A REVIEW OF HYDROGRAPHY OF THE TURKISH STRAITS SYSTEM

Emin ÖZSOY [1,2*] and Hüsne ALTIOK [3]

[1] İstanbul Technical University, Eurasia Institute of Earth Sciences, Istanbul, Turkey
[2] Middle East Technical University, Institute of Marine Sciences, Mersin, Turkey
[3] İstanbul University, Institute of Marine Sciences and Management, Istanbul, Turkey
[*]ozsoyem@itu.edu.tr

1. Introduction

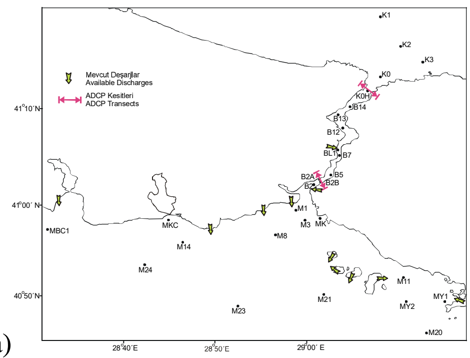
We base this review of the hydrography of the Turkish Straits System (TSS) on the CTD and ADCP data obtained on various cruises performed from 1985 till the present, combining the data from the research vessels R/V BİLİM of the Institute of Marine Sciences (IMS-METU) and R/V ARAR and lately R/V ALEMDAR 2 of the Institute of Marine Sciences and Management (IMSM-IU).

2. Data sources

Consistent observational data sets covering the TSS have been collected with the R/V BİLİM of the IMS-METU during 1985-2001 and sporadically in many other scientific cruises since then. The set of TSS measurements carried out before 1990 were obtained from a national Marine Monitoring Program. The later extensive measurement campaign carried out for Municipality of İstanbul Water and Sewerage Administration (İSKİ) during the early 1990's aimed to determine the environmental fate of the marine waste discharges of the city of İstanbul.

Detailed mapping of the Bosphorus currents and hydrography was later undertaken by the IMS-METU for the TURBO administration in the years 1998-1999, when detailed ADCP and CTD measurements were extended to small bays and bends using a small diving boat Atmaca II as well as the R/V BİLİM. Although measurement campaigns were less frequent during the 2000's, further measurements have been acquired from ships and automated coastal meteorology, sea level and ADCP stations operated under the coastal network established in the MOMA project (Özsoy *et al.* 2009). Additional measurements were obtained during the 2007-2008 campaigns of the SESAME European project in an unprecedented multi-national collaborative sampling program covering the Mediterranean and Black Seas in addition to the TSS.

Based on measurements by the R/V ARAR, the IMSM-IU has carried out a monthly water quality monitoring program for İSKİ between 1996-2010, aiming guide the ISKI Wastewater Master Plan studying the marine environmental effects of the wastewater treatment and marine outfall facilities discharging into the TSS. In the monitoring program, monthly CTD profiles and ADCP transects were obtained at the north and south exits of the Bosphorus and at a total of 28 stations (Figure 1a). Additional measurements were obtained at Golden Horn stations (Figure 1b).

(a) 

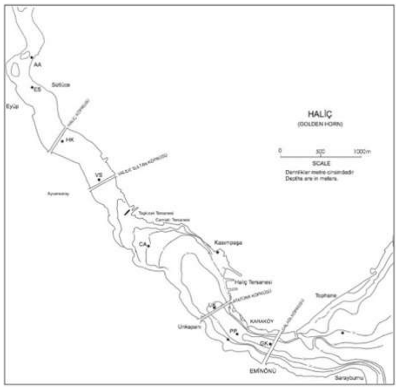
(b) 

Figure 1. Station locations of the monitoring program (a) Bosphorus and exit regions (CTD stations are shown by dots and ADCP transects are marked by the double-sided arrows, while locations of sewage discharges are indicated by arrows), (b) Golden Horn topography and CTD stations.

3. Hydrographic Variability of the TSS

3.1. Variation across the TSS

Selected transects showing variations of temperature and salinity across the TSS in Figures 2 and 3 are used to exemplify the evolution of water properties along the main axis of the system in different seasons. The largest slopes of the interface separating the upper and lower layers, carrying waters typical of the Black Sea and Mediterranean Sea, occur in the two straits. On the other hand, the variation of the interface is much less inside the Marmara Sea and most often it is observed to have relatively constant depth of about 25m in the Sea of Marmara. Figure 2 illustrates extreme cases of winter cooling with uniform cold upper layer. The relatively calmer case of temperature and salinity sections across the TSS in Figures 2a,c,e represents conditions after strong cooling in March 1990, though indicating a relative steady state situation. The waters in the Black Sea end of the TSS are exceptionally uniform till the bottom, with temperature of about 6ºC and salinity of about 17. While the two-layer exchange through the Bosphorus with small amount of mixing and a sloping interface, the subsequent mixing and circulation in the Marmara Sea are responsible for the horizontal variation of properties until values about 10ºC in temperature and 25 in salinity are reached until the Dardanelles Strait. Once again the interface slopes up in the Dardanelles Strait with a transition to shallow depth at the Nara Pass, with the upper layer water exiting to the Aegean Sea with warmer and saltier conditions due to eventual mixing. The lower layer Mediterranean water entering from the Dardanelles with temperature of about 13ºC and salinity of about 39 evolves more gradually along the entire basin. It is also observed in this winter case that the cold and saline waters entering from the Aegean Sea sink towards the lower depths in the Marmara Sea after passing through the Dardanelles Strait, against an interior background of 14.5ºC temperature and 38.5 salinity in the intermediate depths.

An extreme case in February 1993 is illustrated in Figure 2b,d,f, where very cold waters of 5ºC temperature and 17 salinity entering from the Black Sea have pushed into the Bosphorus, blocking the lower layer and pushing it till the southern entrance of the Strait. The upper layer water from the Black Sea floods the Marmara Sea and preserves its temperature of 5ºC until the Nara Pass of the Dardanelles Strait, while the salinity rises until reaching a value of 30 at the same location by entrainment of lower layer waters. The undisturbed temperature of the upper layer surviving through the Bosphorus and the Marmara Sea despite a lot of mixing and entrainment from the lower layer waters demonstrates the extreme atmospheric cooling during the winter conditions of this case. The reserve of this cold water partially survives through the spring and summer months when a residual cold layer remains below the surface waters influenced by warming.

What is even more outstanding in this case is the wild variations in interface depth in the Marmara Sea, indicating transient dynamical situation of internal sloshing as well as what must have been a very strong transient circulation in the Marmara Sea. In the lower layer, a similar situation to the former case is observed, with the cold waters of about 12ºC temperature and 39 salinity entering from the Aegean Sea and passing through the Dardanelles sink to greater depths in the Marmara Sea observed in contrast to the interior waters. The outflow of the lower layer waters into the Bosphorus and therefore to the Black Sea is totally blocked at this instance.

