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Symptoms of a prominent Mediterranean layer blockage in the Strait of Istanbul (March 26-28, 1998) on the interactions of the Golden Horn Estuary

İstanbul Boğazı bütününde gözlenen Akdeniz suyu blokajının (26-28 Mart 1998) Haliç üzerindeki etkisi

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Abstract

The main characteristics of the Golden Horn estuary are dominated by coupling with the Strait of Istanbul. Depending on the atmospheric factors and the water budget, the flows through the Strait of Istanbul are subject to many nonlinear transient variances such as temporary blocking of the flows in either direction. In the present paper, with the aid of short-term oceanographic and meteorological data, we will investigate the response of the Golden Horn to a prominent Mediterranean layer blockage, which occurred at the southern end of the Strait of Istanbul during March, 26-28th 1998.

Keywords: Strait of Istanbul, Golden Horn, Mediterranean water, oceanography, sea level, water masses, blockage, current

Introduction

The Golden Horn is a long (7 km) estuary placed at the southern end of the Strait of Istanbul (Figure 1). Two brooks discharge into the estuary; Alibey and Kağıthane Creeks. Its average width is 370 m and ranges between 293 (Galata) and 685 (Kasımpaşa) metres. The maximum depth is ~40 m at the mouth. More than one third of the area is shallower than 10 m.

The physical oceanographic characteristics, mainly relevant to pollution, of the Golden Horn have been investigated in the past (DAMOC, 1971; Doğusal and Güçlüer, 1977; Saydam et al., 1988; Ergin et al., 1990; Yüce, 1999). The water circulation in the Golden Horn is governed by the volume and rate of flow of the water masses and the meteorological conditions. The topmost of the water masses is the fluvial and brackish water (runoff-rainfall) with a salinity as low as 10 [using the Practical Salinity Scale]. This quasi-fresh water zone is generally 2-3 m thick and is commonly depleted in dissolved oxygen. Below the quasi-fresh near surface water, a two-layer stratification exists in the Golden Horn; the brakish water of the Black Sea overlying the highly saline (38-39) waters of the Mediterranean Sea, similar to those observed at the southern entrance of the Strait of Istanbul. The salinity of the intermediate layer ranges between 10 and 38. Depending on the seasonal climatic and meteorological conditions, the depth (30 m in normal) and thickness of the transient zone between the intermediate and bottom layers changes (Doğan et al., 1998).

The Mediterranean inflow into the Golden Horn has had a profound effect on the water structures in the estuary and their temporal physical behaviours. The Sarayburnu headland (Figure 1) and its underwater prolongation, which cause an anticyclonic eddy in front of Beşiktaş (Möller, 1928), are the most important geomorphic factors on the water flowing. In normal conditions, the southern sill at 38 m depth between Üsküdar and Beşiktaş (Figure 1) does not prevent the Mediterranean inflow into the strait (Yüce, 1996). However, a little is known if it may help the Mediterranean water to steer towards the Golden Horn, particularly during lower-layer blockage.

Recently, the Mediterranean water intrusion into the Golden Horn has been studied for different weather conditions. In normal conditions, the Mediterranean water extends up to Kasımpaşa. This structure varies as a response to changes in prevailing winds and sea-level difference between the Black Sea and the Marmara Sea (Doğan et al., 1998; Yüce, 1999).

