A deterministic approach to the interface layer. variations along the Strait of Istanbul

İstanbul Boğazı boyunca ara su tabakasının değişimlerine deterministik bir yaklaşım

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Abstract

The Strait of Istanbul (Bosphorus) possesses interesting internal hydraulic characteristics and exhibits a complex flow system with considerable temporal and spatial variability. Seasonal or longer time scale variability of the interface layer is related to the changes in the conditions in the Marmara and Black Seas and influenced by the climatic changes. The higher frequency variations, on the other hand, are associated with atmospheric forcing. The variations on the time scale of few days (storm surges) may dominate the flow particularly in winter, giving rise to substantial modification of the two-layer flow and water mass structure. This variability may lead to the blockage of either the lower or upper layer.

This paper describes oceanographic and meteorological measurements taken during February 1996 - January 1997 sea trials along the Strait of Istanbul and its entrance regions. The main objective of this study is to determine the upper Black Sea water flow and underlying Mediterranean water flow along the Strait of Istanbul. The seasonal depth variations of the interface layer of the flow system along the Strait of Istanbul, their relations with sea level difference between adjacent seas and atmospheric forcing have been investigated.

Keywords: Strait of Istanbul, blockage, interface layer, sea level, atmospheric forcing

Introduction

The Strait of Istanbul (SOI) is located in the northern part of the Turkish Strait System (TSS) and creates a water passage between two relatively large inland seas of differing hydrological characteristics; the Black Sea (BS) and the Sea of Marmara (SOM) (Figure 1). It is a long, narrow and shallow strait having an approximate length of 31.0 km, average and maximum depths of 35.8 m and 110 m and width of 0.7-3.5 km (Gunnerson and Özturgut, 1974). It exhibits a varying morphology, with narrow sections and meanders.

The SOI is stratified in two layers with a sharp pycnocline. The degree of stratification, so its depth, varies seasonally depending mainly on the conditions in the adjacent basins. The depth of pycnocline changes from 50 m at the Black Sea entrance to 25 m at the Marmara exit. The intermediate-layer thickness varies along the SOI; it is about 12-14 m at the southern and 9 m at the northern part. Lower-layer slopes (for 30 salinity) are 1.6 and 1.4 m/km at the southern part, 0.5 m/km at the northern part. The slope may increase up to 2 m/km for the narrow passages; e.g. Kandilli. The thickness of the intermediate water between salinity values of 20 and 30 also changes along the SOI from 19 m at the South to 10 m at the North (Yüce, 1996a). The sea level difference along the SOI due to the net fresh water input to the Black Sea provides a barotropic pressure gradient, leading to the southward flow of the brackish surface waters. The opposite underflow of denser waters, on the other hand, arises due to the baroclinic pressure gradient established in response to a marked salinity difference between the adjacent basins (Bogdanova, A. K. 1963, 1965, Çeçen *et al.*, 1981; de Filippi, 1986; Büyükay, 1989; BLACK SEA PILOT 1990, Ünlüata *et al.* 1990; Latif *et al.*, 1991; Oğuz *et al.*, 1990; Yüce, 1990; Oğuz and Rozman, 1991; Özsoy *et al.*, 1993; Alpar and Yüce, 1998).

The hydrological properties of the Black Sea is determined entirely by this exchange which is the only source of deep water ventilation. Depending on the intensity of the net flow and the transient forcing conditions, the flow is controlled at a number of locations; the constricted region, the sills, and entrance regions. The constricted region of the SOI starts South of Kandilli (the narrowest part of the strait) and extends up to Çubuklu (Figure 1). Two sills located at the southern and northern entrances play an important role on these hydrological properties. The southern sill is located at the southern entrance of the SOI between Üsküdar and Kabataş (-33m). The salinity measurements in this study have shown that it does not prevent the Mediterranean water from entering into the strait. The Mediterranean water was always observed in the SOI. Further North from the southern sill, there is a narrow, elongated, continuous deep trough that can be followed approximately 6.0 km into the Black Sea (Di Iorio and Yüce, 1997). The Mediterranean underwater runs along this trough into the Black Sea except times the short-term lower-layer blockage occurs under an adverse combination of strong northerly winds and extreme sea level difference.

The northern sill has a minimum depth of 61 m, width of 575 m and length of 2525 m (Yüce, 1996a). It is the main hydraulic control for Mediterranean water into the Black Sea. Further North of this sill, there is an underwater canyon which is an extension of the deep trough along the SOI. This canyon merges with the continental shelf at approximately 80 m water depth.