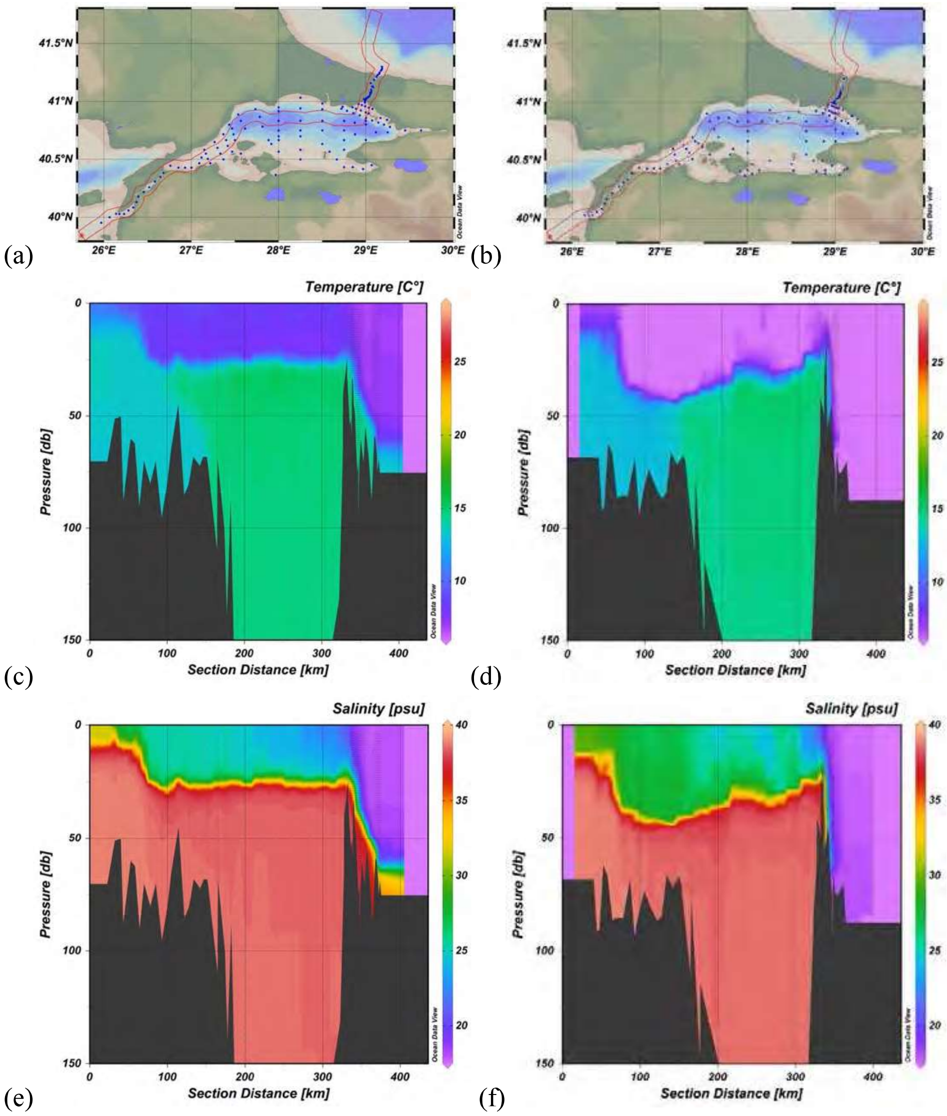


Figure 2. Stations occupied along the main transect of the TSS in (a) March 1990, (b) February 1993, (c,e) temperature and salinity sections in March 1990, (d,f) temperature and salinity sections in February 1993. The transect follows the main axis of the TSS extending from the Aegean Sea to the Black Sea along the Dardanelles Strait at 0-130 km, Marmara Sea at 130-330 km and the Bosphorus Strait at 330-370 km ranges.

The summer and autumn situations are shown in Figure 3. In the first case of August 1987 in Figures 3a,c,e, the Cold Intermediate Water (CIW) of the Black Sea defined with core temperatures of less than 8°C, and in this case with a core as cold as

5°C in temperature invades the Bosphorus and later continues as a submerged tongue transiting across the Marmara Sea, surviving until the Nara Pass (Figure 3c). As demonstrated in the former winter sections of Figure 2, it is believed that local cooling in the Marmara Sea contributes to the cold-water above and at about the pycnocline depth, largely maintained later in the deeper part of the upper layer by remnants of local winter cooling while the near surface waters are re-stratified by surface warming. The upper layer salinity in Figure 3d increases steadily from the Black Sea to the Aegean, with the highest rate in the southern part of the Bosphorus, and western part of the Dardanelles due to hydraulic adjustments. In this case, Aegean lower layer water of 17°C temperature entering from the Dardanelles Strait is warmer than the 15°C water at the same level in the Marmara Sea interior, but because of its higher salinity it is still denser, so that the inflow sinks down as a gravity current. The winter events of dense water sinking have also been shown by earlier observations (Beşiktepe *et al.* 1993, 1994) and modeling (Hüsrevoğlu 1999).

In the autumn case of November 1997 in Figures 3b,d,f, there is hardly any temperature differences between the upper and lower layers of the TSS exchange flows, and the trace of the CIL in the Black Sea below a mixed layer extending to 50 m depth does not seem to be able to penetrate into the Bosphorus or the TSS. Any remnants of the cold-water tongue in summer seem to have been totally mixed. However, the salinity difference between the upper and lower layers are still sufficiently large to determine a two-layer exchange. During these calm conditions of summer and autumn the upper layer salinity in the Marmara Sea is at the level of about 22-24. It is also now observed that the warm and saline waters entering from the Dardanelles are not sufficiently dense to sink to greater depth; instead the entering waters disperse as a subsurface tongue of low density to spread between the upper and lower layers of the interior stratification as shown in Figures 3d,f.

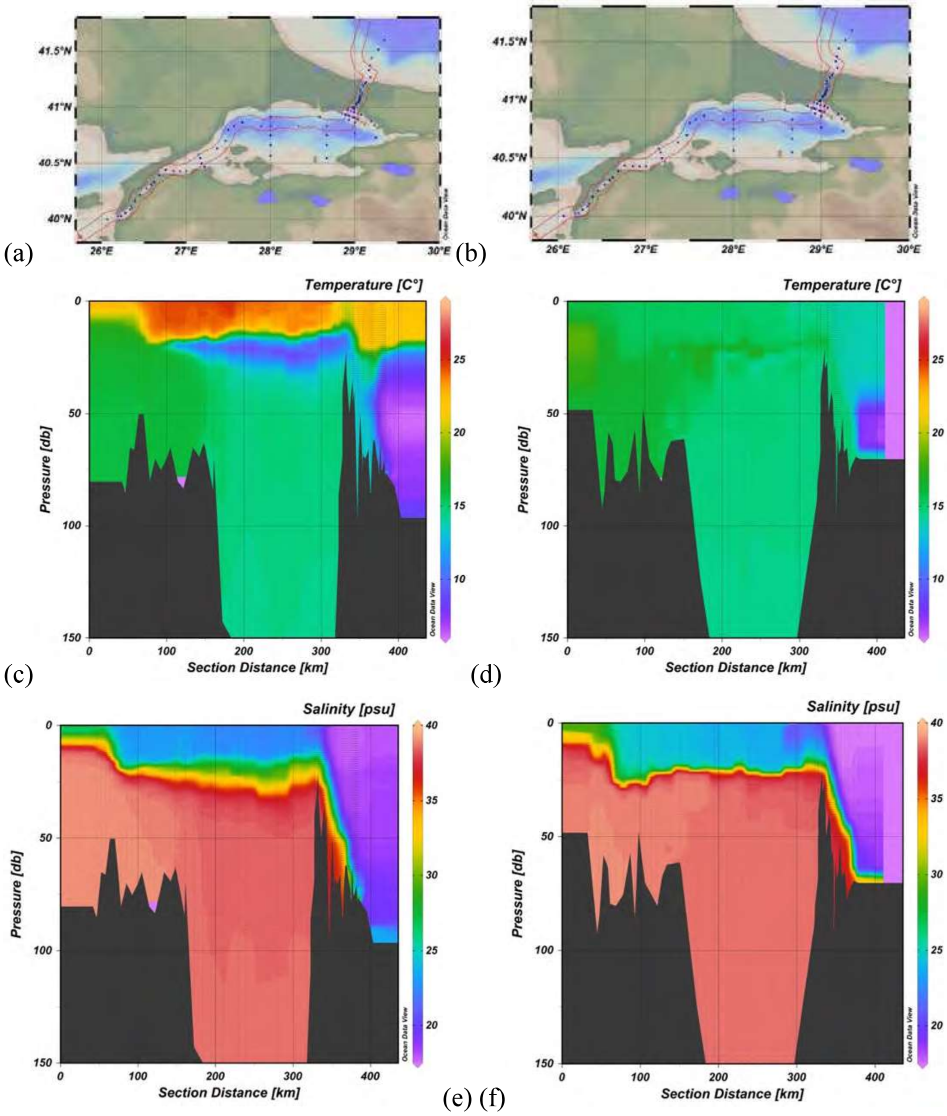


Figure 3. Stations occupied along the main transect of the TSS in (a) August 1987, (b) November 1996, (c,e) temperature and salinity sections in August 1987, (d,f) temperature and salinity sections in November 1996. The transect follows the main axis of the TSS extending from the Aegean Sea to the Black Sea along the Dardanelles Strait at 0-130 km, Marmara Sea at 130-330 km and the Bosphorus Strait at 330-370 km ranges.

