Abstract: The Bosphorus is oceanographically very complicated two layer stratified strait where denser water from the Marmara Sea flows towards North under the lighter water which is frequently flowing from the Black Sea towards South. The water level difference between both ends of the Bosphorus varies seasonally within the range of -0.2 and 0.6m. The seasonal variability depends mainly on the water level changes in the adjacent basins related to the hydrological cycle, short term changes in the atmospheric pressure and the wind characteristics. These variations together with the depth and alignment of the cross section along the strait dominate the spatial and temporal variations and sometimes sharp changes in the flow pattern in three dimensions. Although these hydrodynamic conditions are critical for all marine and hydraulic works along the Bosphorus, there was not continuous long term measurement for a sufficient time span in the strait for detailed evaluation of the current climate. An extensive site surveying work including current, wind, pressure and water level measurements was carried out between September 2004 and January 2006 in relation to the design and construction requirements of the Bosphorus Tube Crossing Project. In this study, the characteristics of stratified flow in the Bosphorus Strait and their relation to local and regional, short and long term changes in the meteorological parameters are studied by using the measurement data and the results are discussed with comparatively.
Responses of the Stratified Flows to their Driving Conditions-
A Field Study
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Abstract

The Bosphorus is oceanographically very complicated two layer stratified strait where denser water from the Marmara Sea flows towards North under the lighter water which is frequently flowing from the Black Sea towards South. The water level difference between both ends of the Bosphorus varies seasonally within the range of -0.2 and 0.6m. The seasonal variability depends mainly on the water level changes in the adjacent basins related to the hydrological cycle, short term changes in the atmospheric pressure and the wind characteristics. These variations together with the depth and alignment of the cross section along the strait dominate the spatial and temporal variations and sometimes sharp changes in the flow pattern in three dimensions. Although these hydrodynamic conditions are critical for all marine and hydraulic works along the Bosphorus, there was not continuous long term measurement for a sufficient time span in the strait for detailed evaluation of the current climate. An extensive site surveying work including current, wind, pressure and water level measurements was carried out between September 2004 and January 2006 in relation to the design and construction requirements of the Bosphorus Tube Crossing Project. In this study, the characteristics of stratified flow in the Bosphorus Strait and their relation to local and regional, short and long term changes in the meteorological parameters are studied by using the measurement data and the results are discussed with comparatively.

Key Words; Stratified flows, density currents, strait flows, the Bosphorus, current climate.
Introduction

Fluid motions in a gravitational field which are originated or influenced by variations in density within the fluid or by differences in density of the fluids involved are referred to as inhomogeneous flows or density currents or stratified flows. Differences in density may result from the following factors, (i) differences in salt content $\Delta \rho / \rho$ (i.e. the ratio of the difference in density over the mean density of the fluids involved) is smaller than a few percent, (ii) by differences in temperature $\Delta \rho / \rho$ is smaller than a few per mille, (iii) difference in concentration of solid matter.

Stratified flow is described as a body of water existing out of two fluids of different densities separated by a distinct interface (Figure 1). Bottom shear, interfacial shear and water depth, and difference in density due to pressure must be taken into account for the equation of motion. Furthermore propagation of discontinuities must be considered.

![Figure 1 Schematic presentations of stratified flow.](image)

A proper understanding of the flow dynamics of sea-straits (Bosphorus or Gibraltar) has gained considerable importance because of navigation, environmental pollution, waste water discharge, underwater constructions and fishing concerns.

The Bosphorus is a strait connecting the Marmara and the Black Seas (Figure 2 (a)). Its width varies from 0.7 to 3.5 kilometers, with an average of 1.3 km. The water depth varies between of 30 m and 100 m. The current scheme in the Bosphorus generally presents a stratified two-layer system, with upper layer current flowing toward the Marmara Sea (southward) and the underlying one is toward the Black Sea (northward). Thicknesses and velocities of both layers display noticeable changes in time across the entire depth. These
overall flow directions have differences due to the shape of the strait and changes in the sectional areas.

This stratified structure is largely controlled by two predominant mechanisms, namely the density and the water level difference between the Marmara Sea and the Black Sea. Özsoy et al. (1988 and 1998) indicated that the Black Sea has a higher water level than the Marmara Sea (difference varies from -20 to 40 cm), and this results in an upper layer current. The reason of the lower current layer is the salinity difference between the two seas and a turbulent interface separates the two currents from each other. The thickness of the interface is around 10 meters at the entrance of Marmara Sea and 2 m that of the Black Sea (Guler et al., 2006).

Flow measurements showed large short and long-term variability in the Bosphorus Strait in the previous studies. Short term effects are mainly due to wind effects, atmospheric pressure differences and tide. Long term effects are mainly Danube, Dnieper and Dniester rivers discharges into the Black Sea (Figure 2 (b)). The net freshwater influx into the Black Sea, atmospheric pressure differences and wind setup are the forcing mechanisms in the Bosphorus Strait (Özsoy et al., 1996).