Yearly water budget (total input and output) of the Black Sea is 735 km^3. The surplus of fresh water from rivers precipitation against evaporation keeps the surface layer in the Black Sea relatively fresh and leads to higher outflow (~370 km^3) through the SOI than the average amount of saline Mediterranean water (~200 km^3) that advances into the Black Sea (Ünlüata et al., 1990). The high salinity water, although warmer than the Black Sea surface layer, is more dense and it flows through the underwater canyon in the Black Sea exit. Once this canyon merges with the continental shelf, the effluent spreads, creating a delta like flow pattern. As the Mediterranean Sea water flows along the shelf, it is diluted (about 6 psu over a distance of 30 km, Di Iorio and Yüce, 1997) as a result of turbulent mixing. Then it sinks to a depth at which it finds a common density. This exchange entirely determines the hydrological properties of the Black Sea and is the only source of ventilation at depth. On the other hand, evaporation is about 3 times higher than precipitation in the Black Sea. Precipitation (725 mm per year) is maximum in December and minimum in July (Ünlüata et al., 1990). As it is seen, the most important agent affecting the water budget in the Black Sea is river inputs.

The tides along the TSS are weak (Bogdanova, 1965; Büyükay, 1989; Yüce, 1986, 1991, 1993 a,b; Yüce and Alpar, 1997; Alpar and Yüce, 1998). Low amplitude (2-10 cm) semi-diurnal tides of the Black Sea is only effective at the northern part of the SOI. Tides dissipate along the SOI and become mainly diurnal with a spring range of 2.5 cm at the south end. Hence, the tidal contribution to the flow field can be ignored.

The study area is affected by two distinct seasonal climatic regimes. During the winter, the weather is dominated by an almost continuous passage of cyclonic systems. During the summer, NE winds coming from the Black Sea, when they are a part of the seasonal N airstream, are dominant. The lack of winds blowing from land to offshore increase the effectiveness of the northerly winds. In the months scale, the dominant wind direction is NE-NW except January when SW winds are also important (De Filippi et al., 1986). When not blowing from the NE direction, winds are most often from SW. The northerly winds are dominant from May to October with a frequency of 60%, while the southerly winds (SW-SE sector) occur 20% of the time, mainly in winter months. The barometric pressure in the study area is low in Spring and Summer while it is high in Fall and Winter.

In general, onshore winds tend to raise, and offshore winds tend to lower the sea level. The range of sea level thus caused depends largely upon local wind

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conditions. At the northern approaches of the SOI, the short-term average sea-level rises up to 20 cm are due to the northerly winds. Storm surges up to 1.0 m can be observed during persistent storms (Ünlüata *et al.* 1990). The correlation between wind and sea level show dispersed relations. Their spectral properties show low signal to noise ratio, probably caused by the semidiurnal processes. Optimum fit in the least squares analysis was established at lags of approximately 0.5 and 0.75 days in the East and North directions, respectively. On the other hand, at the southern part of the SOI, the response in sea level is almost instantaneous (between 0 and 1 day) for the easterly and northerly wind influences. The easterly wind component was found to exert a dominant contribution to the sea level difference along the SOI (Andersen *et al.*, 1997).

The sea level at Fenerbahçe has a tendency to increase with southerly winds due to sea swell at the northern coasts of the SOM and it is very dominant on short time scales even though the seasonal Black Sea inflow component has also a signal on it. The main factors of the sea level difference on shorter time scales (one week) are winds and the phase lag in barometric pressure, in sequence. Easterly winds produce a dominant setdown at the southern end, whereas northerly winds produce a limited amount of setup at the northern end. The phase lag in barometric pressure at the northern and southern ends produce water level difference.

Data Acquisition

The two-layer structure of the SOI was monthly monitored between February, 1996 and January, 1997 by using conductivity, temperature and depth (CTD) profiles. Locations of monitoring stations are shown in Figure 1.

To investigate the subtidal sea level variations and MSL difference between the two seas, sea level data from Karadeniz Ereğli, Anadolukavak, Fenerbahçe and Erdek (Figure 1) have been utilised. The vertical datum planes for these sea level measurement stations are arbitrary at each of the recording sites.

Comparative meteorological data (hourly barometric pressure and wind) for Kumköy and Florya (Figure 1) were supplied by State Meteorological Services. Wind stress components were computed from the wind field from usual quadratic law using a drag coefficient of 2.5×10^{-3} which was chosen for moderate winds. This calculation provides a relative measure to quantify the effects of wind forcing. To obtain subtidal sea level variations, the original hourly-sampled data were low-pass filtered by using $A^2_{25}A_{24}/(25^2 \times 24)$ Godin (1972) tide-killing filter to remove diurnal, semi-diurnal and high-frequency fluctuations. The subtidal sea level variations and the meteorological data (barometric pressure and wind stress components) were given for the oceanographic measurement and its previous 4 days (Figure 2). This presentation is preferred because the barometric pressure influence on the sea level has some time lags (Andersen *et al*, 1997). The lag at Anadolukavak is greater that that at

Fenerbahçe. This is because of the greater scales of the Black Sea and the less efficient drainage through the SOI.

The interface between the upper and lower layers is an area of intense turbulence associated with mixing of two very different water masses, consequently, it can be traced by high contrast (its echo level is 40% of the bottom reflection, Di Iorio and Yüce, 1997) along the SOI and in the Black Sea. Seasonal variability of the 20 and 30 isohalines for 8 stations along the system is presented in Figure 3.