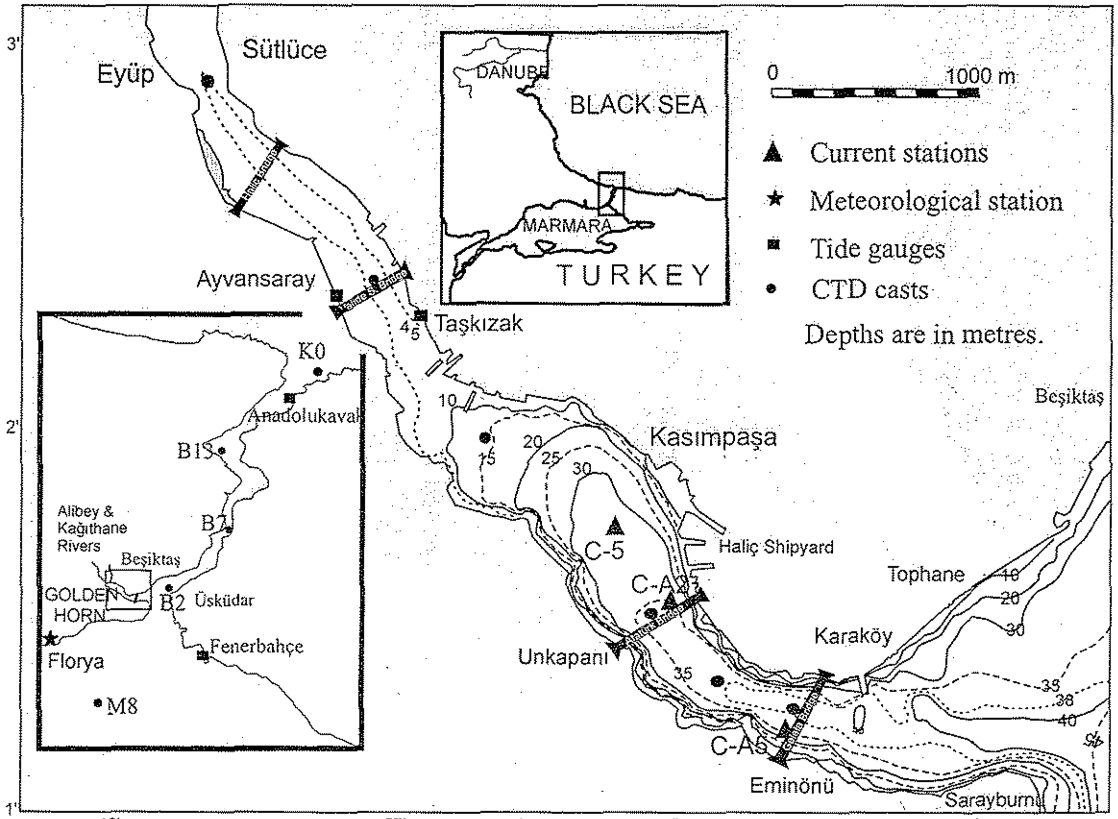

Figure 1. Golden Horn. Its bathymetry and location of stations. The insets show its location and some localities mentioned in the manuscript.

The flow system in the strait responds rapidly to changes in driving forces. Southerly winds in winter may pull up water at the southern end of the strait, destroy layer structure at surface, and often cause upper-layer blocking. The transient changes in the water budget of the Black Sea or setup by persistent northerly winds can temporarily cause the lower layer flow to be blocked (Özsoy et al., 1998). These blocking events may affect the Golden Horn estuary which is coupled to the Strait of Istanbul. In this paper, the effects of a prominent lower-layer blockage event (March, 26-28th 1998) on the Golden Horn will be studied. This lower-layer blockage event was found to be newsworthy since it occurred more in advance before entering to the channel of the Strait of Istanbul.

Material and Method

The satellite images representing the meteorological events occurred in the duration and the preceding days of the cruise have been downloaded from the CNN site in the internet. Surface barometric pressure, wind speed and direction were obtained from nearest meteorological station (Florya) over the period of 20-31 March, 1998. Wind stress components (NS and EW) were computed from the wind field from usual quadratic law using a drag coefficient of $2.5x10^{-3}$.

CTD profiles were obtained using a Sea Bird probe along the strait and in the Golden Horn (Figure 1). The vertical distance between sampling depths ranges between 0.5 to 2 m.

Sea level measurements were operated by the Department of Navigation, Hydrography and Oceanography. Short-term sea level variations were measured at Anadolukavak with a mechanical R. Fuess stilling well type permanent tide gauge. Two mechanical OTT float type temporary sea level stations at Ayvansaray and Taşkızak. The vertical datum planes for these tidal projections are arbitrary at each of the recording sites. Therefore, the time-series differences between the sea levels are not absolute but relative.

On March 30-31, short-term and single-series RCM9 current meter observations were taken at three stations along the Golden Horn (Figure 1) by the research vessel TCG Mesaha I of TN-DNHO. Sampling interval was 1-min and the measurement time was ranging between 58 and 63 min.

Results

In winter, the study area is under the effects of almost continuous passage of cyclonic systems. On March 23rd, frontal cloud systems cover the Black Sea, Marmara Sea and North Aegean Sea (Figure 2). According to the meteorological data, high pressure conditions (1017-1019 mb) were developed on March 23rd. Next day, the frontal system shifted eastward. Therefore, the weather was open and barometric pressure was high on March 24th.

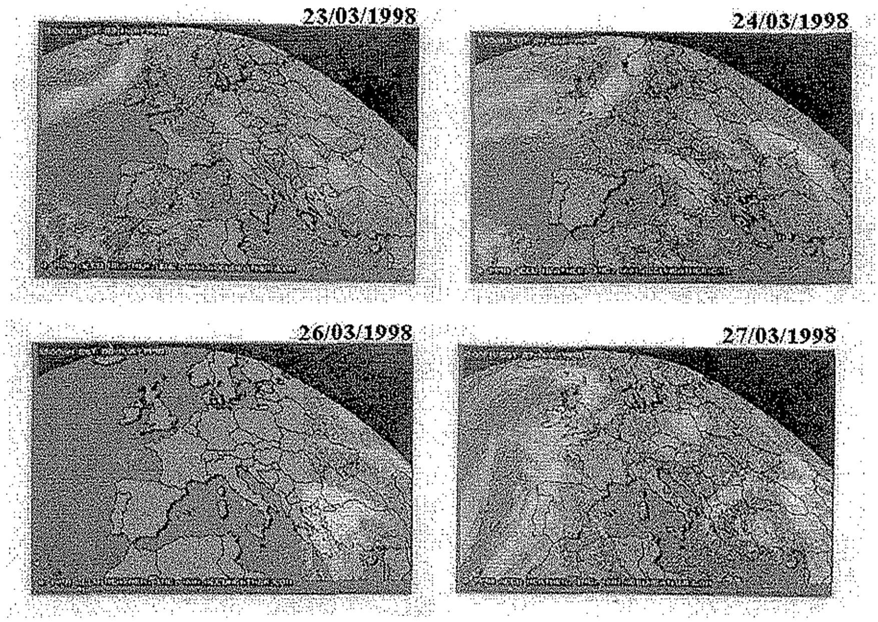

Figure 2. Meteorological data obtained from CNN. See text for explanations.

A warm frontal system transited over the study area on March 25th (just one day before the cruise in the Golden Horn) and then dislodged in a southeastward direction on March 26th. On the cruise day in the Golden Horn, a new frontal system covered the Mediterranean Sea and caused severe winds. According to the meteorological data and on board measurements, barometric pressure started to fall. The weather was closed and rainy (7-8°C).

On March 27th, during cruise in the strait, the frontal system shifted southwards. The barometric pressure started to increase again. The wind speed averaged 14 knots, varying between 11 and 21 along the strait. The sea state in the strait was moderate.