The Black Sea is a landlocked basin, with around 300 km$^3$/year precipitation and runoff around 350 km$^3$/year exceeding evaporation around 350 km$^3$/year; the excess is balanced by a net outflow of 300 km$^3$/year through the Bosphorus (Ünlüata et al., 1990 and Özsoy et al., 1996). Freshwater inflow into the Black Sea displays large seasonal and inter-annual natural variability (Sur et al., 1994, Özsoy et al., 1996). A significant correlation exists between the Danube influx and sea-level, even at annual time scales (Sur et al., 1994, Özsoy et al., 1995, Özsoy et al., 1996).

Stanev and Penava (2002) investigated the Black Sea water level variations in the global forcing. They analyzed the correlation between sea level and water balance in the last 70 years. They obtained a good correlation between the water level and the long term changes of water balance in the Black Sea.
(a) Aerial views of the Bosphorus

(b) The locations of Danube, Dniester and Dnieper

Figure 2
The Danube River is the greatest contributor of river run-off into the Black Sea. The total discharge of the Dniester and Dnieper rivers is about a third that of Danube, and the total discharge of the remaining rivers accounts for a small fraction (<1/5) of the total river run-off (Sur et al., 1994).

Sur et al. (1994) reviewed the effects of river discharges on the Bosphorus Strait using some major investigations reached the following conclusions;

1-The annual mean discharge of the Danube indicates large natural fluctuations within the range of 4000-9000 m$^3$/s. In addition to these inter-annual variations, seasonal changes of about ±30% of the annual mean occur in the discharge. Therefore the variations between the minimum and maximum seasonal discharges can be up to threefold.

2-The annual Danube influx is well correlated with the Black Sea basin sea-level on seasonal and inter-annual time-scales. The net freshwater inflow results affect the long term mean sea level in the Bosphorus.

3- The salinity decrease measured at Constanza (downstream of the Danube) is also closely correlated with the Danube discharge on the seasonal and inter-annual time scales. The Danube water usually flows cyclonically (to South) around Black Sea basin, except during strong South-Western storms that push its waters back into the northwest shelf.

4-The measurements in the Bosphorus indicate minimum salinity at different periods of each year. Although minimum salinity is observed as early as March-April, the more predominant minimum salinity is observed during summer, from June till September. This is attributed to the mean travel time of 1-2 months between the Danube and the Bosphorus assuming a mean current speed of 0.10-0.20 m/s for a distance of about 500 km.

Penava et al. (2001) studied the seasonal variability of the Bosphorus. They analyzed the response of the Black Sea to the water flux due to the river runoff, precipitation and evaporation. They found that the maximum transport of water was in March-April and the minimum was in August.

The width and the depth of the Bosphorus vary along its entire length. At each end there is a threshold that largely affects the characteristics of the current. One of these thresholds is
within the Bosphorus close to the Marmara Sea at depth that varies between 28 and 35 m, causing channel flows at each side. The sill is 34 m deep where it blocks a 40 m deep channel along the coastline of Üsküdar at the Anatolian side. This channel continues southward beyond this sill and joins a submarine canyon where the Bosphorus reaches the Marmara Sea gradually deepening beyond this point. The other sill is at a depth of 60 m, has a length of around 2 km some 3-4 km north of the Black Sea entrance and extends like a narrow channel reminiscent of a natural extension of the Bosphorus into the Black Sea (Özsoy et al., 1988 and 1989). Similar sill effects existed in the Strait of Gibraltar. It was extensively studied by Wesson and Gregg (1994).

At both sides of the Bosphorus, between Emirgân and Kanlıca to the north and between Arnâvûtköy and Vaniköy to the south, there are small bays and contraction areas. The current velocities increase in the latter and the surface current can reach a speed of 2 m/s (Özsoy et al., 1988). The creation of secondary and eddy currents are caused by a combination of the meandering of the Bosphorus, the change that the adjacent bays cause, density differences along the way, the complicated hydraulic situation caused by exchanges of mass between layers and unpredictable effects of winds (Guler et al, 2006).

The average salinity of the top layer is 18 ppt at the exit from the Black Sea. This value gradually increases and reaches 23 to 25 ppt at the entrance of the Marmara Sea. For a lower layer, the average salinity is 38 ppt in the Marmara Sea at the southern end of the Bosphorus, dropping to 33 ppt at the northern sill (Oğuz et al., 1990).

Oğuz (2005) reported a three dimensional model to describe the internal hydraulic characteristics of the Bosphorus flow. He concluded that the upper and lower layers flowed from the strait at both ends with current velocity of 1.0 m/s at layer depths of 10 m.

Previous studies did not provide sufficient data to develop a flow structure in the Bosphorus. In this study, long term continuous current velocity measurements and also meteorological surveys were carried out for 15 months. Data from these surveys were used in an attempt to explain current climate of the measurement stations of the Bosphorus and investigate the short term effects on the current system.
Site Surveying

A comprehensive environmental monitoring system was installed in the Bosphorus to measure the current speed, wind, water level, atmospheric pressure, temperature and salinity. The measurement program has been carried out by TAISEI Corporation Japan on behalf of the General Directorate of Marmaray Project of Ministry of Transportation, General Directorate of Ports, Airports and Railways Construction of Turkey (GDM). A list of measurement stations are given in Table 1. The locations of the measurement stations are also shown in Figure 3. Current was measured by ADCP and its specifications are given in Table 2. The ADCP device consisted of ADCP instrument, steel frame and concrete block, and it was carefully lowered by a crane on a vessel and located on the sea bottom. Water salinity was measured at the stations K₀ and M₈ by ISKI (2004 and 2005).

