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Does Sea Level Change in The Strait of Istanbul, Türkiye?

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Abstract

The Strait of İstanbul (Bosphorus:SoI) is a narrow water passage connecting the Marmara and the Black Sea through a sea-level balance current flow. This study performs change-points in mean and variance and trend analysis to reveal whether the sea level changes. Moreover, simple and multiple linear regressions are calculated to explain the relationships among sea level data in the three stations located in the Black Sea, the Sea of Marmara, and the SoI. The Turkish National Sea Level Monitoring System (TUDES) measures the sea water level in three stations each 15 minutes, to minimize the effect of turbulence. The sea level in the coastal area of Istanbul is one of the most populous regions with high economic importance. The most important reason is the severe decrease in water discharged into the Black Sea due to dams and excessive water usage. The three sea level stations have no change-point on the average of the whole data. The change-points in variance are depicted especially on days when the data gap is filled with average data and in the 2018 year. While the difference in the sea level of the Istanbul and Sile stations contains no seasonality, the difference between the other stations has a sinusoidal component. While this study focuses on understanding the sea level characteristics of the SoI, it also emphasizes the importance of accuracy, completeness, and long-term measurement data requirements.

Keywords: Climate change, Mann-Kendall trend analysis, Change-point analysis, Linear Regression

Introduction

The change in sea level has always intrigued scientists because approximately 10% of the world's population lives along low-lying coastal areas 10 m above sea level (UNDP, 2008). On the other hand, McGranahan et al. (2007) stated that about 634 million people, two-thirds of those living in coastal areas, settle in cities with a population of more than 5 million at 9.1 m above sea level. In addition, the sea level rise (SLR) may significantly affect low-lying coastal areas. For example, brine from the Bay of Bengal in Bangladesh penetrates more than 100 km inland in side channels during the dry season as other environmental factors, such as tropical cyclones, interact with the higher mean sea levels and contribute to the higher storm surges, causing the increase in flooding (Ahern et al., 2005).

Intergovernmental Panel on Climate Change (IPCC) estimated that the average SLR will reach 1 m by 2100 in the high emission scenario in the 4th and 5th Evaluation Reports (IPCC, 2007, 2014, 2023). The IPCC 6th Assessment Report reported the observed sea level changes in 2020 since 1900, and the SLR from 2020 to 2150 is projected even in the cases of low emission scenarios (SSP1-1.9), the global average SLR will reach 0.5 m by 2100. In the middle-to-high emission scenarios (SSP3-7.0), SLR may exceed 2 m.

The climate change scenarios have indicated by assuming no additional adjustment by 2100 that annual coastal area damage costs are more dependent on socioeconomic development than the size of the SLR in some countries. The delicate balance in the SLR causes an increase in the coastal economic activity, and freshwater flow from rivers to the sea is investigated and estimated that marine and coastal ecosystems in South and Southeast Asia will be affected by SLRs with a "high degree of confidence." It also stated that future climate change would seriously affect water security in developing countries and negatively affect human health with a "moderate confidence" degree (URL-1).

The World Bank has analyzed five SSP scenarios for 21st-century income groups and six climate change scenarios from warming less than 1.5°C to 4°C for different countries. The results of these analyses indicate that costs can vary widely from one country to another by assuming no additional adjustments. For example, the cost of coastal damage for China is \$6,865 - \$9,904 billion at warming less than 1.5 °C and \$9,736 - \$12.301 billion at 4 °C warming; for Ghana, \$61.4 - \$87 billion at warming less than 1.5 °C and \$85.5 - 118.2 billion at 4 °C warming (Brown et al., 2021).

Long-term adaptation in port environments, such as upgrading infrastructure as SLR, is essential to prevent damage from SLR caused by climate change. SLR projections for 2100 and beyond, focusing on 100 significant ports in the United States with 704 million m^3 of landfill is required to raise land and infrastructure by 2 m, and about \$57-78 billion are needed according to 2012 values (Becker et al., 2017). In addition to the economic and infrastructure damage, this situation negatively affects livelihoods and increases health risks (Kahana et al., 2016; Vineis et al., 2011). SLR causes the formation of swampy areas on the coasts, the salinization of groundwater, and the formation of natural disasters by moving towards residential areas (Simav, 2012-2015). Hence, subduction in the world's largest deltas is among the most valuable coastal ecosystems with economic importance and dense population, in addition to the changes in the coastline and its surroundings, dynamic morphological changes in coastal structures, and erosion due to SLR rather than river flow, waves, and tides (Van De Lageweg and Slangen, 2017).