There was an important lower-layer blockage starting from the station B2 at the southern end of the strait (Figure 3A). The temperature was almost constant along the strait. The Black Sea water filling the channel mixed with the Mediterranean water in the Marmara Sea along a high-slope interface placed somewhere between the stations B2 and M8. Since this interface was situated in the south of the 38-m sill, there was no Mediterranean water in the strait's channel. This extraordinary pattern is different from the normal two-layer system (Ünlüata et al., 1990; Yüce, 1996) in the Strait of Istanbul and exhibits one of the complex nonlinear responses of maximal exchange regime (Özsoy et al., 1998) in the strait to external forcing.

From the oceanographic measurements in the Golden Horn (March, 26th 1998), the blocking of the Mediterranean water in the mouth of the estuary is evident (Figure 3B-D). Highly polluted, thin (even it was thicker than its normal) and less-saline surface layer (6.3-6.7°C) of the Golden Horn covered all over the estuary. The surface salinities at Sütlüce-Eyüp and the Galata Bridge were ~7.8 and ~13.1, respectively, implying the freshwater discharge of the Alibey and Kağıthane Creeks. Depending on the wind direction and magnitude of the flow from the Black Sea, fluvial, drainage and sewer inflows of surface water may leave the Golden Horn in two directions. It may either flow northward entering into the Beşiktaş eddy or eastward the main surface flow of the strait entering to the Marmara Sea.

The bottom layer in the Golden Horn, which is formed by the intermittent Mediterranean water flowing under the halocline of the Marmara Sea, was rather thin than its normal values. It was about 2-3 meters thick and can hardly extend up to the Unkapanı Bridge.

There is a thick intermediate layer between the surface and bottom layers with temperature of 6-6.5°C and salinity of 18-19 (Figure 3B, C). These figures are the natural values of the Black Sea water, implying that the oxygenated intermediate layer was filled with the inflowing Black Sea waters at the southern strait which upwells and dilutes the polluted surface waters.

Current velocities and stability constants calculated from the short-term measurements at the stations C5, C-A2 and C-A5 (Figure 1) are given in Table 1. Their results are helpful although they span a short period. In two days succeeding the development of lower-layer blockage in the strait, the interface between the inflow and outflow layers of the Black Sea waters in the Golden Horn was ranging between 19-21 m water depths, gently sloping toward the inside of estuary.

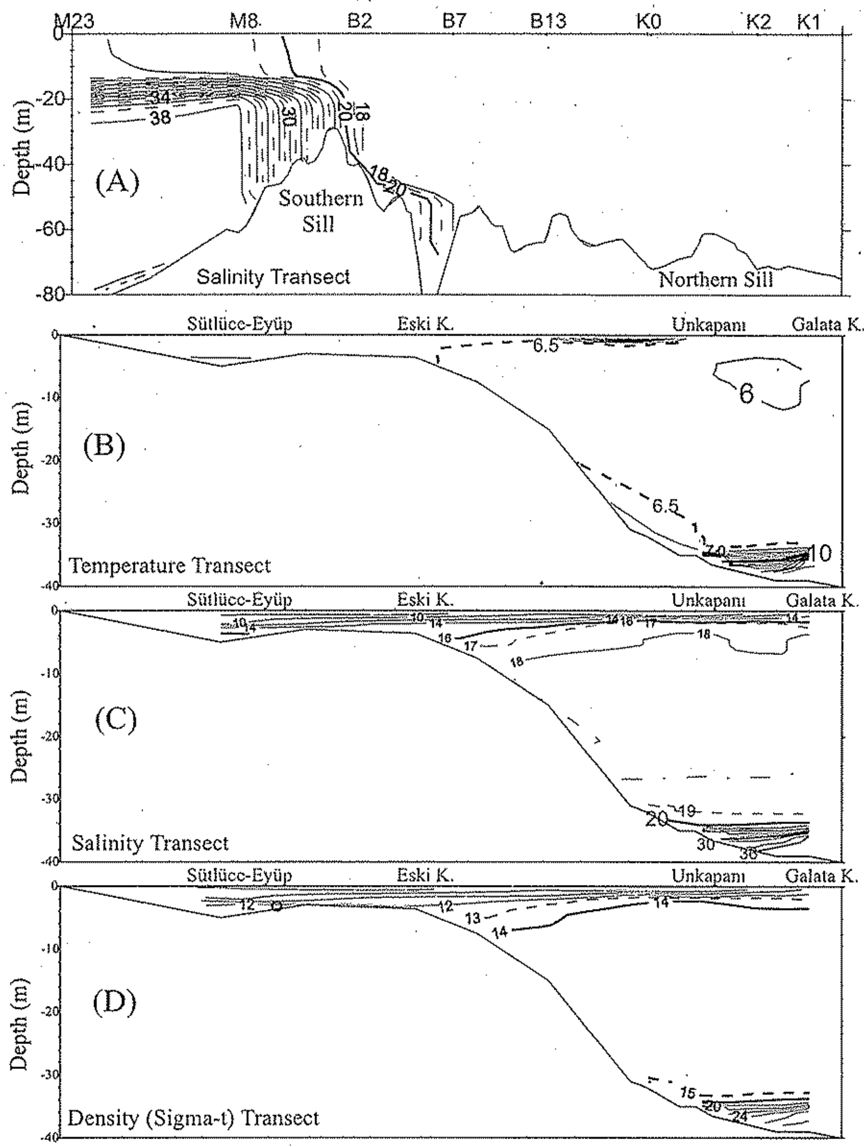

Figure 3. (A) Salinity transect in the Strait of Istanbul, Marmara Sea and Black Sea Exit Region (27-28 March 1998). (B) temperature (°C), (C) salinity (psu) and (D) density (in sigma-t units) transects in the Golden Horn (March 26th 1998).