However, the average salinity of each layer varies along the SOI, so that a simple assumption involving the selection of particular isohaline to represent the transition between layers cause biases in the calculated averages. In order to insure a standard method of averaging at all stations, cut-off values of each layer can be calculated as the criteria given by Özsoy et al. (1986). These seasonal cut-off values for each station were defined as;

$$S_1^* = S_s + 0.2(S_b - S_s) \qquad\qquad (1)$$

$$S_2^* = S_b - 0.2(S_b - S_s) \qquad\qquad (2)$$

where S_s and S_b stand for characteristic (measured) salinity values at the surface and the bottom parts of the profiles, respectively. The depths corresponding to the salinity values of S_1^* and S_2^* were taken as the lower and upper limits of the upper and lower layers respectively. The cut-off values (dashed lines) for the upper and lower layers calculated by the criteria of Özsoy et al. (1986) were superimposed on Figure 3 (dashed lines). Upper and lower layer averages of temperature and salinity (S), on the other hand, were calculated after definition of the cut-off limits. Consequently, $S < S_1^*$ defines the Black Sea's water, $S_1^* < S < S_2^*$ the interface layer and $S_2^* < S$ the Mediterranean water.

Results

On the yearly basis the dominant wind direction is NE which does not show yearly variations. In the months scale, the dominant wind direction is again NE except January in which southwesterly winds are dominant.

For the year 1996, the annual wind speed average for Kumköy was 3.94 m/s. Considering the blowing sectors they are 6.56 m/s (NW), 5.74 m/s (S), 4.50 m/s (W), 3.71 m/s (N), 3.24 m/s (SW), 2.77 m/s (NE), 2.72 m/s (SE) and 2.31 m/s (E). On the other hand, the annual wind speed average for Florya during the observation period was 2.10 m/s. Considering the blowing sectors they are 2.73 m/s (S), 2.55 m/s (NE), 2.36 m/s (E), 2.20 m/s (W), 2.00 m/s (SW), 1.89 m/s (N), 1.65 m/s (NW) and 1.43 m/s (SE). The meteorological and oceanographic conditions measured during the cruises will be given below.

February 13th : The barometric pressure decreased from 1015 to 1008.5 mb during the cruise. It was calm at first, however the wind speed increased to 6.0 m/s, depending on the pressure drop. The wind was from South and then changed to

NE. The upper-layer temperature along the SOI and the Black Sea was very cold (about 3°C), colder than the cold intermediate layer (5.7 °C) which was placed at 55m depth (Figure 4a). The temperature contours indicate that CIL does not enter into the strait. The depths and the thickness of the interface along the SOI decreases from B2 to K0. The mean salinity of the Mediterranean water is 36.69 at B2 and 35.84 at K0 (Figure 4b).

April 04th (cruise for March) : The barometric pressure was high (1015). The northerly winds with medium strength were dominant. The upper layer was very cold but warmer than the previous month (about 3.5 °C). The temperature was 4.1 °C at K0 and 3.6 °C at B2. There was a cold layer at stations B13 and K0 with temperature less than 3 °C. The interface along the SOI get becomes thinner northwards (Figure 3). The Mediterranean water with 37.96 salinity at station B2 reaches to the Black Sea with 36.95 salinity at station K0 (Table 1).

April 24th : The barometric pressure was rather high (1022 mb). The wind from NE with a low speed were dominant. The upper-layer temperature was colder than 7 °C along the SOI. The interface was very thick and deeper. Its thickness was 13m at B2 and 4m at K0 (Figure 5). The mean salinity values of the lower layer were 37.5 and 36.9 at stations B2 and K0, respectively (Figure 4).

May 30th : The barometric pressure was around 1001 mb. The winds were from NNE with average speeds of 0.8-1.7 m/s. During cruise the barometric pressure and wind speed were increased to 1004.5 mb and 3.6 m/s respectively. The upper layer was heated and increased above 10 °C in this month. There was a cold water layer just above the lower layer in the Black Sea (K1) and SOM. At stations B2 and B7, it decreases 9.1 °C due to mixing between upper layer and this cold layer. The salinity of the Mediterranean water was 37.36 and interface thickness was 8 m at B2 (Figure 4b and 5). The Mediterranean water extents to the Black Sea with 35.83 salinity and interface thickness drops to 4 m.

June 25th : The barometric pressure was 1010.9 mb and the wind was from NNE with average speed of 2.9 m/s. The temperature spatiality show two layers in the upper layer; the warm upper layer and the CIL. The thickness of the interface layer was rather thick (15 m) at B2 and decreased to 4 m at K0 (Figure 5). The mean salinity of the lower layer was 35.18 at B2 and 34.42 at K0.

