24	0.21	37.85	35.43	38.46	0.74
9	14.83	14.41	15.10	0.26	37.89	36.39	38.47	0.56
10	15.10	14.73	15.97	0.32	37.85	37.42	38.28	0.28
11	15.30	14.32	16.12	0.51	37.96	37.01	38.35	0.33
12	14.98	9.46	16.69	1.69	36.18	20.64	38.31	4.55

Seasonal Variations of the Monthly Mean Volume Fluxes

The data collected over ten years from the monthly measurements represent the annual cycle of volume fluxes for the layers. For each month, the mean monthly upper and lower layer volume fluxes were calculated and analyzed statistically for the two ends of the strait (Tables 5 & 6). The annual variations in the volume fluxes are shown in Fig. 6.

The annual range of the monthly mean upper layer volume flux from the Black Sea is between 8,030 m^3s^{-1} and 16,610 m^3s^{-1} showing the minimum value in October and the maximum in May (Fig. 6), respectively. In April, the mean upper layer volume flux (16,510 m^3s^{-1}) is very close to the maximum value. The highest values of the upper layer volume flux for the northern exit of the strait are found in April and May. The monthly mean volume flux to the Marmara Sea by the upper layer is in the range of 7,880 to 19,150 m^3s^{-1} with the minimum in October and maximum in April (Table 6; Fig 6). On the other hand, the counter-flows from the Marmara Sea by the lower layer are inversely proportional to the upper layer flows. The minimum monthly mean lower layer volume flux was 4,930 m^3s^{-1} in the northern exit and 4,860 m^3s^{-1} in the southern exit of the strait in April. Their maximum values in October were 13,000 m^3s^{-1} and at 12,010 m^3s^{-1} at K0 and B2, respectively. The annual cycles of the upper layer volume fluxes at the two ends of the strait remained the same and had negative correlations with the lower layer volume fluxes (Fig. 6). Higher standard deviations of the volume fluxes were observed in March and December because both the upper and lower layer blockages are observed frequently in these months. For the upper layer, the standard deviation is also higher in April and May (Table 5 & 6).

The exchange flux variability was related to the sea-level variations, net water budgets and atmospheric pressure variations in the adjacent basins (Özsoy *et al.*, 1998). However, Jarosz *et al.* (2011a) reported that the volume fluxes in both layers can be estimated from the bottom pressure differences between the southern and northern ends of the Bosphorus Strait. They claimed that the upper layer volume flux was also influenced by atmospheric forcing, but its effect was less than that of the

Table 5. Monthly Mean Upper and Lower Layers Volume Fluxes at the Northern Exit of the Strait of Istanbul.

K0	Upper Layer Volume Flux (10^3x m^3/s)				Lower Layer Volume Flux (10^3x m^3/s)			
Months	Q_a	Q_{min}	Q_{max}	std	Q_a	Q_{min}	Q_{max}	std
1	8.95	0.84	16.45	5.94	10.03	2.82	20.80	6.11
2	14.26	7.43	28.14	5.94	5.81	0.02	13.69	4.08
3	15.32	0.15	27.83	10.18	6.86	0.19	27.46	9.23
4	16.51	5.22	33.15	8.05	4.93	0.46	13.73	4.14
5	16.61	3.24	30.06	8.62	5.05	0.26	14.20	4.66
6	15.74	6.87	26.04	6.66	5.53	1.24	11.38	3.89
7	12.51	0.48	24.16	6.57	7.83	1.86	16.74	4.26
8	12.67	2.23	19.19	5.15	8.30	3.04	16.52	4.02
9	9.00	2.13	13.95	4.25	10.19	6.36	14.62	3.23
10	8.03	2.46	16.02	3.94	13.00	5.17	24.99	5.40
11	9.95	4.86	17.65	3.94	9.33	4.92	12.65	2.60
12	14.24	1.96	33.31	10.56	8.41	0.39	18.81	6.92

Table 6. Monthly Mean Upper and Layer Volume Fluxes at the Southern Exit of the Strait of Istanbul.

B2	Upper Layer Volume Flux (10^3x m^3/s)				Lower Layer Volume Flux (10^3x m^3/s)			
Months	Q_a	Q_{min}	Q_{max}	std	Q_a	Q_{min}	Q_{max}	std
1	9.15	0.50	24.03	9.09	9.72	5.60	20.75	4.71
2	16.08	9.68	30.45	7.76	5.52	1.99	9.32	2.42
3	16.19	0.33	33.27	10.33	6.24	2.01	17.46	5.29
4	19.15	3.62	38.56	10.51	4.86	0.64	9.67	3.06
5	18.41	2.53	33.27	9.92	4.98	1.23	9.62	2.54
6	17.59	7.15	32.69	8.41	5.73	3.39	9.05	2.23
7	12.21	0.55	18.60	5.54	8.22	4.83	14.72	2.56
8	13.89	3.35	20.69	5.53	8.27	4.76	12.32	2.36
9	9.06	1.11	13.79	5.06	9.96	7.59	12.63	2.08
10	7.88	0.05	21.14	6.52	12.01	6.80	19.11	4.25
11	9.21	1.47	13.96	3.80	9.10	6.49	11.42	2.13
12	14.80	0.49	33.51	12.70	8.73	1.10	20.21	6.37

bottom pressure difference. Instant changes in volume fluxes with atmospheric forcing are clearly evident from the monthly time series. The annual cycle of the volume fluxes based on long-term measurements indicate the total effects of atmospheric and oceanographic conditions on the volume fluxes. According to Aydoğan *et al.* (2007), their study showed a roughly two-month phase shift between the long-term monthly average Danube River inflow and the sea level difference on both sides of the strait. The maximum sea level differences were recorded in June and July, whereas the maximum inflows of the Danube were in April and May (Aydoğan *et al.,* 2007). The annual cycle of the volume fluxes coming in from the Black Sea appear well correlated with the long-term average monthly Danube River discharge.