Table 1. Current data at the stations C5, C-A2 and C-A5. See Fig. 1 for location. Inflow and outflows in the intermediate layer were shaded. The measurements denoted by the symbol "*" are rather close to interfaces.

Station Name	Measure Depth (m)	Date March 1998	Vector Mean Speed	Vector Mean Direction	Scalar Mean	Stability Coef.
5	*5	30	0.8	46	7.8	0.09
	20	30	10.4	337	12.3	0.84
	25	30	4.8	79	11.5	0.42
A2	5	31	16.5	253	16.7	0.99
	20	31	3.4	325	4.3	0.78
	*28	31	4.9	138	12.9	0.38
A5	5	31	21.4	264	21.5	1.00
	20	31	8.2	99	8.4	0.97
	28	31	4.4	128	4.8	0.92

Discussions

The sea level difference curve ($\Delta\zeta$) between Anadolukavak and Taşkızak sea levels during the period of 20-31 March 1998 was plotted in Figure 4. For comparison, the meteorological data from the Florya Observation Centre were added in the same figure. They are the barometric pressure [mb], NS and EW components of the wind stress [dyne/cm^2], viz. $\wp$, ϖ_{NS}, and ϖ_{EW}, respectively. The detailed descriptive statistics of these data set are given in Table 2.

Table 2. Detailed descriptive statistics of the related parameters.

	Min	Max	Mean	St.Dev.	Skewness
$\wp$ [mb]	1005.8	1021.3	1013.9	4.5	-0.095
ϖ_{NS} [dyne/cm^2]	-342	272	-10.86	84.2	-0.163
ϖ_{EW} [dyne/cm^2]	-1332	247	-156.71	283.9	-1.687
$\Delta\zeta$ [cm]	9.90	40.0	22.24	5.4	0.458

The hourly values of the sea level difference between the Anadolukavak and the Taşkızak ($\Delta\zeta$) ranged between 9 and 40 cm during the observation period. We know from analytical analyses that the sea levels in the Golden Horn are mainly established by the sea level variations at the southern entrance of the strait. In addition, the effects of atmospheric forces, particularly short-term effects of wind (Figure 4) are evident on the sea level variations (not given here) in the Golden Horn.

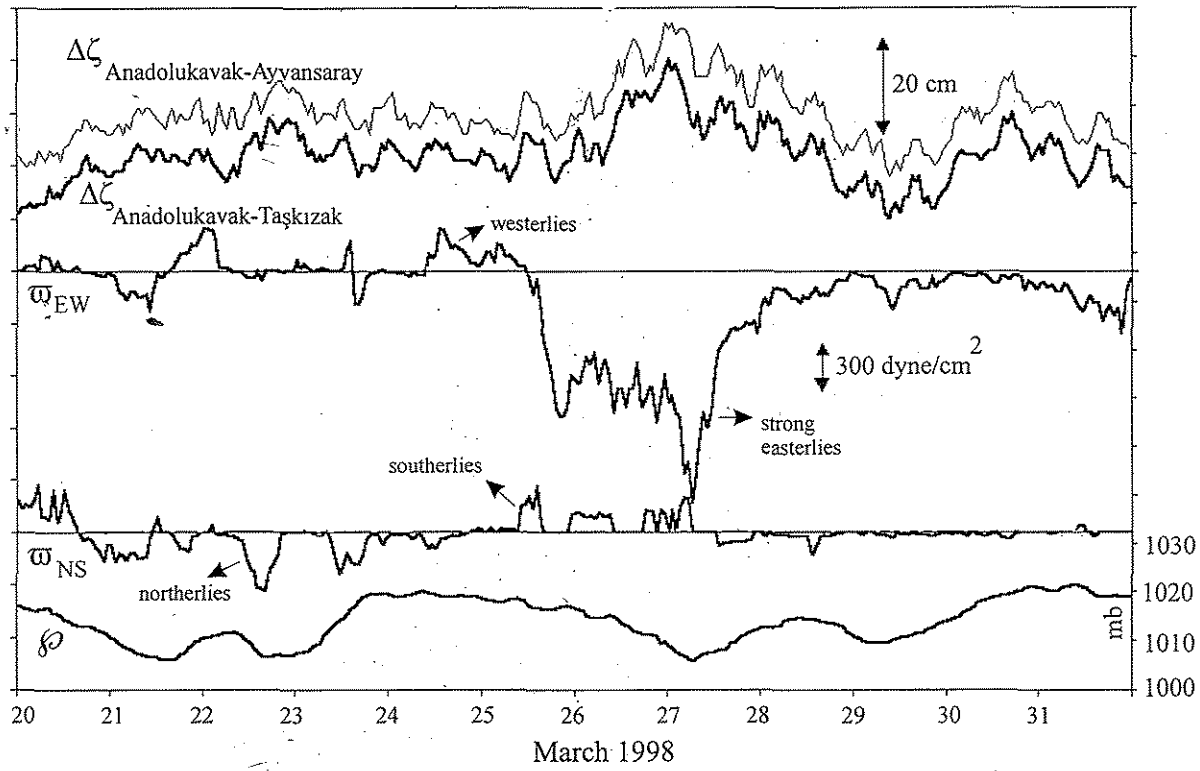

Figure 4. Sea level and meteorological data during the period of 20-31 March 1998; sea level difference between Anadolukavak and Ayvansaray, sea level difference between Anadolukavak and Taşkızak, barometric pressure and wind stress components in Florya.