<table>
<thead>
<tr>
<th>Stations</th>
<th>Measurement Period</th>
<th>Measured characteristics</th>
<th>Measuring interval</th>
<th>Locations</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. A</td>
<td>24.09.04 – 03.01.06</td>
<td>Current speed, directions (ADCP)</td>
<td>hour</td>
<td>41° 05’ 26.7” N 28° 59’ 20.9” E</td>
<td></td>
</tr>
<tr>
<td>St. B</td>
<td>24.09.04 – 03.01.06</td>
<td>Current speed, directions (ADCP)</td>
<td>hour</td>
<td>41° 00’ 52.4” N 28° 59’ 53.6” E</td>
<td>There is no measurement between 13.11-04.12.04</td>
</tr>
<tr>
<td>St. C</td>
<td>24.09.04 – 03.01.06</td>
<td>Current speed, directions (ADCP)</td>
<td>hour</td>
<td>41° 01’ 35.1” N 29° 00’ 30.1” E</td>
<td></td>
</tr>
<tr>
<td>St. D</td>
<td>25.09.04 – 05.01.06</td>
<td>Water level</td>
<td>hour</td>
<td>41° 01’ 31.4” N 29° 00’ 30.3” E</td>
<td></td>
</tr>
<tr>
<td>St. E</td>
<td>22.09.04 – 05.01.06</td>
<td>Water level</td>
<td>hour</td>
<td>41° 12’ 13” N 29° 05’ 54” E</td>
<td></td>
</tr>
<tr>
<td>St. F</td>
<td>18.11.04 – 04.01.06</td>
<td>Wind speed, directions, air pressure</td>
<td>10 minutes</td>
<td>41° 00’ 32.2” N 29° 00’ 07.2” E</td>
<td></td>
</tr>
<tr>
<td>St. G</td>
<td>19.11.04 – 05.01.06</td>
<td>Wind speed, directions, air pressure</td>
<td>10 minutes</td>
<td>41°24” N 29°6’ E</td>
<td></td>
</tr>
<tr>
<td>St. K₀</td>
<td>09.04 – 09.05</td>
<td>Salinity</td>
<td>monthly</td>
<td>41°13.50’N 29°08.00’E</td>
<td>ISKI(2004 and 2005)</td>
</tr>
<tr>
<td>St. M₈</td>
<td>09.04 – 09.05</td>
<td>Salinity</td>
<td>monthly</td>
<td>40°56.40’N 28°55.66’E</td>
<td>ISKI(2004 and 2005)</td>
</tr>
</tbody>
</table>
Water level was continuously measured by a wave gage sensor to determine the water level difference between the stations D and E in the Strait. Weather stations (stations F and G) were installed to monitor wind speed, wind direction and atmospheric pressure at both ends of the Strait. These wind sensors measured average wind direction, average and maximum wind speed in a sampling interval. The accuracies were less than ±5° for the wind direction (Aanderaa 3590) sensor and ±2% or ±0.2m/s for wind speed sensor (Aanderaa 2740). The accuracy was ±0.2hpa for the air pressure sensor (Aanderaa 2810). The weather station G was intended to monitor the northern wind while the weather station F was for the southern wind. The environmental monitoring system was part of the immersed tube construction project between Asian and European parts of Istanbul. The monitoring process lasted long enough for the continuous measurements.

**Current Environment**

Current measurements were carried out for 15 months at three different stations close to the entrance of the Marmara Sea. A time history of the current speed measurements at different depths at the station B is shown in Figure 4. The southern velocities are indicated negative while the northerns are positive. The velocities varied between -2.5 m/s and 1.5 m/s. Maximum velocities were observed at the surface (-1 m depth). In general, the current

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### Table 2 Recording Doppler Current Profiler (ADCP)

<table>
<thead>
<tr>
<th>Current Profiler (Aanderaa Recording Doppler Current Profiler)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Acoustic centre frequency</strong></td>
<td>600 kHz</td>
</tr>
<tr>
<td><strong>Number of beams</strong></td>
<td>4 beams</td>
</tr>
<tr>
<td><strong>Processing</strong></td>
<td>ARMA parametric model</td>
</tr>
<tr>
<td><strong>Speed Range</strong></td>
<td>0-500 cm/s</td>
</tr>
<tr>
<td><strong>Horizontal Accuracy</strong></td>
<td>0.5 cm/s</td>
</tr>
<tr>
<td><strong>Vertical Accuracy</strong></td>
<td>1.0 cm/s</td>
</tr>
<tr>
<td><strong>Single ping statistic noise</strong></td>
<td>4.0 cm/s</td>
</tr>
<tr>
<td><strong>Cell size</strong></td>
<td>2 m</td>
</tr>
<tr>
<td><strong>Cell overlap</strong></td>
<td>50%</td>
</tr>
<tr>
<td><strong>Parameters measured</strong></td>
<td>Horizontal speed, vertical speed, single-ping std, signal strength, ping count, pulse attenuation, Heading, Pitch and Roll</td>
</tr>
</tbody>
</table>

**Compass and Tilt Sensor**

| Heading Accuracy                                            | ±4° |
| Tilt Accuracy                                               | ±1.5° |
speed of the upper layer decreases along the depth till the interface between upper and lower layer. Then it increases till the bottom in the opposite direction. A typical current speed variation by depth is shown in Figure 5. Four different vertical current velocity profile patterns were observed from the measurements at the station B. One layer flow pattern in the southern and the northern directions were monitored 31% and 2.2% respectively and 1.5% of the year the flow pattern was three-layer for the measured period. The current structure was two-layer at the rest of the measurement year (65.3%).