The two seas, the Black Sea and the Aegean Sea, are connected via the Sea of Marmara (Figure 1). The strait links between the Sea of Marmara and the Black Sea, called the Strait of Istanbul (Bosphorus), with a delicate balance. In this study, the observed time series of sea levels in the three stations in the coastal regions of SoI, Sea of Marmara, and Black Sea are analyzed to capture the sea level change caused by climate change. Therefore, Mann Kendall (MK) trend (Mann, 1945), Sen (1968). Slope analysis, and the change-points in both the mean and variance are calculated on the daily sea level time series to determine if there are any trends or sharp changes. Moreover, the simple linear regression equations describe the relationships among sea level data in the three stations. Determining the sea level changes in the SoI may help predict more accurately possible impacts so that managers can reduce or eliminate these impacts. This information will identify future risks to historical monuments and economically essential industry structures, and necessary measures can be taken.

Materials and Methods

This section explains the data and methods in detail: MK trend, Sen Slope, change-points, simple and multiple linear regression.

Study Area

The SoI is chosen as the study area because it forms the Asian and European coasts of Istanbul, has a high population, and has many historical buildings and industrial structures. The locations of three stations for the sea level changes are in the SoI, Sea of Marmara, and Black Sea, and their locations are shown in Figure 1. The length of the SoI, one of the strategically essential waterways connecting the Black Sea and the Sea of Marmara, is 29.9 km, and its width varies between 698 m (between Anatolia and Rumeli Hisari) and 3,600 m (between Anatolia and Rumeli Feneri in the north). It is formed when the waters overflow an old river valley (Taşlıgil, 2004; Gazioğlu et al., 2010).

There are two currents, top and bottom, depending on the level and density difference in the SoI waters. The surface current is formed by transporting the Black Sea waters to the SoI and the Sea of Marmara. The water level differences of the Black Sea are due to many rivers and has a salinity of 0.17 %, whereas the Sea of Marmara has a salinity of 0.23 % (Artüz, 2007; Mutlu et al., 2023).

The bottom current is formed when the Mediterranean water flows into the Black Sea, first through the the Strait of Çanakkale (Dardanelles:SoC) and then through the SoI straights. This current is controlled by the 50 m high threshold made of sand and gravel located in the northern extension of the SoI. The bottom layer current reaching the Black Sea forms a salt wedge on the continental shelf (Alpar and Yüce, 1998; Iorio and Yüce, 1999 Alpar et al., 2000). Considering the correlation between the salinity values of this salt wedge at 50 m - 300 m depths from the surface and the salinity values of the upper layer of the Aegean Sea, the bottom current is the continuation of the Mediterranean flow (Tsimplis et al., 2004).