In the natural science, regression analyses are very widely used in research. A line in a two dimensional or two-variable space is defined by the equation Y=a+b*X. In other words, the Y variable can be expressed in terms of a constant (a) and a slope (b) times the X variable. The constant is also referred to as the intercept, and the slope as the regression coefficient.

In order to understand how closely these variables co-vary; we calculated the linear correlations between data sets in Figure 5. The linear correlations between the $\Delta\zeta$ and other data sets can be formulated as below;

$$
\begin{aligned}
\Delta\zeta &= 1080.0 - 0.183\ \wp && (R^2=0.049) \\
\Delta\zeta &= 8.66 - 0.878\ \varpi_{NS} && (R^2=0.003) \qquad (1) \\
\Delta\zeta &= 420.61 - 25.735\ \varpi_{EW} && (R^2=0.245)
\end{aligned}
$$

where R^2 is correlation coefficient to measure how variables are related. These linear lines were superimposed on the bivariate scatterplots in Figure 5.

An important aspect of the "description" of a variable is the shape of its distribution, which gives the frequency of values from different ranges of the variable. In order to determine the probability that the sample came from a normally distributed population of observations, many precise statistical tests of normality such as Kolmogorov-Smirnov test, or the Shapiro-Wilks' W test, can be performed. However, none of these tests can entirely substitute for a visual examination of the data using a histogram which is a graph that shows the frequency distribution of a variable. The histograms help us to evaluate the normality of the distribution and to examine various aspects of the distribution qualitatively. The oblique asymmetry in the data sets of ϖ_{EW} and $\Delta\zeta$ can be evidently seen on their own histograms (Figure 5). Simple descriptive statistics can provide some information relevant to this issue. For example, if the skewness, which measures the deviation of the distribution from symmetry, is clearly different from 0, then that distribution is asymmetrical, while normal distributions are perfectly symmetrical. The skewness of ϖ_{EW} and $\Delta\zeta$ in Table 2 confirms the oblique asymmetry (long left tails) in these data sets. In addition, the box-shaped distribution of $\Delta\zeta$ with shorter tails is significant (a negative value of Kurtosis).

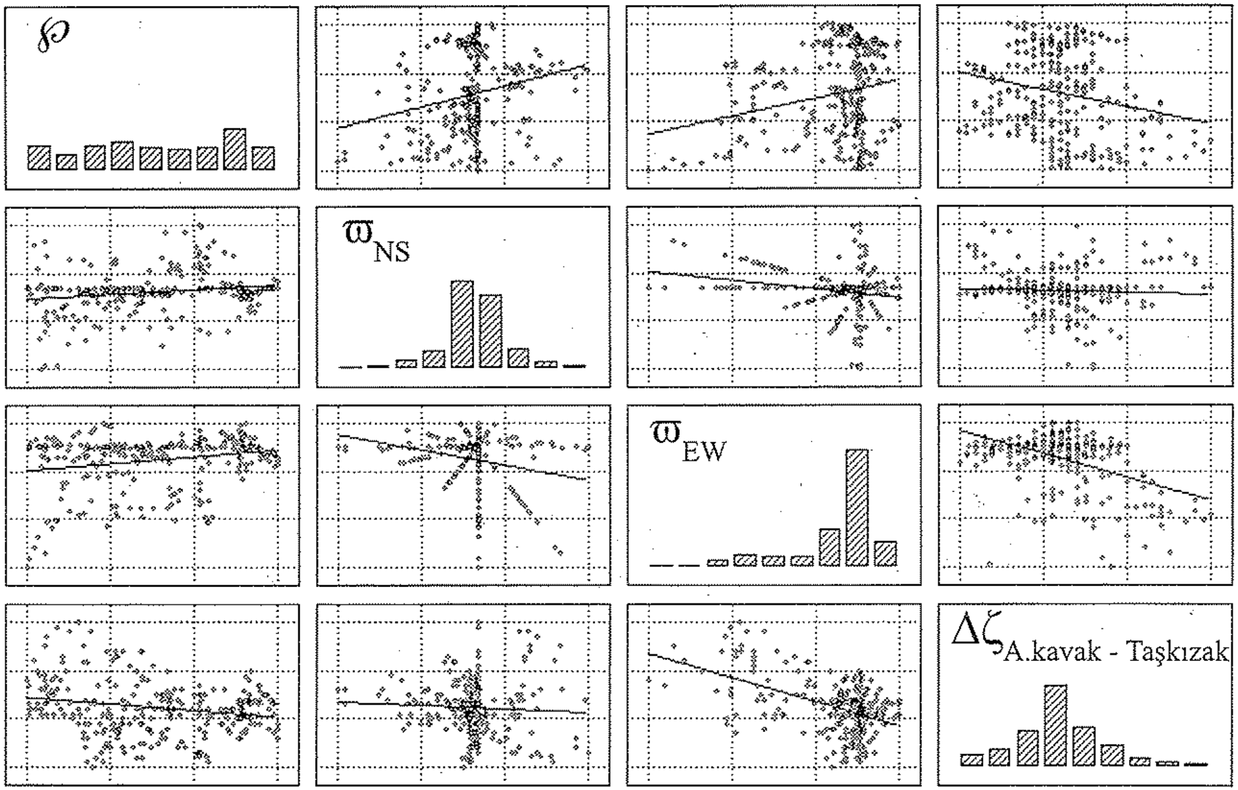

Figure 5. Histograms of the meteorological parameters (Florya) and sea level difference between Anadolukavakand and Taşkızak. The scatterplots showing linear correlations between parameters.