Figure 3 Measurement Stations (GDM)
Figure 4 The time history of northern and southern current speeds at station B
During 15 months survey water level variations were obtained at the stations E and D. The time history of the water level differences ($\Delta h$) between station E (at the entrance of the Black Sea) and station D (at the entrance of the Marmara Sea) are shown in Figure 6.

Figure 5 Two layer flow pattern, 23.01.2005, 10:01 (left hand side is Marmara Sea side and right hand side is Black sea side)
During the monitoring process -0.2 m and 0.6 m water level change around the reference level were observed. The water level at the Black Sea mostly was higher than that of the Marmara Sea. The difference of the water level has four main components. These are due to (i) wind set up \((\Delta h_w)\), (ii) meteorological atmospheric pressure \((\Delta h_p)\), (iii) tide \((\Delta h_t)\) and (iv) long term hydrological changes (river discharges) \((\Delta h_r)\). The first three water level changes are due to short term effects but the last one is due to long term effects which represent the seasonal variations. Figure 6 shows that the fluctuation of the water level difference started to increase from October 2004 to April 2005 since the meteorological conditions were more severe, and it was more stable between April 2005 and October 2005. A similar response was observed for the current speed at the station B.

Figure 6 Water level differences between the Black Sea and the Marmara Sea.
The Effect of the Extreme Weather Conditions

(i) One layer current case from the Black Sea to the Marmara Sea in the southern direction

The extreme weather conditions (i.e. storms) also caused the one layer current in the Bosphorus from the Black Sea to the Sea of Marmara as a whole one layer flow in the southern direction or vice a versa. Figure 7 shows a typical current profile for one directional flow. The speeds of the southern upper layer flow from the Black Sea to the Sea of Marmara exceeded 2 m/s and reached 2.5 m/s at 1m depth below the water surface for the extreme conditions during the monitoring process.

As seen from Figure 8, the speed of the northern wind increased and reached 14.94 m/s and 14.17 m/s at stations G and F respectively (Table 3). The storm duration was almost 98 hours. The wind direction was around NE direction during the storm (Figure 9). As seen water level measurements in Figure 10 that the water level difference was 0.5 m between the Black Sea and the Sea of Marmara during this extreme meteorological condition. The maximum current speed below water surface (at -1m depth) was 2.51 m/s at the station B. The current profile shown in Figure 7 was occurred during this storm. The observations showed that the sudden changes of the water level were due to extreme meteorological conditions. The strong northern storms caused wind set up at the entrance of the Black Sea but it caused set down at the Sea of Marmara.

Figure 7 One layer flow pattern in S direction, 16.01.2005, 20:01 at station B (Left is the Marmara Sea side and Right is the Black Sea side)
Figure 8 Wind speed variation at stations F and G; during the storm between 14.01.2005 and 18.01.2005

Figure 9 Wind directions at stations F and G; between 14.01.2005 and 18.01.2005
(Directions increase in clockwise starting from North as 0°)
Figure 10 Water level differences between the Black Sea and the Marmara Sea; between 14.01.2005 and 18.01.2005

Table 3 Wind storm between 14.01.2005 and 18.01.2005

<table>
<thead>
<tr>
<th>Station</th>
<th>Beginning of the storm</th>
<th>End of the storm</th>
<th>Duration of the storm (hours)</th>
<th>Effective direction</th>
<th>Maximum wind velocity (m/s)</th>
<th>Occurrence of time</th>
<th>Beaufort scale (wind)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>14.01.05 12:00</td>
<td>18.01.05 14:24</td>
<td>98</td>
<td>NE</td>
<td>14.17</td>
<td>16.01.05 20:45</td>
<td>6-7</td>
</tr>
<tr>
<td>G</td>
<td>14.01.05 12:00</td>
<td>18.01.05 14:24</td>
<td>98</td>
<td>NE</td>
<td>14.94</td>
<td>16.01.05 20:05</td>
<td>6-7</td>
</tr>
</tbody>
</table>

(ii) One layer current case from the Marmara Sea to the Black Sea in the northern direction

The current rarely flowed in the northern direction under the extreme meteorological conditions during the surveying period. The speed of the northern one layer flow from the Sea of Marmara to the Black Sea exceeded 1 m/s and reached 1.5 m/s at 1m below the water surface from time to time for very strong meteorological conditions. Figure 11 shows a typical example of the current profiles for the unidirectional northern flow at the station B. The variation of the wind speed which caused this typical current structure is shown in Figure 12. The wind speed reached to a maximum value of 13.29 m/s at the station F. As
seen from Table 4 the storm lasted 55 hours and the direction was around of the SSW direction (Figure 13). The strong southern storms caused set up and set down at the entrance of the Marmara Sea and the Black Sea respectively. Figure 14 shows the time history of the water level difference between the Black Sea and the Marmara Sea. The water level of the Marmara Sea was 0.10 m higher than the Black Sea for this typical current structure.