3.2. Bosphorus and Dardanelles Straits

The first scientific study of the Bosphorus Strait by Marsili (1681) in the 17th century established the counter-current of Mediterranean water below the surface flow of Black Sea water (Defant 1961; Soffientino and Pilson 2005; Pinardi 2009; Pinardi *et al.* 2016), although this fact was first revealed to Marsili by local fishermen, also referred to in the sixth century note of Procopius of Ceasarea (Gill 1982; Deacon 1982; Neumann 1993) and by Gylii (1561) based on *Anaplous Bosporou* by Byzantios (Gungerich 1958) as early as 5th century AD, but still until recently debated. Early exploration up to the early 20th century (Makarov 1885; Shpindler 1896; Nielsen 1912; Möller 1928) established further understanding of the TSS.

Tidal oscillations are exceptionally small, on the order of ~10 cm in the TSS, especially east of the Nara Pass of Dardanelles. Basin oscillations with periods of 2-5 h have been observed in sea level records (Alpar and Yüce 1998). Coupled Helmholtz mode oscillations of the Black Sea and the TSS (e.g. Ducet *et al.* 1999) with 14.7 d and 1.9 d periods and a two-layer exchange adjustment time scale of 42 d have been estimated (Özsoy *et al.* 1998). Current-meters and both ship-mounted and bottom mounted ADCP measurements in the Bosphorus (Pektaş 1953; De Filippi *et al.* 1986; Gregg *et al.* 1999; Çetin 1999; IMS-METU 1999; Özsoy *et al.* 1998, 2009, 1999; Gregg and Özsoy 2002; Yüksel *et al.* 2008; Güler *et al.* 2006; SHOD 2009; Jarosz *et al.* 2011a,b) and Dardanelles (Jarosz *et al.* 2012) have revealed many different time-scales of oscillations in the TSS, ranging from inertial, semi-diurnal, diurnal to several days periods influenced by the adjacent basins (Yüce 1993; IMS-METU 1999).

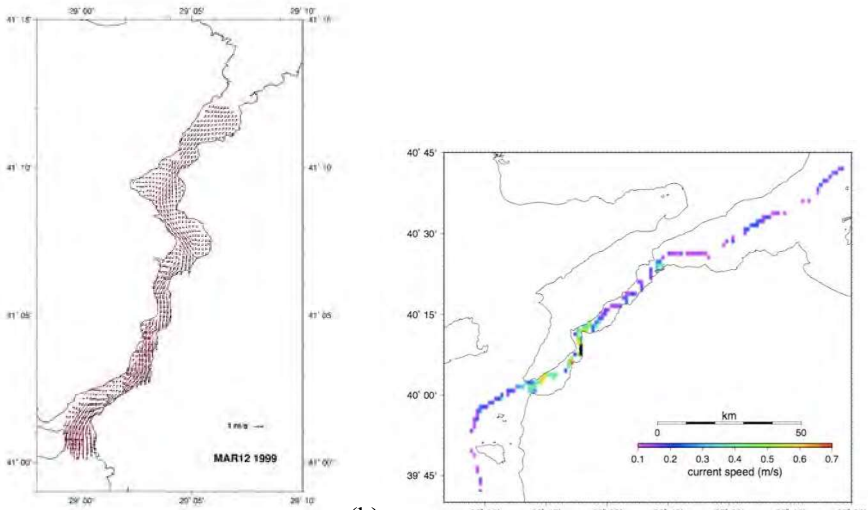
A sill standing at 60m depth on the canyon cutting across the Black Sea shelf and a contraction in the southern Bosphorus (Latif *et al.* 1991) are the expected locations of two hydraulic controls, establishing the unique maximal exchange regime of Farmer and Armi (1986), while a single contraction at the Nara pass subjects the Dardanelles Strait to submaximal hydraulic control (Latif *et al.* 1991; Ünlüata *et al.* 1990). The exchange flows in both straits have many small-scale features linked to turbulence, interfacial instabilities, hydraulic transitions and downstream “jumps” revealed by high-resolution measurements (Özsoy *et al.* 2001; Gregg and Özsoy 2002).

The northern and southern sills control the lower and upper layer flows causing maximal exchange and 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 quasi-steady. Additionally, Gregg and Özsoy (2002) have revealed that the exchange is also partially controlled by friction. In the Bosphorus, 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 (socalled Orkoz) during the low sea levels in the region (Alpar and Yüce, 1998; Alpar *et al.* 1999; Latif *et al.* 1991; Özsoy *et al.* 1986).

The surface currents often exceed 1 m/s past the contraction in the southern Bosphorus (Figure 4a) and reach 2-3 m/s at the southern exit. Similarly, surface currents of about 1 m/s occur past the narrows (Nara Pass) of the Dardanelles Strait (Figure 4b). The flows along along the straits create meandering streams and recirculation zones, for instance at the S-shaped area of bends in the northern part (Büyükdere and Beykoz bays) and north of the Golden Horn Estuary (Beşiktaş) in the southern part (Figures 4a,b), evident in current-meter and ship-mounted ADCP measurements (IMS-METU 1999; Özsoy *et al.* 2002), but also in model simulations. The last one of these recirculation cells at Beşiktaş, described by Marsili (1681) and Möller (1928), was recognized earlier in *Anaplous Bosporou* of Byzantios (5th century AD) and recorded by Gyllii (1561), who attributed it to the interception of the flow by the protruding Sarayburnu (Byzantion Pt.). The eddy diverted schools of Pelamydes (palamut, bonito) into the Keras (Golden Horn) estuary, caught to benefit the fish trade from ancient until recent times (Bursa 2010; Tekin 2010).

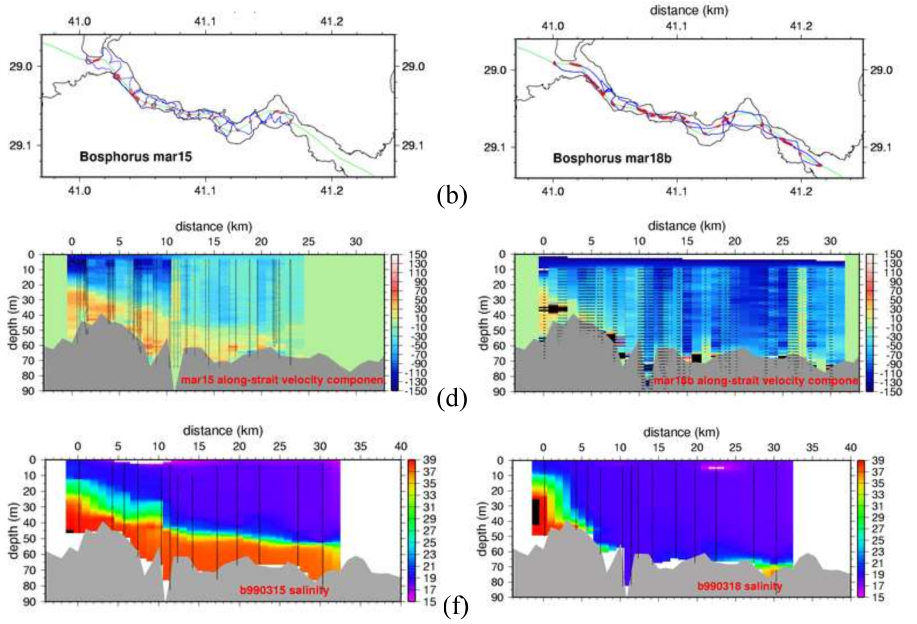
Short-term blocking of the flows in either layer is a well-known phenomenon in the Bosphorus (Ünlüata *et al.* 1990; Latif *et al.* 1991; Özsoy *et al.* 1995, 1996, 1998, 2001; Özsoy and Ünlüata 1997, 1998; Jarosz *et al.* 2011a,b) in response to transient events in the adjacent basins. Oğuz *et al.* (1990) contended that a sea-level difference of more than 50 cm and less than 10 cm would be needed, respectively for the upper or the upper layers to be blocked, although barometric pressure, winds and net water fluxes of adjacent basins are indicated as dynamical forces creating blocking conditions (Özsoy *et al.* 1998, Gregg and Özsoy 1999).