First we assumed that the relationship between variables is linear, so the correlation coefficients given in Eqn. (1) are measures of linear associations. However, in practice this assumption can virtually never be confirmed. Fortunately, multiple regression procedures are not greatly affected by minor deviations from this assumption. However, as a rule it is prudent to always look at bivariate scatterplot of the variables of interest. If curvature in the relationships is evident, these correlation coefficients given in Eqn. (1) are not an appropriate statistic for measuring variables associations.

Therefore, we may consider to test explicitly for the significance of a nonlinear component in the relationship between two or more variables. The dependence of the sea level difference between Anadolukavak and Taşkızak ($\Delta\zeta$) on the independent meteorological variables measured in Florya meteorological station can be shown by a set of contour (spline) diagrams (Figure 6). The dotted areas in this contour graphs represent the distribution of data samples. $\Delta\zeta$ is calculated as a function of pairs;

$$\Delta\zeta = 69544.2 - 136.8\wp + 4.6\varpi_{NS} + 0.067\wp^2 - 0.005\wp\varpi_{NS} + 5.78E\text{-}5(\varpi_{NS})^2$$

$$\Delta\zeta = 55765.3 - 109.8\wp - 0.87\varpi_{EW} + 0.054\wp^2 - 0.001\wp\varpi_{EW} + 6.23E\text{-}6(\varpi_{EW})^2 \qquad (2)$$

$$\Delta\zeta = 20.58 - 0.018\varpi_{NS} - 0.008\varpi_{EW} - 6.37E\text{-}6(\varpi_{NS})^2 - 4.88E\text{-}5\varpi_{NS}\varpi_{EW} + 9.42E\text{-}7(\varpi_{EW})^2.$$

In nature, the forces are more complicated and there is more than one independent variable. Therefore, multiple regression procedures are very widely used in many researches. The general purpose of multiple regression (the term was first used by Pearson in 1908) is to learn more about the relationship between several independent (predictor) variables and a dependent (criterion) variable.

Table 3. The Pearson correlation coefficients between the related parameters. Number of data points is 288 and "*" denotes significant correlation at the 0.01 level (2-tailed).

Pearson Correlation	Barometric Pressure	Wind Stress (NS)	Wind Stress (EW)	Sea Level. Difference
$\wp$ [mb]	1.0	0.21*	0.23*	-0.22*
ϖ_{NS} [dyne/cm^2]	0.21*	1.0	-0.24*	-0.06
ϖ_{EW} [dyne/cm^2]	0.23*	-0.24*	1.0	-0.49*
$\Delta\zeta$ [cm]	-0.22*	-0.06	-0.49*	1.0

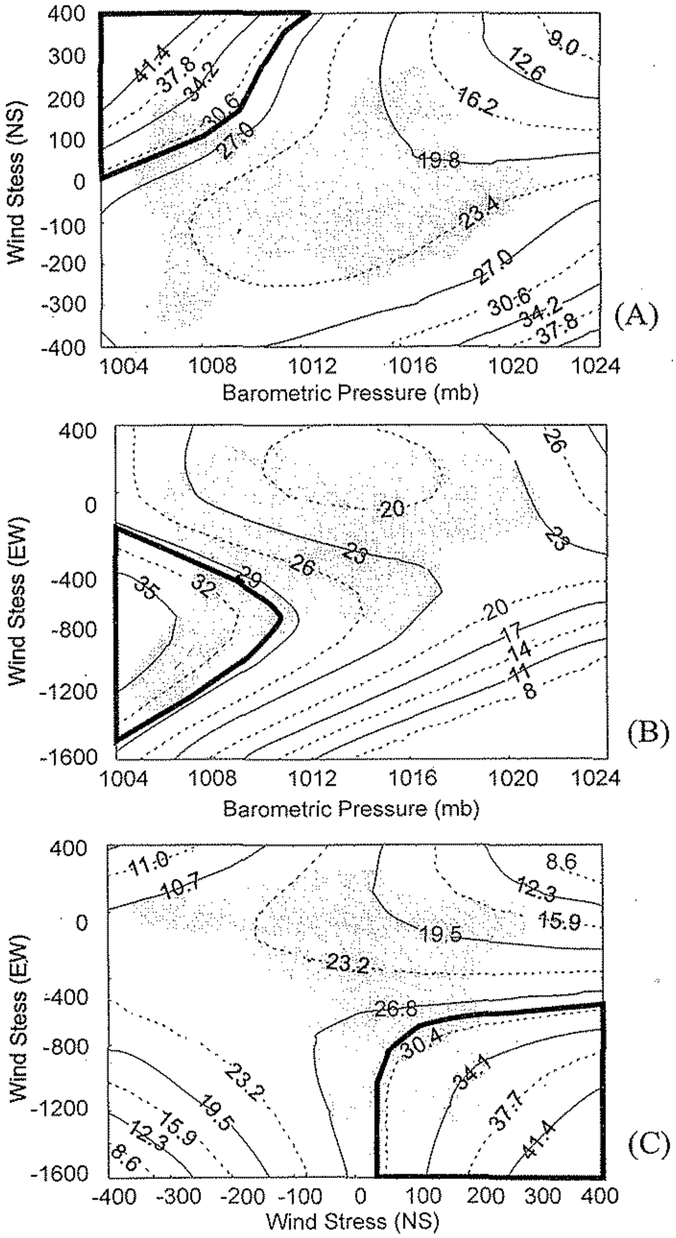

Figure 6. Spline contour diagrams showing the dependence of the sea level difference ($\Delta\xi$) between Anadolukavak and Taşkızak (Golden Horn) on (A) $\wp$ and ϖ_{NS}, (B) $\wp$ and ϖ_{EW} and (C) ϖ_{NS} and ϖ_{EW} at Florya. Dotted areas represent the distribution of data samples. The areas bounded with a thick line correspond to lower-layer blockage.