July 15th : Before and during the cruise, the mean daily barometric pressure was between 1007.1 and 1010.2 mb. The wind was from NNE with average speed 3.8-5.4 m/s. The temperature of the upper layer is also high in July. A cold interface layer was placed in the upper layer with an increasing temperature from K0 to B13. However, this cold layer could not be observed as a different layer at stations B2 and B13 since its temperature was higher than that of lower layer. The salinity of the Mediterranean water decreased from 37.29 at B2 to 35.33 at K0 (Figure 4a). The high input of Black Sea water driven by the northerly winds into the SOI

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possibly caused this difference (1.96). The thickness of the interface layer decreases from the southern entrance (8 m) to the northern exit (4 m) (Figure 5).

August 26th : During the cruise, the barometric pressure was increased and reached to 1016 mb. Northerly winds with average speed of 11 m/s were dominant. The CIL was observed in the Black Sea (K1 and K2). The thickness of the interface layer is 14 at B2 and 2 m at K0 (Figure 5).

September 24th : There was an upper-layer blockage. The barometric pressure was 1001 mb and the easterly winds with speeds of 1.2-2.8 m/s were dominant. The water of the SOM in the upper layer was observed at stations B2 and B7. This was caused by the winds blowing from SW (Figure 2). The Mediterranean water enters the SOI from the SOM with salinity 37.96 (27 m depth at B2). The thickness of the interface layer was 2 m at the same station (Figure 5). At K0 where the salinity of the lower layer was 35.35, a reduction of 2.6 over a 30 km path, the interface layer was placed between the depths of 47 and 49 m. The sudden drop of the salinity at B13 (Figure 4b), indicates high mixture. Even the subtidal sea level difference between Anadolukavak and Fenerbahçe was steady, the difference between Karadeniz Ereğli and Erdek rapidly decreased more than 50 cms in 5 days (Figure 2).

October-24th :The barometric pressure, which was 1008 mb before the cruise, increased to 1017 mb during measurements. Mild winds was from ENE and NNE. There was little temperature difference between homogeneous upper and lower layers. The intermediate layer was thin, 4 m at B2 and 3m at K0 (Figure 5). The average salinity of lower layer decreases from B2 to K0 (Figure 4) because of mixing processes.

November 27th : The barometric pressure increased from 1000 to 1006 mb during cruise. Southerly winds (8-10 m/s) were dominant. There was an upper-layer blockage. Surface salinity values are 17.8, 19.4 and 23.1 at stations K0, B13 and B7, respectively. The upper layer of the SOM entered into the SOI. CIL can be observed at stations K1 and K2, but not at station K0 and along the SOI. The thickness values of the interface layer are 4, 18 and 9 metres at stations B2, B13 and K0. respectively (Figure 5). Since the interface layer is rather thick at the northern end of the SOI, the salinity of the lower layer decreases from B2 to K0 (about 2.7). This is because the interface layer is rather thickened at the northern part of the SOI.