The lower layer is occasionally blocked in spring and summer, with increased Black Sea influx, mostly under the effect of northerly winds. Chosen as examples from the many similar sets of measurements, the March 15, 1999 the ADCP current and salinity vertical sections in Figure 5 (left) indicate exchange flows across the Bosphorus, with currents of about 0.5 m/s in either layer, the upper layer currents increasing to about 1.5 m/s past the contraction region, where the halocline also becomes thicker. The lower layer was completely blocked on March 18 (Figure 5, right) after northerly winds, creating southerly currents of 1 m/s almost completely flushing out the Mediterranean water, replaced by Black Sea water. Upper layer blocking events (‘Orkoz’) coincide with the reversal of the net flow in response to southerly winds (‘Lodos’) in the fall and winter (Gunnerson and Özturgut 1974; Ünlüata *et al.* 1990; Latif *et al.* 1991), often causing a three-layer situation with the Marmara waters backed up into the strait.



(a) (b)

Figure 4. Surface currents based on (a) ADCP measurements on March 12, 1999 (interpolated to grid) and (b) ADCP current magnitude on March 22, 1999 in the Dardanelles (IMS-METU 1999).

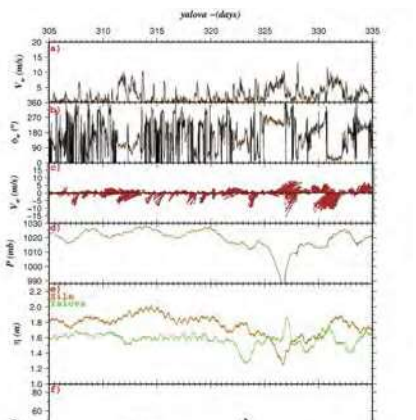


(a) (b) (c) (d) (e) (f)

Figure 5. ADCP current and CTD measurements along the Bosphorus on March 15 (left) and March 18 (right), 1999, top: details of the channel crossing routes followed by the ship (blue), the thalweg (green) and stations where ADCP vector current data are projected and rotated along the thalweg (red), middle: ADCP current velocity aligned along the thalweg (cm/s), bottom: salinity at CTD stations projected along the thalweg.

Time series of the bottom-mounted ADCP currents at Baltalimanı, sea level, wind velocity and barometric pressure at stations in adjacent seas are presented in Figure 6 for selected monthly periods, to illustrate typical variations in the Bosphorus currents as a function of environmental conditions. During the initial part of the record in Figure 6a, rather steady currents of 0.5-1.0 m/s are observed in the upper 30m under calm weather conditions. The sudden drop of barometric pressure (30 mb in about 30 h) of an atmospheric disturbance creates temporary reversals in flow direction and subsequent oscillations. The oscillatory and mixing effects created by this particular storm have been likened to a 'meteorological bomb' (Book *et al.* 2014), based on an extensive set of measurements by Jarosz *et al.* (2011a,b, 2012, 2013). Interestingly, during the event, the sea level rises in the Marmara Sea and falls in the Black Sea in response to the southwesterly winds of the storm, resulting in a negative sea-level difference of about 40 cm, with the Marmara Sea being higher than the Black Sea, as opposed to the positive difference of about 10-50 cm earlier. Sustained northerly winds in January 2010 (Figure 6b), following an initial period of reversals in the first days, result in the sea level difference building up to about 1m, with currents of up to 2 m/s covering the entire depth, leading to blocking of the lower layer currents.

(a)



(b)

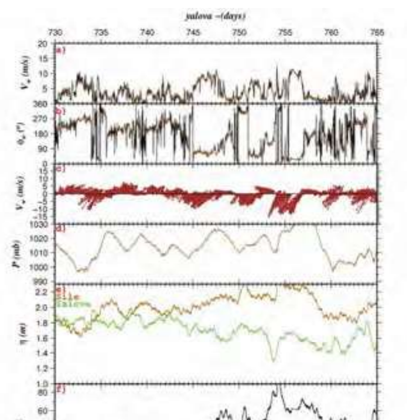


Figure 6. Monthly time series of wind, pressure, sea-level and ADCP currents in (a) November 2008 and (b) January 2010. In each panel, the wind speed and direction (measured from east), wind vector and barometric pressure at the Yalova station, inverse barometer corrected sea level at Şile (red) and Yalova (green) stations and their differences, the magnitude and sense of ADCP currents in the north-south direction (north is positive) at Baltalimanı are shown from top to bottom.

Somewhat similar behavior is expected at the Dardanelles Strait. Under typical conditions represented by 21 May 1987 (Figure 7, left), the halocline is located at 25 m depth east of the Nara Pass and remains about the same in the rest of the Marmara Sea, but rises sharply at the narrows so that it remains at a depth of about 5-10 m upon exit to the Aegean Sea. The cold intermediate water (Marmara CIW) of about 8°C sneaks in from the east, but terminates past Nara Pass where it encounters intensive mixing.

During the exceptional cold winter of 17 February 1993 (Figure 7, right), temperatures of less than 4°C are observed, when the upper layer depth increased to 40 m in the eastern part the Marmara Sea in response to wind stirring, decreasing to about 20 m after the Nara Pass where the temperature is increased to about 8°C by mixing with the warmer waters below. The lower layer water entering from the Aegean entrance with a temperature of 12°C terminates at the plunge point at the exit of the strait where it sinks to the depths of the Marmara Sea. While the lower layer salinity is about 38.5 in both dates illustrated above, the upper layer salinity is about 24 near the surface on 21 May 1987, while it increases up to 28 at entry to the Dardanelles and to about 32 at exit into the Aegean Sea on 17 February 1993, as a result of mixing processes.

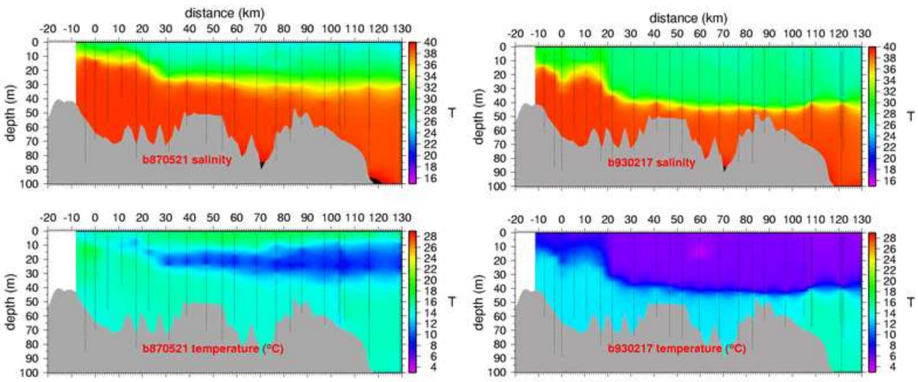


Figure 7. Salinity (top) and temperature (bottom) on the dates 21 May 1987 (left) and 17 February 1993 (right) in the Dardanelles Strait based on CTD measurements.

In the Marmara Sea, the property variations in the lower layer are indeed very small, with typical mean values of about 14.2-14.5 and 38.5 in temperature and salinity respectively, despite some small changes due to long-term instrument and climate drifts. A temperature maximum of 14.5-15°C is often observed at depths of 50-70m, surviving after the summer-autumn influx of the Dardanelles inflow below the halocline. Further below, the temperature monotonically decreases to 14.2-14.3°C at mid-depth. The salinity on the other hand reaches a minimum at about 200m and is either uniform or increases slightly till the bottom (Beşiktepe *et al.* 1994).