In order to indicate the relationship between independent and dependent variables, Pearson correlation coefficients were calculated (Table 3). The most important forces on the $\Delta\zeta$ sea level difference between Anadolukavak and Taşkızak are ϖ_{EW} (0.49) and $\wp$ (0.22). The ϖ_{NS}, on the other hand, has little effect on $\Delta\zeta$ and the cross correlation coefficient (0.06) is under confidence limits. Andersen et al. (1997) have also reported the importance of the easterly winds on the sea level data, particularly for the southern part of the strait.

In our example, multiple regression may allow us to ask and hopefully answer the question "what is the best predictor of the blockage events in the strait". In the multivariate case, the regression line cannot be visualised in the two dimensional space, but can be computed via multiple regression. For example, if we had, in addition to $\wp$, additional predictors of achievement (e.g., ϖ_{NS} and ϖ_{EW}) we could construct a linear equation containing all those variables. By using multiple regression procedures on the data sets of March 20-31, 1988, we estimated a linear equation;

$$\Delta\zeta = 103.0763 - 0.08134 * \wp - 0.010993 * \varpi_{NS} - 0.01 * \varpi_{EW} \qquad (3)$$

The coefficient of multiple correlation (Multiple R), a useful statistic in multivariate regression in describing the relationship between the variables, was obtained as 0.531. Multiple R is the positive square root of the coefficient of multiple determination (R^2). R^2 measures the reduction in the total variation of $\Delta\zeta$ due to the multiple or independent variables of $\wp$, ϖ_{NS} and ϖ_{EW}.

$$R^2 = 1 - [\text{Residual Sum of Squares/Total Sum of Squares}] \qquad (4)$$

$$R^2 = 1 - [6135.657/8543.827] = 0.282 \qquad (5)$$

The R^2 is adjusted by dividing the error sum of squares and total sums of square by their respective degrees of freedom, where $f\delta$ is (3, 284).

$$\Re^2 = 1 - [(\text{Residual Sum of Squares}/f\delta_R)/(\text{Total Sum of Squares}/f\delta_T)]$$

$$\Re^2 = 0.274 \qquad (6)$$

In addition, the "standard error of the estimate" which measures the dispersion of the observed values about the regression line was calculated as 4.648.

Since the most important parameters on the sea level difference are easterly winds and barometric pressure (Table 3), we may plot a 3D graph of the quadratic surface showing the barometric pressure versus the EW component of wind stress versus the sea level difference (Figure 7). The small circles superimposed on the quadratic surface represent data points.

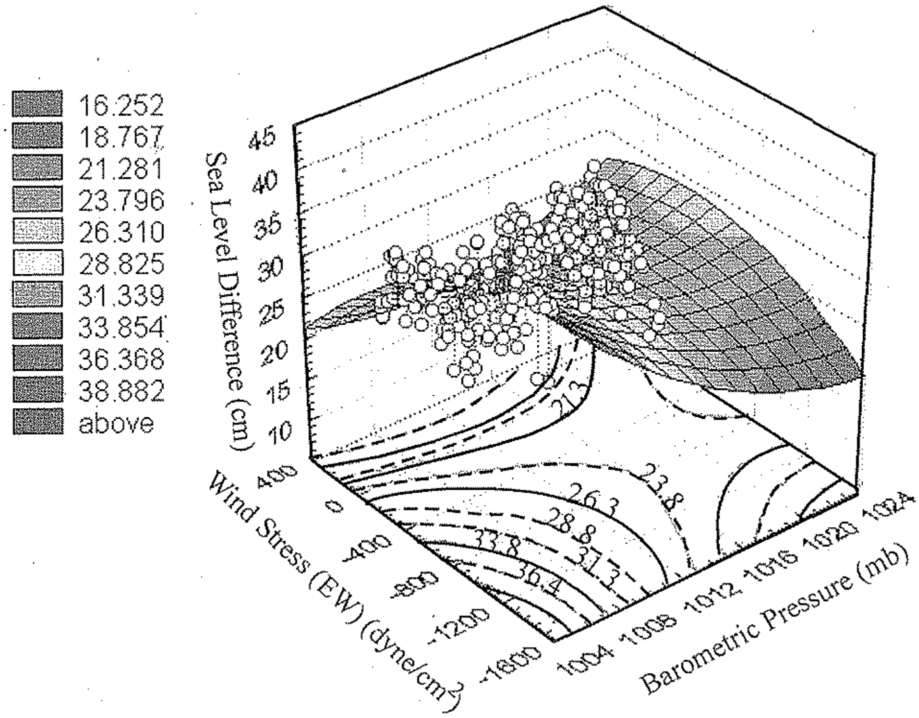

Figure 7. Quadratic surface. The barometric pressure $\wp$ (mb) versus the EW component of wind stress (ϖ_{EW}) versus the sea level difference ($\Delta\zeta$) between Anadolukavak (Black Sea) and Taşkızak (Golden Horn). Small circles represent data samples.