December 17th : The barometric pressure was around 1024 mb during the cruise and mild and easterly winds were dominant. The upper layer was rather homogeneous, without any cold layer, and its temperature decreases northwards (Figure 4a). The salinity of the lower layer is 37.38 at B2 and 35.70 at K0 (Figure 4b). The thickness of the intermediate layer is about 6 metres at stations B2 and K0 (Figure 5).
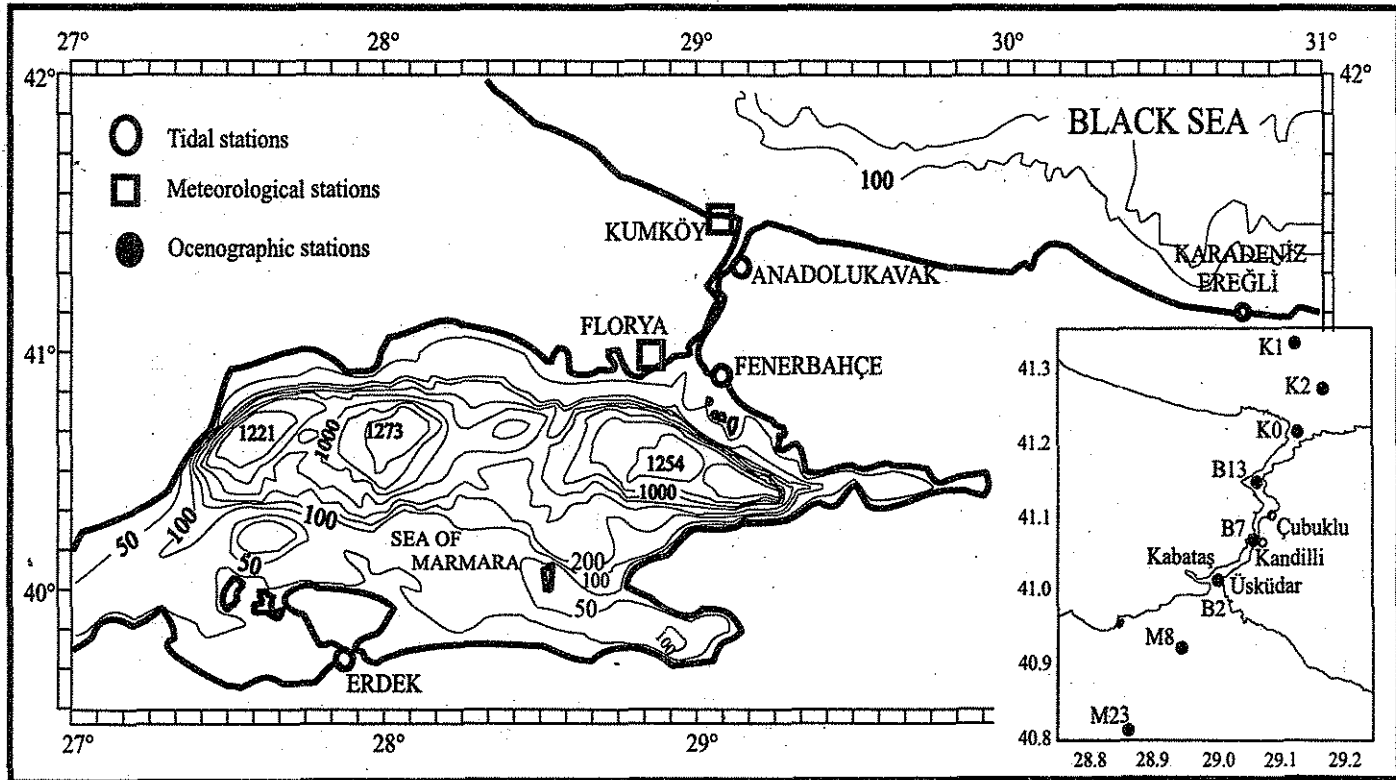
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Figure 1. Map showing the location of tide gauges, meteorological stations and where *RV Arar* was stationed for CTD measurements.
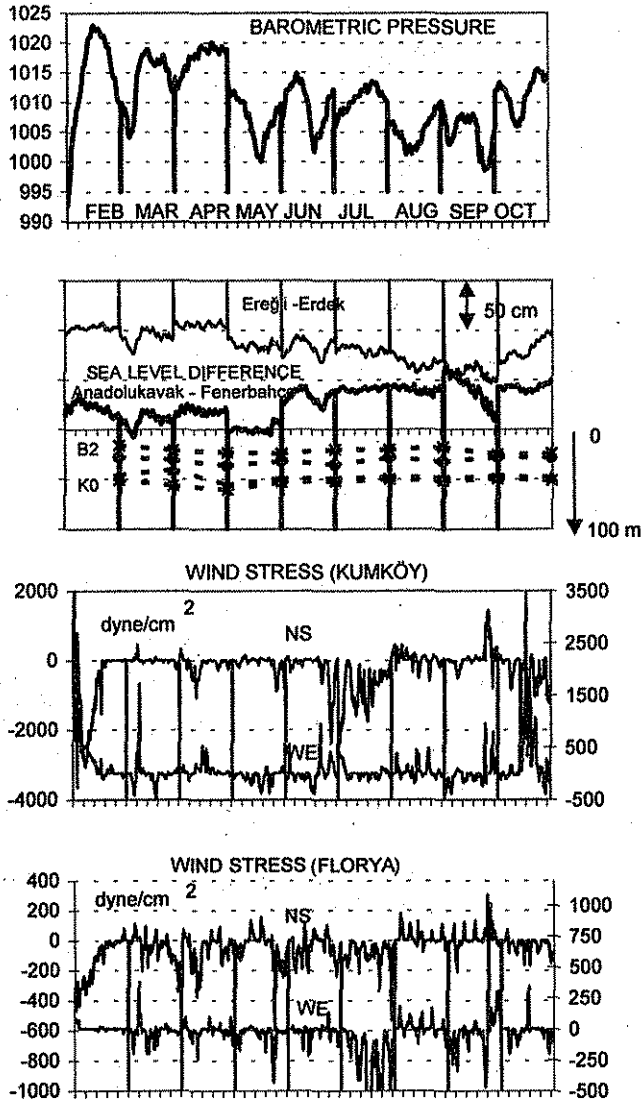