Table 4 Wind storm between 25.01.05 and 28.01.2005

<table>
<thead>
<tr>
<th>Station</th>
<th>Beginning of the storm</th>
<th>End of the storm</th>
<th>Duration of the storm (hours)</th>
<th>Effective direction</th>
<th>Maximum wind velocity (m/s)</th>
<th>Occurrence of time</th>
<th>Beaufort scale (wind)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>25.01.05 16:33</td>
<td>28.01.05 23:45</td>
<td>55</td>
<td>SE-SSW</td>
<td>13.29</td>
<td>27.01.05 07:08</td>
<td>6-7</td>
</tr>
<tr>
<td>G</td>
<td>25.01.05 16:33</td>
<td>28.01.05 23:45</td>
<td>55</td>
<td>SW</td>
<td>3.62</td>
<td>26.01.05 12:45</td>
<td>2-3</td>
</tr>
</tbody>
</table>

Figure 11 One layer flow pattern in N direction, 27.01.2005, 16:01 (left is the Marmara Sea side and right is the Black Sea side)
Figure 12 The time history of wind speed at the stations F and G; between 25.01.05 and 28.01.05

Figure 13 Wind directions at the stations F and G; between 25.01.05 and 28.01.05
Another typical flow structure is three-layer current system. At the governing southern wind upper layer flow may be blocked at the surface and the current structure of the Bosphorus becomes three layers. A typical velocity profile is given in Figure 15. A layer of the northern current at the surface occurred (i.e. a current flowed in the opposite direction at the surface) and the southern current also flowed below the surface layer, further depths the northern current (lower layer) water still existed as in Figure 15.
Figure 16 shows the flow duration and percentage of the northern and southern currents at -1 m below the water surface at the station B. The northern unidirectional current rarely occurred during the measurement period. The northern unidirectional current (one layer flow cases) was observed at a depth of -1 m below the surface between November and May. The monthly average current speeds of the southern and northern flows were plotted in Figure 17. The average speed of the southern current was frequently over 1 m/s and dominant in June and July. The northern one layer current rarely appeared from June to November. Figure 18 shows the upper layer flow duration and percentage over 1 m/s in a year at the station B. The southern flow increased between April and October and decreased later in the year.

![Figure 16: Current duration and percentage of occurrence along the year at -1 m depth at the station B](image_url)
Figure 17 Average current speeds at -1m depth at station B

Figure 18 Current duration and percentage of occurrence over 1 m/s along the year at -1 m (in the Southern direction)

*The Effect of the In-Flow Conditions*

Previous studies such as Sur et al. (1994) showed that the net fresh water flux into the Black Sea affected the long term response of the mean sea level in the Bosphorus. However the previous investigations did not provide long term measurements to compare the effect of the fresh water inflow. The monthly mean discharge of the rivers (Danube, Dniester and
Dnieper) was determined by analyzing the discharge data between 1921 and 2001 [1]. Figure 2 (b) and Figure 19 (a) show the locations of the rivers and the variations of the mean discharges in a year respectively. The monthly mean discharge of the Danube indicates large natural oscillation within the range of 4,500-9,000 m$^3$/s in a year. The average total discharge of Danube, Dniester and Dnieper changed between 5,500 and 11,000 m$^3$/s. The river discharges cause the water level changes of the Black Sea (Figure 19 (b)). Danube carries large amount fresh water to the Black Sea. The discharge of Danube was around 80% of the other river discharges to the Black Sea. Figure 20 shows monthly maximum and minimum Danube discharge variations in a year. The range of maximum and minimum discharges changes between 15,000 and 2,000 m$^3$/s respectively. The discharge of Danube starts to increase from February and reaches its maximum value in May. The minimum discharge is observed in October. The monthly mean water level variations were also obtained from the measurements at the Black Sea entrance of the Bosphorus (Station E) (Fig. 19, b). Occurrence probability of the maximum and minimum monthly discharges was plotted in Figure 20. The maximum and minimum water levels observed in July and December respectively at the entrance of the Black Sea (Figure19 (b)). The variation of the mean water level and Danube discharge indicates 2 month phase lag (Figure 19 (b)). Figure 19 shows that the fresh water inflow results the effect in the long term response of the mean water level in the Bosphorus.

Salinity profiles were obtained at station K$_0$ (at the entrance of the Black Sea) and M8 (entrance of the Marmara Sea) between September, 2004 and August, 2005 by ISKI (2004 and 2005), and are plotted in Figure 21 and 22 respectively. Figure 21 shows that, the salinity of the upper layer flow is around 18ppt along the year while salinity of the lower layer flow is about 36.5 ppt. Top of the interfacial layer changes between ~35 m and ~50m depth while bottom of the interfacial layer varies between ~50 m and ~55 m depths, resulting an interfacial layer thickness of maximum ~20 m and minimum ~5 m. Maximum interfacial layer thickness occurred in January with 20 m while the thickness of the upper layer is about 35 m. Starting with February, upper layer thickness increases first to 45 m and then reaches to 50 m in March while the thickness of the interfacial layer decreases to 10 m and then to 5m respectively. This period also overlaps with the period in Figure 19b where water level of the Black Sea starts to increase in February till June. In Figure 22 the
The salinity of the upper layer is around 21 ppt along the year while salinity of the lower layer is about 38 ppt. Although the M8 station is deep in the Marmara Sea, 5 – 10 m thick upper layer flow can still be identified with some mixing. It is difficult to identify interfacial layer or the upper layer but the lower layer can be clearly identified. Top of the lower layer varies between ~30m and ~25m. As it is seen from Figure 22 the salinity has increased to 25 ppt at the water surface in January, the reason is thought to be the southern wind storm (see Table 4) which may cause convective mixing.