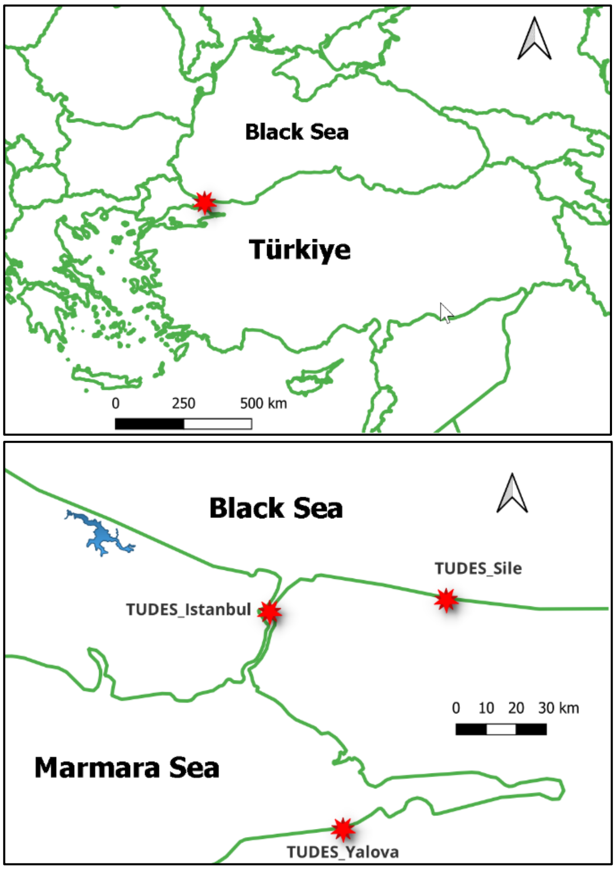

Fig. 1. Location of the SoI and three TUDES Stations: Sile station in the coastal Black Sea, Istanbul station in the nearshore of SoI, and Yalova station in the coastal area of Sea of Marmara.

Data

The General Command of Mapping carries out the Turkish National Sea Level Monitoring System (TUDES), which consists of 20 digital and automatic tide stations all over the coastal regions of Türkiye. Within the scope of this study, 15-minute average sea level measurement data are obtained for three stations, namely, Istanbul, Sile, and Yalova (Figure 1). Sea level measurement data covers 1 January 2009 to 31 December 2022 and has some gaps. After the missing data is replaced with the overall average of the station, a daily average is taken to minimize noise effects on the calculation, as shown in Figure 2. The key statistical parameters of daily sea level measurements are calculated and given in Table 1.

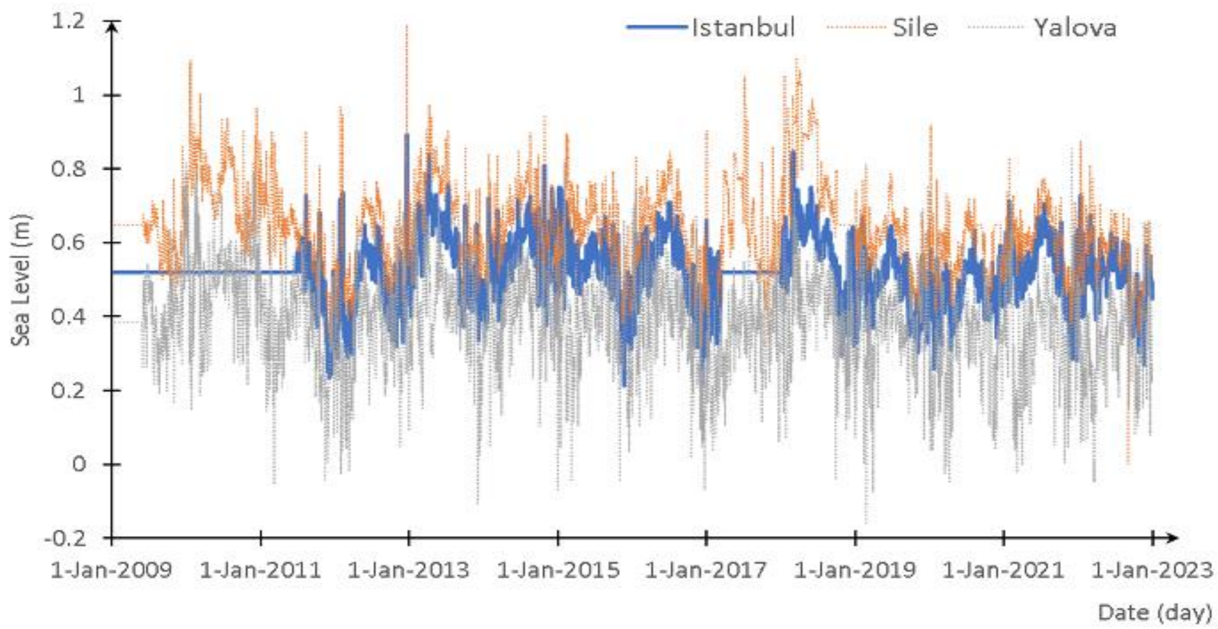

Fig. 2. Time series of the daily sea level data measured in meters at the TUDES Stations: Istanbul, Sile, and Yalova.

Table 1. Key Statistical Parameters of the daily sea level data measured in meters at the TUDES Stations are Istanbul, Sile, and Yalova.