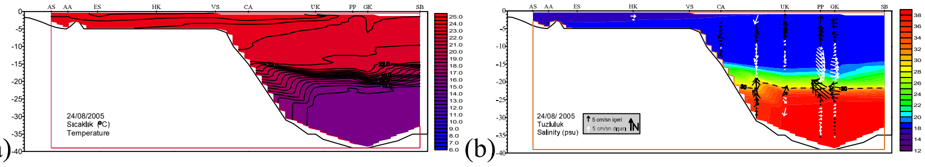
The relatively small but significant changes in the lower layer of the Marmara Sea reflect deep-water renewal processes in the Marmara Sea (Beşiktepe *et al.* 1993, 1994, 2000). The dense water entering via Dardanelles entrains water and sinks to the depth of equilibrium with the interior. Depending on the initial density contrast Dardanelles and the weak interior density stratification of the interior, the renewal process has inter-annual dependence. A reduced gravity model has shown the influx to reach the bottom of the western basin in winter, later to overflow into the central basin in a time frame of few months. In summer, with a smaller density contrast, the flow is found to first proceed preferentially along the shallow depths of the southern shelf, eventually overflowing into the interior (Hüsrevoğlu 1999).

3.3. The Golden Horn (Haliç)

The Golden Horn, is the estuary of Kağıthane and Alibeyköy Rivers, is influenced from the hydrodynamic conditions of the Bosphorus. It is 7 km long, and 750 meters wide at its widest section and has a maximum depth is about 40 meters (Ergin *et al.* 1990). Its maximum depth and widest part is placed in downstream, where it flows into the Bosphorus. The bottom depth is about 5 meters in 1 km inside from the downstream (Figure 1b).

The total volume fluxes of the Alibeyköy and Kağıthane Rivers have been decreased from its former value of $3x10^5 m^3/d$ (Kor, 1963) to about $3x10^5 m^3/y$ (Öztürk *et al.* 1998) in recent years. Today, the amount of the fresh water coming from these rivers is high when the rainfall is heavy. Since 2012 October the salty water taken from the Bosphorus upper layer (almost 4 meters depth) have been carrying via Alibeyköy River to the Golden Horn. The volume flux of this water is not regular. According to flow values obtained from İstanbul Water and Sewerage Administration (İSKİ) of İstanbul Metropolitan Municipality the average flux is $1.8x10^5 m^3/d$ for July and August 2013.

Studies related to oceanographic features of the Golden Horn were revealed to be closely related to characteristics of the Bosphorus. Temperature and salinity across the estuary given in Figure 8 shows two-layer hydrographic structure in the deeper part of the estuary. The top layer temperature showed large changes in salinity (18-21 psu) within the year, depending on atmospheric conditions, the waters of the Bosphorus originating from the Black Sea, and the influence of rivers and rainfall. The lower layer of Mediterranean origin has high salinity (~37 psu) and warm temperatures (~15°C) in which very little change is evidenced during the year and the temperature (Ergin *et al.* 1990). The transition layer separating the two layers can be of different thickness and depth due to the impact of mixing by the wind.



(a) (b)

Figure 8. Temperature, salinity and current variations in the Golden Horn, August, 2005 (Müftüoğlu 2008).

The vertical structure of the Golden Horn can be characterized as a three-layer system under the influence of the discharge system of its small rivers, the Bosporus and atmospheric conditions. These layers consist of the upper layer of Black Sea origin, the lower layer of Mediterranean origin and the transition layer between them. Waters from the Alibeyköy and Kağıthane streams can reach the throat of the freshwater estuary at the surface. Although these waters of river origin can be detected at the top layer of water on the surface of the 2-3 m layer the Bosphorus origin water just below does not carry the same characteristics; the surface water being distinguished by low levels of dissolved oxygen and high concentrations of suspended matter (Sur *et al.* 2001). Surface salinity is lower by about 2 psu from the upper layer salinity. As a result of limited light penetration below the surface waters with high suspended matter concentration, the surface water is typically warmer than the water just below (Özsoy *et al.* 1988).

4. Trends and Variability

4.1 Temporal Variability in the TSS and neighboring Seas during 1985-2015

We next examine temporal hydrographic variability in the TSS and its neighboring domains by examining collective oceanographic data merged together from IMS-METU and IMSM-IU sources. The 30-year data set covers the period 1985-2015, from which we produce the analyses in Figures 9-11. The CTD station positions in the TSS region are shown in Figure 9a.

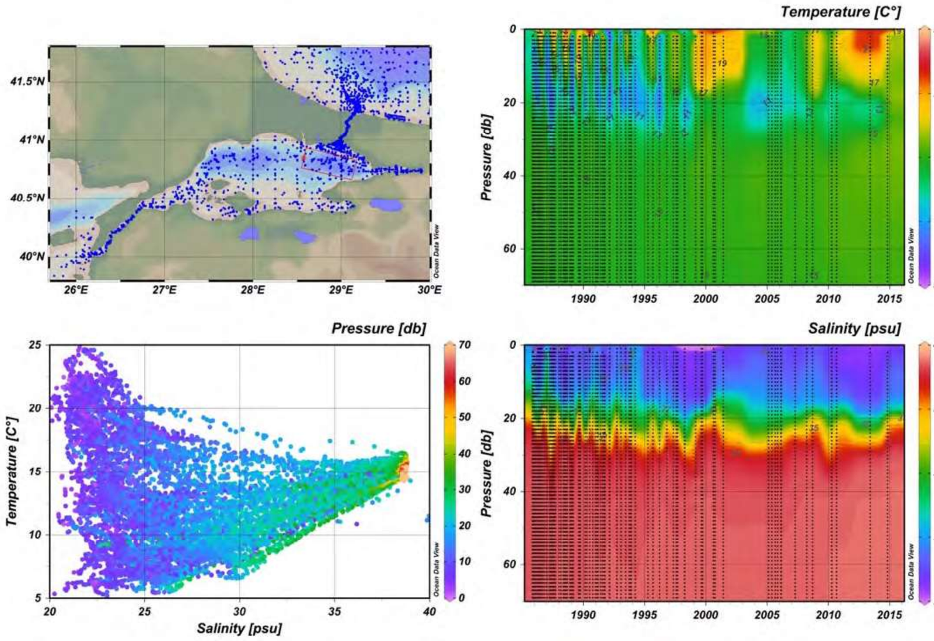


Figure 9. (a) Locations of oceanographic stations in the TSS and its neighboring domains, with the selected area of analysis in the eastern Marmara Sea marked by the rectangular box encircled by the red line, (c) the corresponding T-S diagram with depth of data points indicated on a color scale, (b) temperature and (d) salinity time series of depth profiles.

We sample the data within the eastern Marmara Sea box bounded by a red line in Figure 9a for analysis. The temperature and salinity versus depth time series are shown in Figures 9b,c, where the data in the first 15 years until 2000 appears more abundant than the later years. In the temperature time series, seasonal changes are well captured in the first 15 years. It is evident that the cold intermediate waters of the Marmara Sea that were shown to be present from late winter until summer are cyclically observed in the first part of the record, but seem to be reduced in strength after the 2000's, despite the reduced number of profiles in this period. It is also seen in the first 15-year period that the average depth of the core of this cold water in the upper layer has been slightly increased from about 20 m to about 25 m, possibly indicating slight changes in stratification in the longer term. The same trend appears in the salinity time series showing a shift in the mean depth of the halocline within the same range in the first period of 15 years, later leveled off at 25 m depth, with superposed seasonal oscillations.