Figure 2. Comparative meteorological data when the sea level data was available. Each block represents the measurement and previous 4 days. The depth of the interface layer for the stations K0 and B2, which will be given in detail in Fig. 5, were also plotted below the sea level data for comparison purposes.
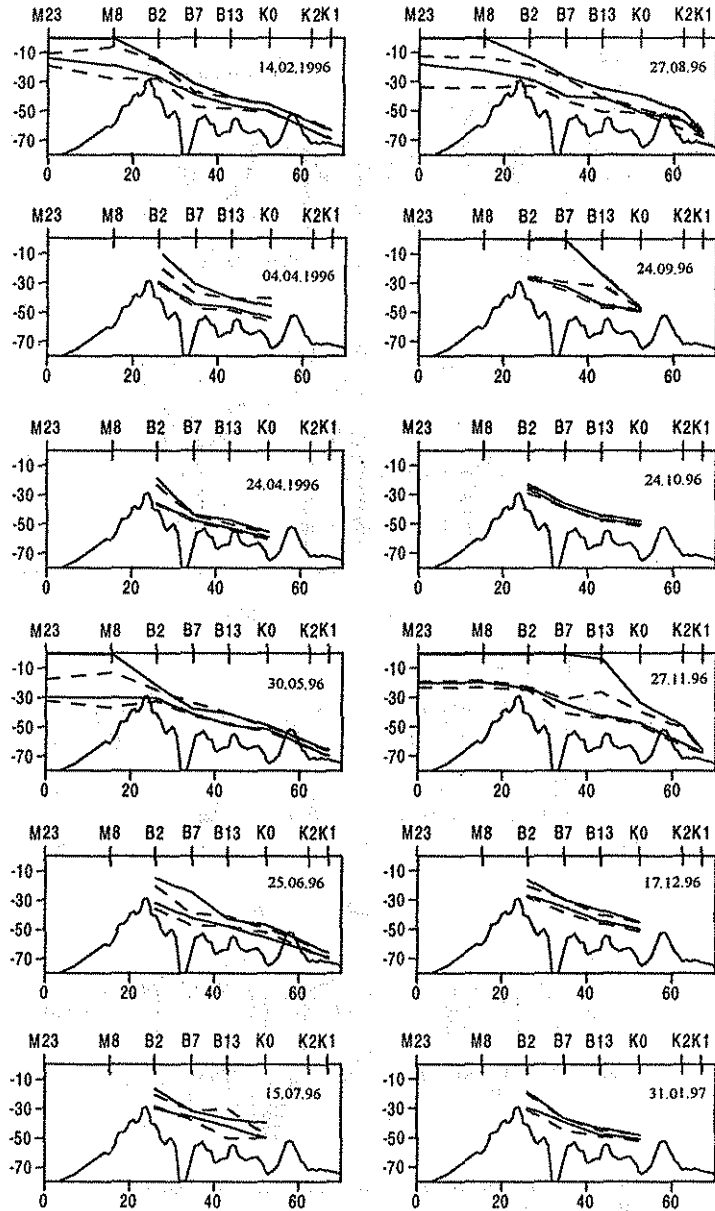
Figure 3. Seasonal variations of the interface layer depth based on the salinity values of 20 and 30 psu. The cut-off values (dashed lines) for the upper and lower layers calculated by the criteria of Özsoy et al. (1986) were also superimposed.
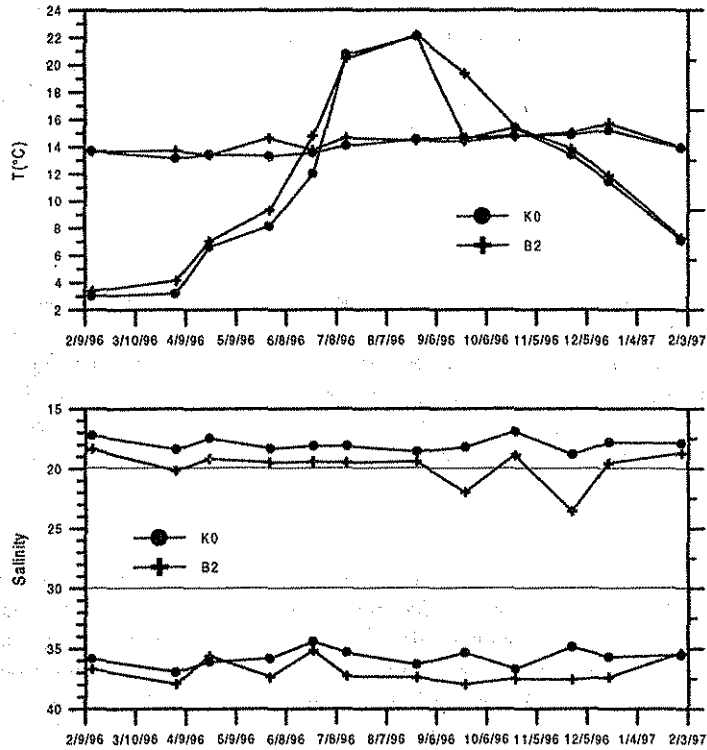
Figure 4.Time series of the average temperature and salinity
values for the upper and lower layers calculated from the
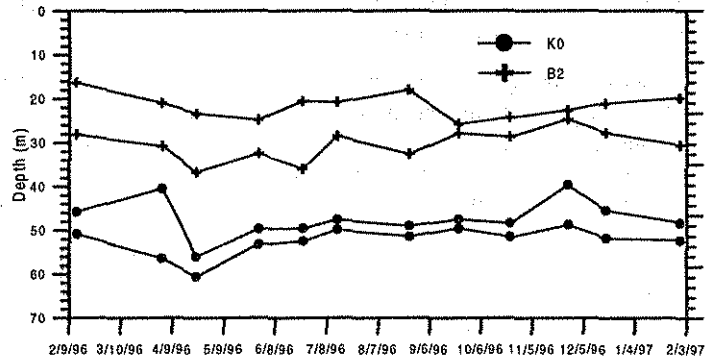criteria given by Özsoy et al. (1986).