![Graph of monthly mean discharge variations](image1)

(a) Monthly mean discharge variations [1]

![Graph of Danube monthly mean discharges and Black Sea monthly mean water level](image2)

(b) Danube Monthly mean discharges and Black Sea Monthly Mean Water Level in a Year

Figure 19 Fresh water discharges into the Black Sea
The meteorological conditions are more dominant between October and April while the fresh water discharge to the Black Sea becomes dominant from April to October and cause the seasonal variations which is called long term effect. Long term response is more stable in the Bosphorus. The meteorological conditions cause fluctuations of the water level and hence the current speed (short term effect). The short term responses superimpose on the long term variations.
Figure 21 Salinity variations along the depth at the station K0, (ISKI, 2004, 2005)

Figure 22 Salinity variations along the depth at the station M8, (ISKI, 2004, 2005)
Presence of the Current Responses

Short term effects due to meteorological conditions and long term effects due to fresh water inflow mainly control the water level variations in the Bosphorus. In order to perceive the correlation between the water level difference and current speed at -1m depth in the Bosphorus Strait, Figure 23 was drawn. Figure 23 shows the variation of the current speeds for all directions at the station B against the water level differences. The negative velocities indicate southern (upper layer) flow but the positive velocities represent the northerns (lower layer). The negative water level means that the water level of the Black Sea is lower than that of the Marmara Sea. Figure 23 shows the correlation between the current speed and the water level difference obtained by the least squares method.

As shown in Figure 24 similar correlations were obtained for the depths of -5 m, -10 m, -15 m, -20 m and -25 m. General current structure at the station B showed that there was an interface between the upper layer and the lower layer which was around -20 m water depth. Figure 24 shows that the slope of the correlation lines become milder when going deeper. This means that the response of the current at upper layers is more than lower layers under the water level variations between the Black Sea and the Marmara Sea.

![Figure 23 Current speeds for all directions at the station B versus water level difference at -1m depth](image-url)
In order to describe the current characteristics at the measurement site, the current speed roses are presented for the depths of -1 m, -5 m, -10 m, -15 m, -18 m, -20 m, -23 m and -25 m at the station B in Figure 25. While the first four figures in Figure 25 represent the upper layer, different characteristics could be seen at each depth. Current rose given in Figure 25 (a) shows that the flow is primarily in the direction of S, but there is some scattering to the directions of SW-SE portion. The scattering is thought to be due to the wind effect. In Figure 25 (b) there is more clear southern flow in comparison with Figure 25 (a). After the depth of –5m the flow direction changes towards SSE. This change in direction is considered to be due to the following mechanisms.

1- Upper layer flow, from the Black Sea to the Marmara Sea, is deflected towards SSE by the flow exiting Golden Horn. This effect can be seen in Figures 25 c, d,e and partly in Figure 25 f.

2- Secondary flow (meandering effect) is thought to be deflecting top of the upper layer flow (first ~5 meters) towards W causing the resulting flow direction to change from
SSE to S. This effect becomes minor after -5m as the secondary flow velocities decrease by depth.

Lower layer flow, as seen in Figures 25 e, f, g, h, is flowing in directions N-NNW although the tangent of the Bosphorus is towards N at the location. Lower layer flow enters the Bosphorus in N direction but it is deflected by the geometry of the Bosphorus at the entrance of the Marmara Sea (Fig. 2(a)) and then it tends to enter the Golden Horn. This flow pattern causes the resulting flow in the N-NNW direction at the measurement point.

Figure 25 Current speed roses at the station B
At the water surface (-1 m depth), the current direction percentages were 19% SSW, 58% S and 10% SSE. At -5m depth, the current directions were 80% S and 10% SSE and 5% SW. At -10m depth, the current directions were 42% S and 45% SSE. As it is seen from the current roses, the current direction shifted from S to SSE and the dominant direction became SSE with 50% of the year at -15 m water depth. Northern currents were also observed at -15m depth. At the intermediate depths, the current direction percentages varied drastically due to the stratified flow. At -18m depth, the current directions were 20% S, 38% SSE and 19%N and the percentage of northern directions increased to 28% N and
10% NNW at -20 m while the southern direction percentages decreased. At -22m of the depth, the northern current direction became dominant with 30% N and 20% NNW and the southern currents were less observed in this layer. At -25 m, the current direction was almost 70% to the northern directions.

As the variation of the current roses with depth is traced, the depth of interface layer changes in a year and it is observed to be between -15 and -20m at the station B during the measurement period.