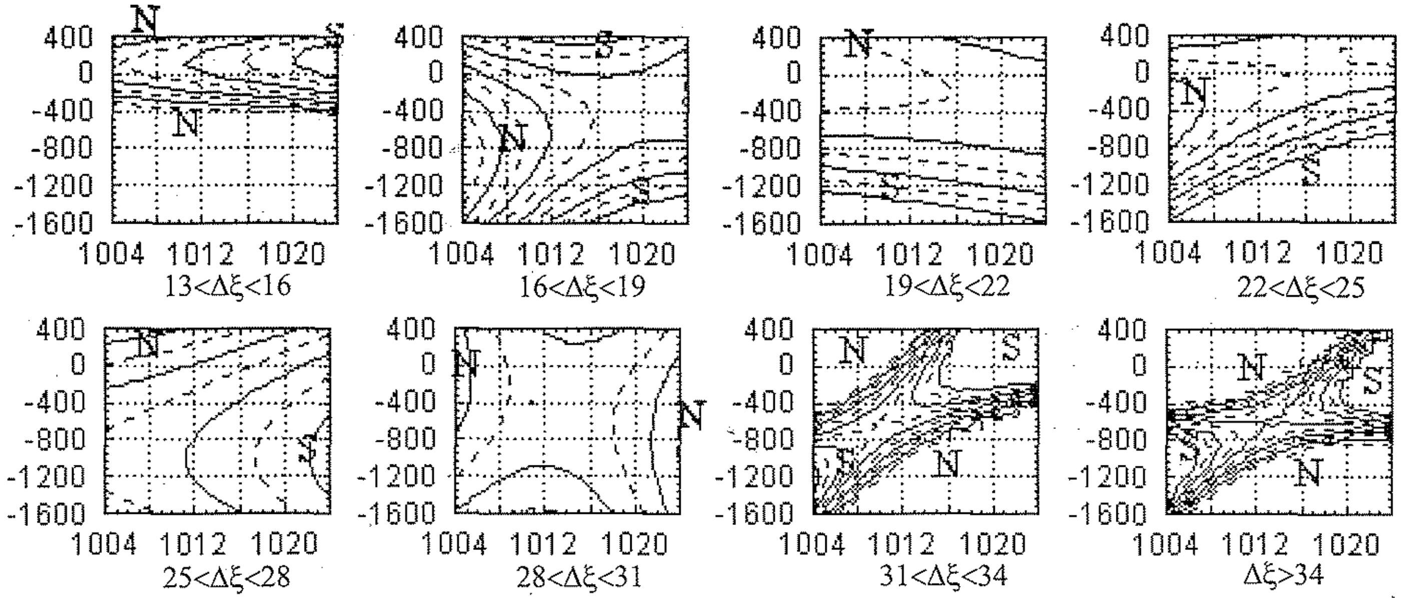

Figure 8. 3D categorised graph according to classified sea level difference ($\Delta\xi$) between Anadolukavak and Taşkızak. The x-axes represent the Florya barometric pressure in mb, while the y-axes stand for the EW component of wind stress at the same meteorological station. Negative values of the EW component represent easterlies. Bacause colour printing is impossible, the contours which the "N" and "S" letters have been written on, represent the sectors where northerly and southerly winds are dominant, respectively.

Conclusions

On 26-28 March, 1998, an important lower-layer blockage occurred at the southern end of the Strait of Istanbul. During this period, the relative vertical difference between the sea levels at Anadolukavak (Black Sea) and Taşkızak (Golden Horn) increased. This increment can be a criterion which is directly related with the independent variables of meteorological forcing.

The statistic analyses indicated that the most important forces on the sea level difference between Black Sea and Golden Horn are easterly winds and then barometric pressure. The contribution of the NS wind stress component on this difference is little. This can be best shown on a 3D categorised graph according to sea level differences with 3 cm steps (Figure 8). If the relative difference between Anadolukavak and Taşkızak sea levels is greater than about 30 cm, simultaneous meteorological forces (strong easterly and southerly winds accompanied with low barometric pressure) are believed to be sufficient to cause a lower-layer blockage in the strait.

Even though a lower-layer blockage in the strait endures about 2-3 days, up to 5 days on occasion, it may have a great importance on the pollution of the aquatic environment because of the wastewater discharges in the lower-layer. Therefore it is a boon to predict a lower-layer blockage in advance and ward off the impending threat of the available wastewater discharges. Fortunately, the sea level difference between the Black Sea and the Golden Horn can be used, in a theoretical manner, as an indicator of lower-layer blockage events in the strait. In addition, contrary to what we have expected, the southern sill seems to have no steering role on the Mediterranean water towards the Golden Horn during lower-layer blockage events. Further direct measurements of fluxes and sea level and more detailed data analyses are needed for a better understanding of the interactions of the Golden Horn estuary.

Özet

İstanbul Boğazı ve Haliç'te düzenli aralıklarla toplanan meteorolojik ve oşinografik verilerin yardımıyla, meteorolojik etmenlerin İstanbul Boğazı-Haliç oşinografik etkileşimi üzerindeki etkileri incelenmiştir. Bu amaçla, Karadeniz sularının bütün boğaz oluğunun kaplaması sonucunda, İstanbul Boğazı güneyinde 26-28 Mart 1998 tarihleri arasında oluşan şiddetli bir alt su blokajının Haliç üzerindeki etkileri incelenmiştir. Meteorolojik ve oşinografik zaman serileri aralarındaki ilişkilere yorum getirilmeye çalışılmıştır. Karadeniz ile Haliç deniz düzeyleri arasındaki göreceli farkın bir blokaj modeli için iyi bir gösterge olup olamayacağı araştırılmıştır.

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