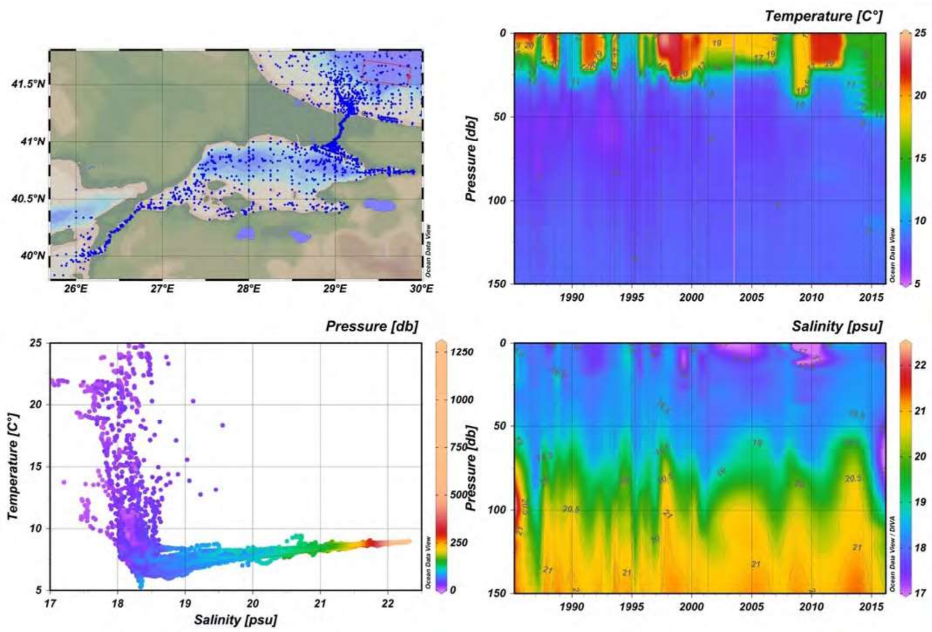


Figure 10. (a) Locations of oceanographic stations in the TSS and its neighboring domains, with the selected area of analysis in the adjoining Black Sea region marked by the rectangular box encircled by the red line, (c) the corresponding T-S diagram with depth of data points indicated on a color scale, (b) temperature and (d) salinity time series of depth profiles.

The conditions in the adjacent seas in the same period are reviewed in Figures 10 and 11. In the Black Sea for stations within the box chosen for analysis in Figure 10a, the situation is similar to that observed in the Marmara Sea; once again the number of samples until the 2000's are greater than the observations available later. However, it is quite significant that the Cold Intermediate Layer (CIL), defined to consist of waters colder than 8ºC in the Black Sea, appears to be colder in the first period with core temperatures as low as 5ºC, which however is observed to become warmer after the 2000's despite the decreased number of available data. Recently, there is increasing evidence that the CIL water mass formation by winter cooling is on the decrease. The volume of CIL in the Black Sea has been variable over the last decades as a function of winter mixing, with a decreasing trend in recent years linked to increasing surface temperature (0.6°C/decade from 1982 to 2002; Belkin 2009) influenced by climate variability and change (Oğuz *et al.* 2003; Stanev *et al.* 2013, 2014; Capet *et al.* 2016; Miladinova *et al.* 2016).

The comparable analysis for the Aegean Sea box immediately outside the Dardanelles Strait as shown in Figure 11 does not seem to indicate consistent patterns of long term changes. It should be noted however that the analyses should be further extended to include basin-wide data to conclude on trends in the adjacent basins. At present we only compare changes in adjacent areas to the TSS.

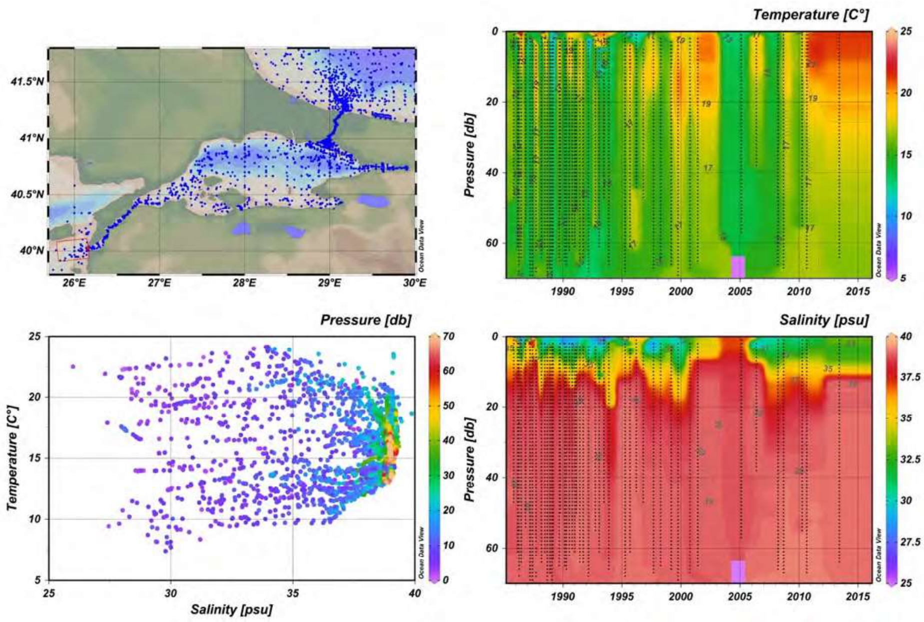


Figure 11. (a) Locations of oceanographic stations in the TSS and its neighboring domains, with the selected area of analysis in the adjoining Aegean Sea region marked by the rectangular box encircled by the red line, (c) the corresponding T-S diagram with depth of data points indicated on a color scale, (b) temperature and (d) salinity time series of depth profiles.

4.2. Temporal Variability in the Bosphorus during 1995-2005

Hydrodynamic conditions in the Bosphorus 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 long term changes of temperature and salinity of these water masses and their trends are useful information about climatic investigation for the Marmara Sea and neighbouring seas. The monitoring program of the IMSM-IU for İstanbul Water and Sewerage Administration (İSKİ) provided high resolution data collected monthly from 28 stations in the strait and the junctions (Figure 1a). Temperature and salinity variation and volume fluxes through the Bosphorus were analyzed using the long-term monthly time series of temperature, salinity and current profiles obtained from this monitoring program (Altıok and

Kayışoğlu 2015). Influence of local meteorology is inferred from air temperature and barometric pressure measured at Kumköy and Florya meteorological stations (Figure 12).

The mean values and trends obtained from the CTD and meteorological variables are provided in Table 1.

Table 1. The means and trends of CTD and meteorological variables

Station / depth	**temperature, T**		**salinity, S**		**density, σ_θ**	
oceanographic station	mean (°C)	trend (°C y^{-1})	mean	trend (y^{-1})	mean	trend (y^{-1})
B2 at 5 m	14.02	0.153	18.48	-0.019	13.27	-0.040
K0 at 5 m	15.10	0.073	17.36	-0.010	12.16	-0.020
B2 at 37 m	14.74	0.072	37.07	0.086	27.62	0.052
K0 at 67 m	14.36	0.060	35.80	0.037	26.71	0.016
	air temperature, T_{air}		**barometric pressure, P_{bar}**			
Meteorological station	mean (°C)	trend (°C y^{-1})	mean (mb)	trend (mb y^{-1})		
Florya	14.81	0.097	1012.08	-0.048		
Kumköy	14.32	0.104	1012.26	-0.033		

The minimum air temperature in both meteorological stations and the upper layer temperature in the Bosphorus were observed in February 2003. The higher air temperature and upper layer temperature values were observed for the years 2001, 2002 and 2006. The temperature of the upper layer in the strait fluctuated in the range of 2.3-27.0 °C at the northern exit of the Bosphorus and 2.7-25.7 °C at the southern exit during the 14-year period (Figure 13).