Figure 5. Time series of the depth variations of the
interface layer for stations K0 and B2 calculated from
the criteria given by Özsoy et al. (1986).

January 31st 1997 : The barometric pressure decreased from 1028 to 1023 mb during cruise. Southerly winds (6-8 m/s) were dominant. The temperature of the homogeneous upper layer decreases northward (Figure 4a). The salinity of the lower layer is 35.38 at B2 and 35.54 at K0 (Figure 4b). The higher salinity at K0 was possibly caused by the high thickness of the lower layer calculated by Eq. (2), which was 20 m at K0 while it was only 10 m at B2.

Conclusion

Temperature

The upper layer temperature is lowest at K0 for all seasons and rises rapidly within the SOI. Between December and June, the upper layer is colder than the lower layer (Figure 4a). At station B2, the upper layer warmed up rapidly by mixing with the underlying water during the cruises between December and May. On the other hand, in late Summer and early Fall, the colder lower layer water is rapidly entrained into the upper layer. Lower layer temperature along the SOI varies between 12.98 (B7 in May) and 15.71 °C (B2 in December).

Salinity

The average salinity values of the Black Sea and Mediterranean waters which are effective on the SOI are 17 and 38, respectively (Figure 4b). The seasonal variability of the lower-layer properties along the SOI occurs within the salinity ranges of 34.4-38.0 depending on the intensity of local vertical mixing processes along the interface layer. During Spring and early Summer, when the water input from the Black Sea was high, the salinity difference between stations B2 and K0 was found high. This is because, as stated by Yüce (1996b), the mixture between two layers decreases when the current speed increases.

High saline Mediterranean layer extending as a salt wedge toward the Black Sea was observed in the lower layer throughout the entire length of the SOI in all surveys (Figure 3). Its depth varies along the SOI and tapers off northwards.

The salinity values of upper layer are more uniform for K0 (Figure 4b). The short-term salinity increments in the upper layer in September and November 1996 can be explained by the dramatic transient mixing events in the SOI caused by strong southerly winds. The salinity increment of the upper layer towards south is due to the vertical mixing processes along the SOI. The highest salinities occurred during the end of Winter. Storm surges may dominate the flow particularly in winter, giving rise to substantial modification of the regional flow structure. In June, the salinity of lower layer at B2 and K0 decreased as a result of decreasing Mediterranean inflow.

Interface

Slopes and spatial variations of the thickness of interface layer indicate that the underflow proceeds northward in a progressively thinner layer towards the Black

Sea and controlled over the northern sill (Figure 3). They show the absence of controlled lower-layer flow at the southern sill. Contrary to sea level slope, the interface slope varies along the SOI. Higher slopes are observed (2.9 and 1.2 m/km) between B2 and B7 (southern part). Smaller slope (0.4-0.9 m/km) between stations B13 and K0 (northern part) is observed. During upper-layer blockages these values increase. Intermediate layer has a varying thickness of 12-14 m at the South and 2-6 m in the northern part. These results are consistent with previous findings of Büyüközden *et al.*, 1985; Yüce, 1990; Ünlüata *et al.* (1990); Latif *et al.* (1991) and two-layer model results of Oğuz *et al.* (1990).

Table 1. The mean sea level slopes (cm/km) between Anadolukavak and Fenerbahçe and between Karadeniz Ereğli and Erdek. The interface slopes (m/km) of upper and lower layers. Their average and standard deviations.

Measurement Dates	AKA-FEN (cm/km)	ERE-ERD (cm/km)	[20 psu]				[30 psu]			
			B2/ B7	B7/ B13	B13/ K0	B2/ K0	B2/ B7	B7/ B13	B13 /K0	B2/ K0
February 13th	1.88	1.32	1.88	1.47	0.58	1.16	1.46	1.22	0.48	0.90
April 4th	1.80	1.24	2.29	1.71	0.60	1.33	1.79	1.02	0.78	0.94
April 24th	2.00	1.36	2.90	1.67	0.91	1.41	1.39	1.01	0.68	0.89
May 30th	1.60	1.15	1.89	1.13	0.91	1.05	1.24	1.06	0.33	0.81
June 25th	2.70	1.22	1.15	1.63	0.44	1.22	1.21	0.93	0.88	0.91
July 15th	2.77	1.09	1.74	1.18	0.33	0.89	0.69	0.70	0.88	0.76
August 26th	2.70	0.99	1.59	1.28	0.55	1.03	1.38	0.76	1.10	0.88
September 24th	1.97	0.70	-	1.37	2.55	1.78	0.62	1.06	0.42	0.84
October 24th	2.88	1.26	1.54	1.24	0.43	0.96	1.47	1.22	0.35	0.92
November 27th	1.87	-	-	0.17	3.24	1.24	1.23	1.09	0.55	0.90
December 17th	-	-	1.61	1.22	0.91	1.11	0.92	1.00	0.66	0.88
January 31st 97	-	-	2.10	1.45	0.52	1.13	1.10	1.06	0.34	0.81
Average	2.22	1.15	1.86	1.29	0.99	1.19	1.21	1.00	0.62	0.87
St. Dev.	0.46	0.19	0.48	0.40	0.91	0.23	0.33	0.15	0.25	0.05