The 10-year average of the volume flux of the upper layer originating from the Black Sea was 12,816 m^3s^{-1} (404 km^3y^{-1}) whereas the counter flow from the Marmara Sea was 7,939 m^3s^{-1} (250 km^3y^{-1}) at the northern exit of the strait. In the southern exit of the Strait, the upper and lower layer volume fluxes were 13,656 m^3s^{-1} (430 km^3y^{-1}) and 7,777 m^3s^{-1} (245 km^3y^{-1}), respectively. The volume fluxes of the layers at both ends of the strait indicate not only seasonal variations but also interannual variations, as mentioned in Section 3.1. For example the annual volume fluxes in 2003 (up:350, low:299 km^3y^{-1} in the north end; up:403, low:275 km^3y^{-1} in the south end of the strait recorded in Altıok *et al.,* 2014) were different from the long-term average.

The annual average volume fluxes (404 km^3y^{-1} upper, 250 km^3y^{-1} lower) presented in this study are lower than the estimations (600 km^3y^{-1} upper, 300 km^3y^{-1} lower) calculated from the steady state salt budget reported by Beşiktepe *et al.* (1994). Our results, based on a 10-year long *in-situ* measurement campaign concur well with the annual average fluxes estimated from mooring the ADCP and CTD data at both ends of the strait (400 km^3y^{-1} upper layer; 300 km^3y^{-1} lower layer) at the northern exit of the strait (Jarosz *et al.,* 2011a). According to Bondar, (2007), the net Black Sea fresh water flux calculated from evaporation, river discharge and rainfall is 207 km^3y^{-1} (evaporation: 395.6 km^3y^{-1}, river discharge: 364.9 km^3y^{-1}, and rainfall: 237.7 km^3y^{-1}). This value is very close to that of the net flux, which is about 206 km^3y^{-1} calculated in this study, in the northern exit of the strait.

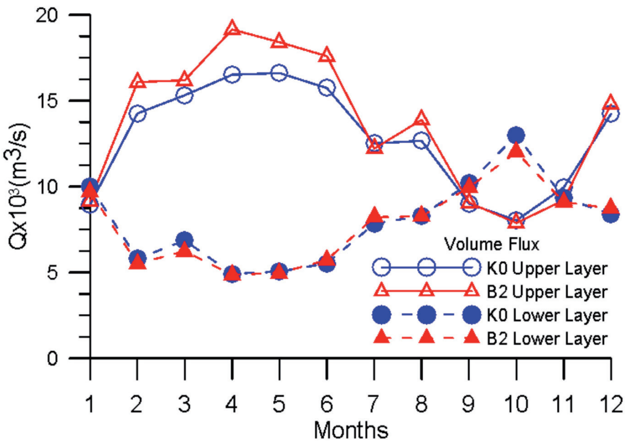

Fig. 6: Monthly mean upper and lower layer volume fluxes.

Conclusions

The CTD and ADCP observations in this study described the seasonal, interannual and annual variations of the water mass characteristics and volume fluxes in the Strait of Istanbul. We have presented the statistical analysis of the values recorded of the long-term (1996-2010) monthly temperature and salinity at 5 m depth for the upper layer and at 37 m and 67 m depths for the lower layer at the southern and northern exits of the strait, respectively. The monthly volume fluxes of the layers obtained from the ADCP cross-section at the two ends of the strait were also evaluated.

The monthly mean annual upper layer temperature in the Strait of Istanbul reveals strong seasonal variation, with the minimum in February and maximum in August. The cold intermediate water advected from the Black Sea into the strait caused a decrease in the temperature of the upper layer at the southern end of the strait from May to August. The annual salinity cycles in the upper layer was affected by the fresh water flux to the Black Sea. Its low values were observed between April and September.

Seasonal variations in the lower-layer temperature and salinity result from enhanced mixing often associated with blockage events. Both the temperature and the salinity of the lower layer are at a minimum in February and March when the lower layer blockages are observed frequently. Their higher values are found between August and November.

The Black Sea inflow to the Marmara Sea shows strong seasonal variation with the minimum value recorded in October and the maximum in April. The counter-flow by the lower layer also has strong seasonal variation, but its behavior is the opposite of the upper layer. The minimum lower layer inflow is found in April, while the maximum in October. The 10-year average volume fluxes (Up_North:404, Low_North:250; Up_South:430, Low_South:245 km^3y^{-1}) indicate that the water budget through the Bosphorus is not balanced within a 10-year period. The interannual and seasonal variations of the sea level, net water budgets and atmospheric conditions between the Black Sea and the Marmara Sea play an important role in this balance. One of the important conclusions drawn from this study revealed the requirement of a revised water budget calculation with an updated, high-resolution, long-term data set.

The time series of the temperature indicates a positive trend at both the upper and lower layers while the time series of the salinity shows a negative trend in the upper layer and a positive trend in the lower one. The trend of the volume flux time series is in keeping with the salinity trend.

The findings in this study, using the high-resolution data set, provided us a more accurate result in the numerical and ecosystem model studies. Also, the new observations noted in the region can be compared using these annual/monthly averages of the long-term data.

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