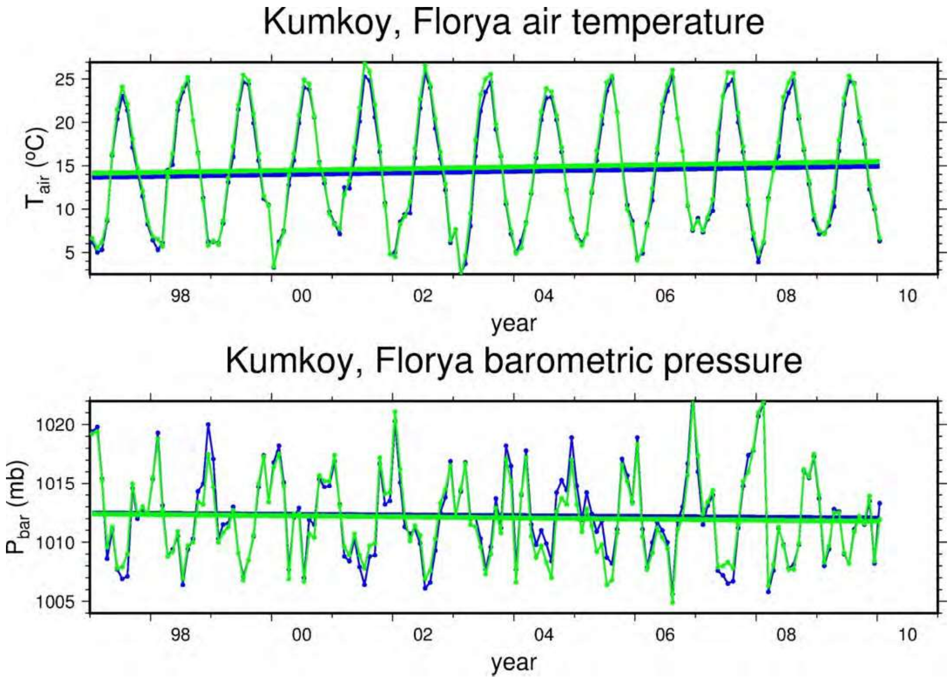
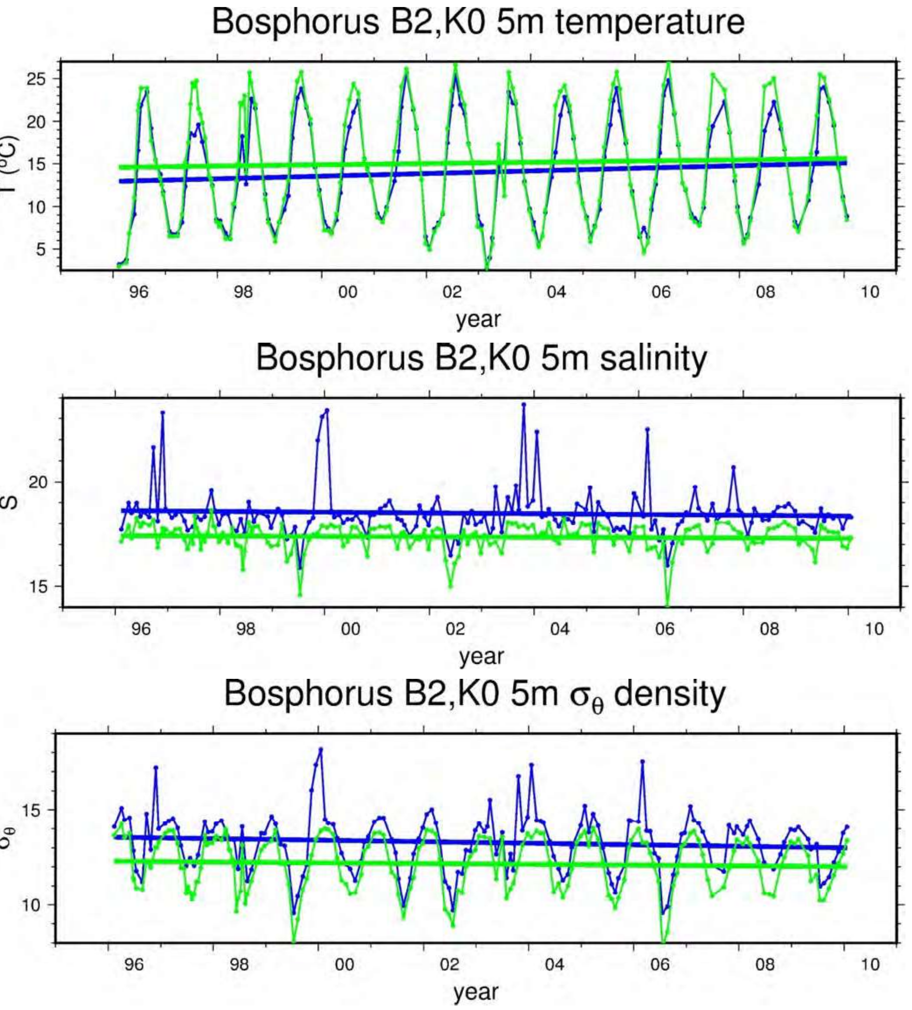


Figure 12. (a) Air temperature and (b) barometric pressure at Kumköy (blue) and Florya (green) meteorology stations.

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 upper layer temperature decreased abruptly at the northern exit of the strait 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 upper layer temperature at the both ends of the strait 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.

Ginzburg *et al.* (2004) estimated a value of 0.08°Cy^{-1} for the western Black Sea region during 1982 and 2000. The monthly time series of the upper layer temperature at the northern exit of the strait revealed a positive linear trend of about 0.07°Cy^{-1} (Table 1 and Figure 13). The upper layer temperature 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 the southern exit of the strait, indicating that the temperature increased in the 14-year period by about 2.1°C (Figure 13). 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 upper layer salinity at the both ends of the strait were 14.03-18.62 psu and 15.88-23.67 psu, respectively (Figure 8). The difference between these value ranges 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 salinity values at the northern exit were usually lower than 17.0 psu. The minimum salinity at the northern exit, 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 (Figure 9a). 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 salinity values at the southern exit were observed in December 1999, January 2000, October 2003, January 2004 and March 2006. The upper layer salinity was always higher at the southern compared with the northern exit due to the mixing along the strait (Ünlüata *et al.* 1990; Oğuz *et al.* 1990).



(a)

(b)

(c)

Figure 13. Time series of (a) temperature, (b) salinity and (c) σ_θ density at 5 m depth at station B2 (blue) near the southern exit and at station K0 (green) at the northern sill outside the northern exit of the Bosphorus Strait. Straight lines indicate respective linear trends.

The monthly upper layer salinity at the northern exit (Figure 8) 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 the southern exit 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.

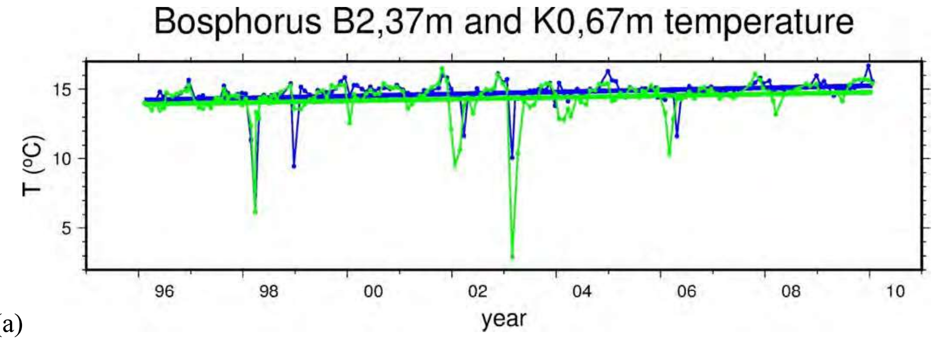
4.3. Trends in Bosphorus Lower Layer Temperature and Salinity

The time series of the monthly temperature and salinity of 67 m depth at the northern exit of the strait and 37 meter depth at the southern exit of the strait reveal minor variations with sudden peaks and their long-term trends (Figures 10a,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 north and south exits of the strait, respectively. The lower layer, characterized by warm and saline waters, exhibits slight variations for most part of the year (Figures 10a,b). However, the temperature and salinity values indicate sudden peaks during the blockage events.

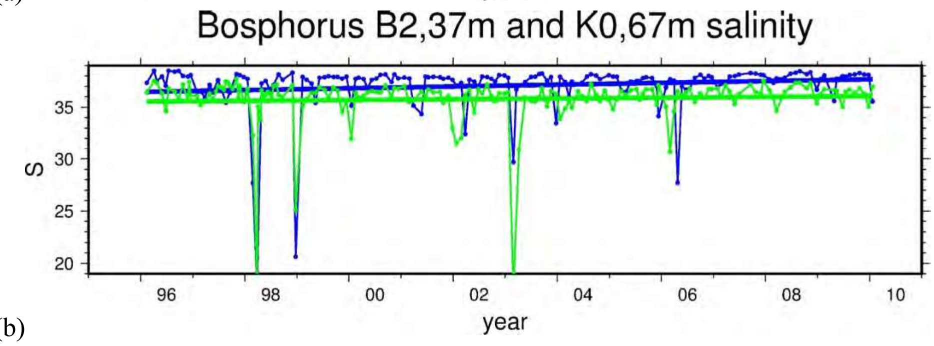
The temperature values of the lower layer at both ends of the strait were close to each other with just a few exceptions. During some months due to the presence of the cold intermediate layer in the northern section of the strait, the lower layer of the northern exit of the strait values were lower than those of the temperature of the lower layer at the southern exit of the strait. When the cold layer was absent in the strait, the lower layer temperature values of the northern exit were slightly higher than those of the southern exit 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. On the other hand, during the complete lower layer blockage as seen in March 1998, December 1998 and February 2003, the lower layer salinity at the northern exit showed the same value as the Black Sea upper layer water salinity, which was less than 18.5 psu.