The seasonal variability of the interface layer depth along the SOI (Figure 3 and 5) demonstrates that the upper layer has considerable seasonal variations together with additional shorter term changes in response to local sea level difference and meteorological forcing. The upper layer deepens occasionally during the periods of increased surface inflow caused by strong northerly winds in winter months (see, Figure 3 for January, February, March, April, May and December). In the opposite case, the upper layer structure is lost due to short term effects of southerly winds (see Figure 3 for September and November).

The slopes of upper and lower layers between the specific stations are presented in Table 1. When the Black Sea input is low (September - December) and the southerly winds are dominant, the slope of the interface layer increases. The

slope of the interface layer decreases during the periods of maximum surface inflow from the Black Sea (in Spring and early Summer). Hence, the lower layer can hardly reach the Black Sea and mainly forced to mix with the upper layer. Consequently, the sea level difference between the two seas plays an important role in controlling the upper and lower flow. When the difference is high, the lower-layer blocking may occur. The asymmetry observed in the interface slopes reflects the influence of hydraulic controls along the SOI and adjacent seas.

The sea level differences of Anadolukavak-Fenerbahçe and Karadeniz Ereğli-Erdek (Figure 2) during the oceanographic measurements were compared with the variation of the interface layer (Table 1). In 1996, the seasonal MSL difference in the Black Sea was as high as 30 cm; with a seasonal rise between March and August and fall for the rest of the year depending on the regime of river input to the Black Sea. This result is consistent with the computation of Yüce (1993b, see figure 8) for the average (1962-1973) fluctuations of the mean monthly water level at Samsun. The sea level difference between Anadolukavak and Fenerbahçe was maximum in July. The wind and low barometric pressure were in phase in late Summer and Fall, causing an increment in sea level difference between Anadolukavak and Fenerbahçe. During upper layer blockages occurred in September and November, the northward slope of the interface layer increased and the southward slope of the sea level difference decreased.

The main results obtained in this study have generally compiled with theory. According to the theory: the sea levels depend strongly on especially the northerly wind components, as well as seasonal variations in river runoff to the Black Sea. Provided a sufficient barotrophic forcing, the blocking of either the upper of lower layer may arise. The sea level difference equivalent to blocking of lower layer is given at about 45 to 50 cm, whereas the upper-layer flow is blocked at a difference below 10 cm (Sümer and Bakioğlu, 1981; Oğuz et al., 1990; Akyarlı and Arısoy, 1995). It is believed that the blocking events are not regular but occur only during periods of extreme southerly or northerly winds (Ünlüata et al., 1990; Akyarlı and Arısoy, 1995). The modelling studies indicated a lower-layer blocking frequency of 13% (Andersen et al., 1997).

A detailed quantitative description of the internal hydraulic characteristics of the SOI remains to be explored by future computational and observational studies which require current velocity profiles of sufficient resolution and duration, in addition to the closely spaced CTD casts.

Özet

İlgi çekici iç hidrolik karakteristikleri ile İstanbul Boğazı önemli zaman ve mekan değişiklikleri olan karmaşık bir akış sistemi sergiler. Alt ve üst tabakalar arasındaki geçiş tabakasının mevsimsel ve daha uzun süreli değişkenlikleri Marmara ve Karadeniz'de iklimsel değişikliklere göre oluşan şartlara bağlıdır. Diğer taraftan, daha yüksek frekanslı değişimler atmosferik güdümleme ile ilişkilidir. Özellikle kış

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aylarında görülen fırtına dalgaları gibi birkaç günlük değişimler akışa galebedir ve bölgedeki akış sisteminde önemli değişimlere neden olurlar. Bu gibi değişimler alt veya üst su blokajına neden olabilirler.

Bu çalışmada Şubat 1996 ve Ocak 1997 tarihleri arasında İstanbul Boğazı boyunca ve giriş bölgelerinde aylık olarak yapılan oşinografik ve meteorolojik ölçmelerden yararlanılarak, üst Karadeniz suyu ile altındaki Akdeniz suyu araştırılmıştır. İstanbul Boğazı boyunca yer alan akış sisteminin ara tabakasının mevsimsel değişimleri ile bunların komşu denizler arasındaki ortalama deniz düzeyi değişimleri ve atmosferik güdümleme ile olan ilişkileri araştırılmıştır.

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