The directional exceedence probability distribution of the current speeds at depths of -1 m, -10 m, -20 m and -25 m at the station B were plotted in Figures 26 to 29. The figures showed that SSE and S were dominant directions in the upper layer while N and NNW were leading directions in the lower layer. The direction of upper layer at the surface was mostly in the directions of S then it was deflected to SSE. The secondary direction of the upper layer was SE because of the geometry of the Bosphorus at the entrance of the Marmara Sea, this is actually typical meandering effect.

![Figure 26 Cumulative exceedence probability distribution of current speeds for each direction at the station B at -1m water depth.](image-url)
Figure 27 Cumulative exceedence probability distribution of current speeds for each direction at the station B at -10m water depth.

Figure 28 Cumulative exceedence probability distribution of current speeds for each direction at the station B at -20m water depth.
Figure 29 Cumulative exceedence probability distribution of current speeds for each direction at Station B at -25m water depth.

All southern and northern directions were gathered then they were plotted to get their cumulative exceedence probability of current speeds at the depths of -1 m, -15 m and -25 m in Figures 30, 31 and 32 respectively for the stations A, B and C. The upper layer current speed exceeded 1.5 m/s for 36 days per year, but it was over 1 m/s for 183 days per year (half of the year) at the station B. When the lower layer (in the north direction) was governing the whole depth, it exceeded 0.5 m/s for almost 175.2 hours (7.3 days) per year at the station B. Both current speeds exceeded (i.e. in the northern and southern directions) 0.5 m/s for 14.6 days per year at the bottom at the station B. The cumulative exceedence probability distributions of current speeds at the stations A, B, and C are quite different from each other as seen from Figures 30, 31 and 32. The reason of the difference is probably due to the topography of the strait. The current intensity at the station B was higher than the others.
Current speed was lower at the station A because the location of the station A was affected by the reverse flow due to the head of Golden Horne entrance. Guler et al. (2006) showed the secondary flow effects in the strait and the measurements at the station A agree with Guler et al. (2006). The lower layer current structure shows milder cumulative exceedence probability distributions than the upper layer current structure at the stations A, B and C because the response of the lower layer probably was not as much of the upper layer for two-layer current.

Figure 30 Cumulative exceedence probability distribution of current speeds for N and S directions at -1m water depth.
Figure 31 Cumulative exceedence probability distribution of current speeds for N and S directions at -15m water depth.

Figure 32 Cumulative exceedence probability distribution of current speeds for N and S directions at -25m water depth.
Numerical Modeling of the Short Term Effects

Wind and atmospheric pressure changes are short term effects, which cause variations in water level difference by water and wave setup between the Black Sea and the Marmara Sea, effecting current structure. Flow structure of the Bosphorus depends on the intensity and direction of the storm and atmospheric pressure distribution over the Black Sea and the Marmara Sea. Southern current (upper layer) from the Black Sea to the Marmara Sea increases when the northern winds blow over both basins and the strait. If the northern storm is strong enough, lower layer current (northern current) will be blocked and southern current will dominate all the current structure at the station B (Figure 7). If the southern storm is strong enough, the southern current (upper layer) is completely blocked and the northern current flows in the whole depth at the station B (Figure 11). However it is very difficult to define the threshold wind and atmospheric pressure for the extreme cases because the other driving effects such as the net fresh water inflow also controls the current. The superposition of the driving forces organize the water level changes and hence the current structures.

Wind climate was presented by using ECMWF (The European Centre for Medium-Range Weather Forecasts) data for the Black Sea and the Sea of Marmara. Wind climate shows also very complex phenomena because wind doesn’t always blow in the same direction over the Black Sea and the Marmara Sea and also over the Strait. An example of the wind circulation over the area is shown in Figure 33.

Figure 33 Wind vectors over the Bosphorus.
To predict the short term effect on water level change, a two-dimensional hydrodynamic numerical modeling (MIKE 21 HD) was applied for the simulations of the water (both wind and atmospheric pressure) and wave set-up and set-down. MIKE 21 SW (Mike21 Spectral Wave Model) was used to calculate radiation stress in the modeling area as an input parameter for MIKE 21 HD.

MIKE 21 FM Hydrodynamic Flow (HD) is a general two-dimensional modeling tool for oceanographic, coastal and estuarine applications. The model comprises a hydrodynamic model. The model depends on a number of external forcing, as meteorological effects and boundary conditions, which can be incorporated in a flexible manner. The model is based on an unstructured flexible mesh and uses a finite volume solution technique, which provides an optimal flexibility while retaining an efficient numerical solution. The meshes are based on linear triangular elements.

The effect of tide on the water level variation was also examined. Tidal oscillation in the Bosphorus was predicted from water level measurements in the station E using Mike21 tide analysis and prediction toolbox. The results were compared with Alpar and Yüce (1998). Four of 38 predicted tidal harmonic constituents are shown in Table 5. Alpar and Yüce (1998) studied the tidal variation in the strait. They predicted the tidal oscillations from measurements in Anadolu Kavagi (Fig. 2(a)). Tidal oscillations were small in amplitude and the tide was diurnal. Four main diurnal parameters from Mike21 prediction and predicted tidal oscillations of Alpar and Yüce (1998) were plotted in Figure 34. Results are in agreement with Alpar and Yüce (1998)’s data. Figure 34 shows only the tidal oscillations in July, 2005.