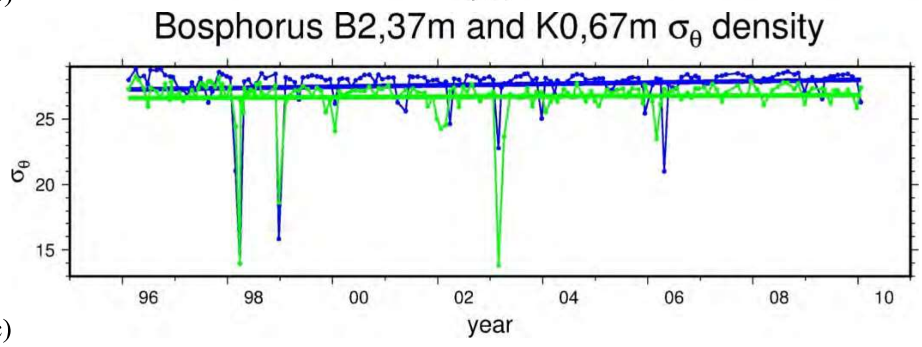
The monthly time series of the lower layer temperature and salinity at the northern exit of the strait showed a positive trend of about 0.06 $°Cy^{-1}$ and 0.04 psu y^{-1}, respectively. In the southern exit of the strait, the lower layer temperature and salinity trends were 0.07 $°Cy^{-1}$ and 0.09 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 (Figure 10).



(a)



(b)



(c)

Figure 14. Time series of (a) temperature, (b) salinity and (c) σ_θ density at 37 m depth at station B2 (blue) near the southern exit and at 67 depth at station K0 (green) near the northern sill outside the northern exit of the Bosphorus Strait. Straight lines indicate respective linear trends.

4.4. Time-dependent changes of surface salinity in the Golden Horn

The Golden Horn has been subject to various attempts of reclamation to recover its health. Vertical mixing of the highly polluted surface waters is limited due to the strong density stratification of the estuary. The old pontoon bridge of Galata has been removed in 1992 to provide faster recirculation of the surface water near the estuary mouth. After the completion of dredging work at the entrance of the mouths of the small streams feeding the estuary in 2000, the fresh water input has been increased. through the river estuary shortly after completion in 2000. Starting from October 2012, additional water of about 18psu salinity withdrawn from the Bosphorus is pumped into the upper part of the estuary.

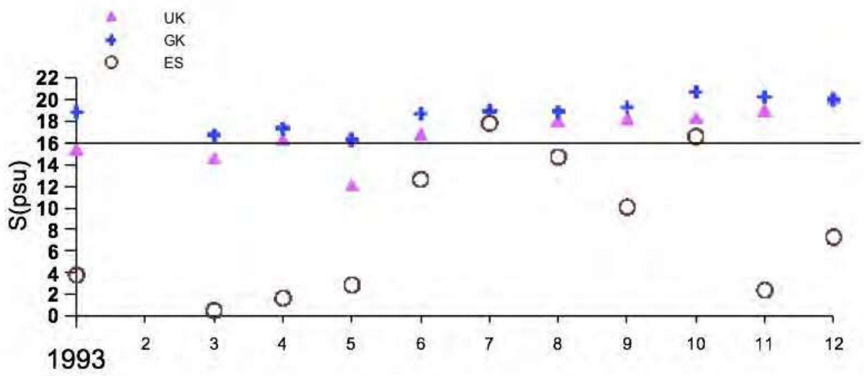


Figure 15. Monthly variation of Golden Horn surface salinity in 1993 (Emin, N. 1994)

In a study conducted on a monthly basis in 1993, at stations GK (Galata Bridge), UK (Unkapanı Bridge) and ES (Eyüp Sütlüce section) of surface salinity values large salinity differences have been found between the head and the mouth of Golden Horn (Figure 1). In the ES station near the head of the estuary, surface salinity in spring and winter has a minimum of 8 psu, as a result of rainfall. This fresh water effect can also be observed at the UK and GK stations during the same season, with salinity values dropping to less than 16 psu.

Since the period of accelerated reclamation in the Golden Horn, when the mud was being dredged up until 2005, monthly values of surface water salinity measurements obtained by the IMSM-IU in the Water Quality Monitoring Project are given in Figure 11. Salinity measurements at the same station from 2009 until today by the Water and Waste Administration of the Municipality of İstanbul (İSKİ) are also shown on the same plot. In addition, values measured by IMSM-IU in summer (July, August and September) in the scope of this project are shown in the same Figure. An SBE25 Sealogger CTD device was used from May 2000 until the end of 2005 in the salinity measurements by the Institute, excluding shallow stations with depth less than 0.5m. Despite noticeable variations in the surface salinity at shallow stations indicating the influence of freshwater input, surface salinity during the 2000-2005 period at the GK station had a maximum of 20.6 psu. The effects of the rainy season can be seen in the time dependent observations since 2009 (Figure 12). The annual average values at the GK station varied from 17.63 psu in 2009 to 18.4 psu in 2012 and 2013

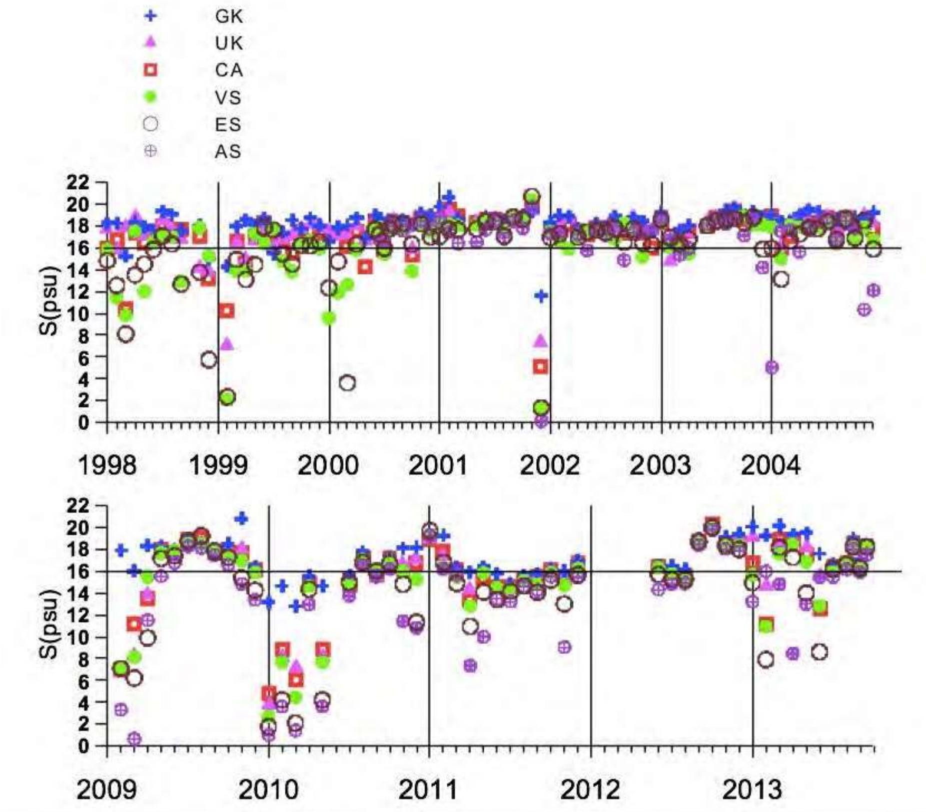


Figure 16. monthly surface water salinity changes between 1998-2005 and 2009-2013

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