<table>
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<tr>
<th>Station Name</th>
<th>Station Coordinates</th>
<th>M2 amplitude (m)</th>
<th>S2 amplitude (m)</th>
<th>K1 amplitude (m)</th>
<th>O1 amplitude (m)</th>
<th>Reference</th>
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</thead>
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<tr>
<td>Station E</td>
<td>41°12'13&quot; N 29°05'54&quot; E</td>
<td>0.015 83.39</td>
<td>0.0063 97.39</td>
<td>0.0091 103.71</td>
<td>0.006 104.43</td>
<td>Alpar ve Yüce, 1998</td>
</tr>
<tr>
<td>Anadolu Kavagi</td>
<td>41°30' N 29°15' E</td>
<td>0.0126 93</td>
<td>0.0052 101</td>
<td>0.001 110</td>
<td>0.0063 106</td>
<td></td>
</tr>
</tbody>
</table>

Table 5 Tidal harmonic constituents
Figure 34 Tidal oscillations in the Bosphorus in July, 2005.

The modeling of wind, wave, atmospheric pressure, tide and hydrological impacts on the water level change is shown in Figure 35 at the Black Sea entrance of the Bosphorus. ECMWF wind and atmospheric pressure data were used for the simulation. Measured water level fluctuations and modeled water level fluctuations show similar trend in time history for the station E (Figure 35).

Figure 35 Measured water level versus modeled water level at the station E.
The modeled short term effects (wind, wave and atmospheric pressure) are given in Figure 36 together with the measured data and its monthly average. As seen in Figure 36 short term fluctuations are more dominant between October and April while the fluctuations have smaller amplitudes at the rest of the year (summer time). The seasonal water level change (long term variation) was also observed due to river discharges to the Black Sea. Their positive contribution mostly dominated the water level from the beginning of April to the end of September. The short term effects fluctuate around the long term water level changes. However the amplitudes of the short term variations are smaller in summer compared to the rest of the year because of the meteorological conditions. When the seasonal variation of the monthly averages of the water levels was assessed, two-times difference was obtained between the highest and lowest averaged water levels in the observation period.

![Figure 36 The Black Sea water level changes at the station E](image)

**Conclusions**

1-Short-term effects of wind and atmospheric pressure are evident in the Bosphorus Strait current structure, which is affected by two distinct seasonal climatic regimes. The weather is dominated by an almost continuous passage of cyclonic systems through the region.
Short-term changes mainly occur between October and April and the rest of the year current structure is smoother in the Bosphorus (Figures 4 and 18). Long-term effects of freshwater discharges due to mainly Danube, Dnieper and Dniester drive the current structure of the Bosphorus Strait with a phase lag of two months (Figure 19). The measurements show that the freshwater influx dominates the current system mainly between April and October (Figures 18, 19).

2-During the monitoring process -0.2 m and 0.6 m water level change around the reference were observed (Figure 6).

3-The northern winds cause water level at the northern entrance of the strait to rise while lowering the sea level at the southern entrance of the strait (Figures 8, 9 and 10). The range of sea level change causes short-term fluctuations of the current speed in the strait (Figures 4, 6).

4-Current speed of the upper layer decreases along the depth till the interface while it again increases in the lower layer (opposite direction) in the Bosphorus Strait when two layer current structure exists (Figure 5).

5-There is a correlation between the water level difference at both end of the Bosphorus and the current speeds in the strait (Figures 23 and 24). Although there is a strong correlation between the water level and current speed in the upper layer, the correlation in the lower layer is not strong enough (Figure 24). The water level difference is more dominant effect in the upper layer.

6- Generally S and SSE are dominant directions for the current in the upper layer while N and NNW are leading directions in the lower layer (Figure 25). However the dominant current at the surface is indeed deflected by secondary flow from direction SSE & S to S. The effect is minimized with increasing depth. So the secondary flow in the counter clockwise direction was observed at the entrance of the Marmara Sea at the measurement
location. The geometry of the Bosphorus causes the reverse flow and secondary current systems in the Strait.

7-The measurements show that the upper layer current speed exceeds 1 m/s for 183 days per year at the surface (Figure 18). Both the current speeds in the northern direction and the current speeds in the southern direction (when the lower layer blocked and the current system is occupied by upper layer at the measurement station) exceed only 0.5 m/s for 14.6 days at the bottom. However, the current speeds are strongly affected from the strait geometry and the bottom topography.

8-Tidal oscillations in the strait are small in amplitude and tide is diurnal type (Figure 37). The seasonal variation of the water level in summer and winter is twice of their monthly average values (Figure 36).

Acknowledgement

The authors wish to express their sincere thanks to the General Directorate of Marmaray Project of Ministry of Transportation, General Directorate of Ports, Airports and Railways Construction of Turkey to let the evaluation of measured data in the Istanbul Bosphorus Strait. The efforts of TAISEI Corporation for the difficult measurement program and the efforts by AVRASYA Consultants are also acknowledged.

References


Subject: Thanks to Reviewers for their valuable efforts for the paper. The corrections were made in English.

Best Regards

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Besiktas ISTANBUL
Reply to reviewers
1-English corrections were made
2-The abstract was shortened