Parameter	Istanbul	Sile	Yalova
Minimum	0.216	0.000	-0.157
1st Quartile	0.517	0.605	0.352
Median	0.521	0.649	0.386
Mean	0.519	0.645	0.383
3rd Quartile	0.524	0.665	0.428
Maximum	0.893	1.191	0.849

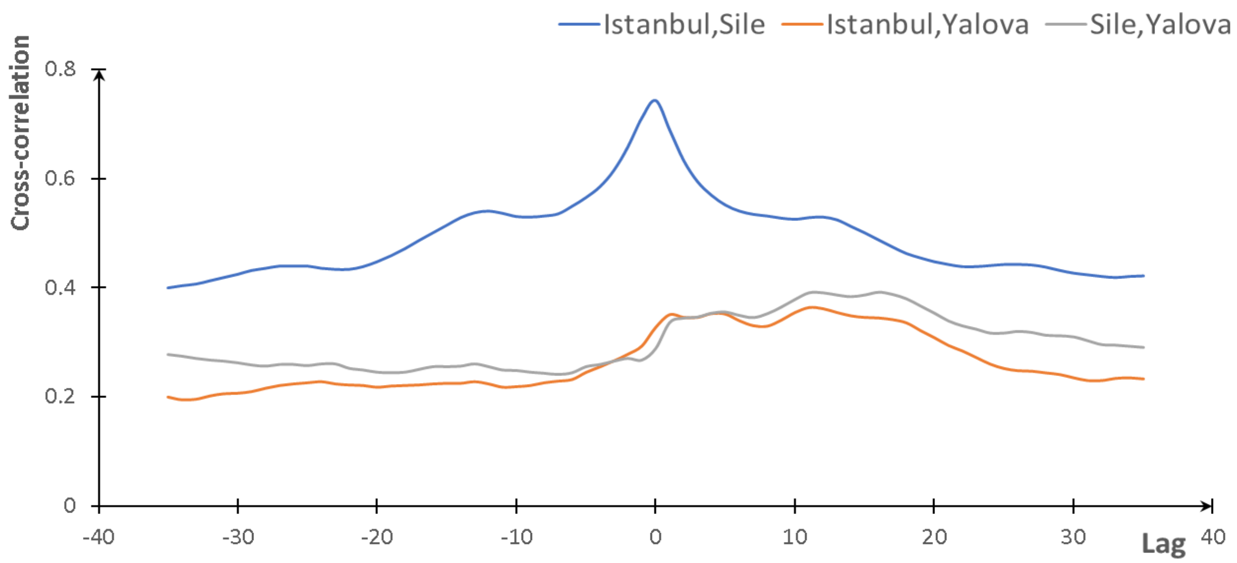

Fig. 3. The cross-correlation curve for a lag time ranging from -35-day to +35-day for the three TUDES Stations: Sile,

The cross-correlation of the daily average of the measured sea level data is calculated as 0.744 between the Istanbul-Sile stations, 0.327 between the Istanbul-Yalova stations, and 0.289 Sile-Yalova. The cross-correlation curves for lag time ranging from -35-day to +35-day for stations are given in Figure 3. The highest cross-correlation was obtained at 0-, 11-, and 16-day lag time for Istanbul-Sile, Istanbul- Yalova and Sile-Yalova stations, respectively. This result shows that the water level in the SoI is closely related to İstanbul-Sile stations, which are in the Black Sea region.

Trend Analysis

Mann-Kendall (Mann, 1945), Sen's Slope Test (Sen, 1968), and change-point analysis are used in this study as they are among the most widely used nonparametric analysis methods (Sharma et al., 2016).

Mann (1945) introduced the nonparametric trend test approach, and Kendall (1975) expanded the same method. The MK test is widely used to analyze hydro-meteorological time series trends. The MK test S statistic is determined by examining all the measurement pairs in the analyzed data set (Nguyen et al., 2022).
The following equation gives the MK test S statistic.

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \quad \text{(Eq.1)}$$

$$sgn(x) = \begin{cases} 1, & x > 0 \\ 0, & x = 0 \\ -1, & x < 0 \end{cases}$$

where xi and xj are ordinal data values, and n is the number of recorded data.
The mean of S is E[S] = 0, and the variance available (σ^2) is given as,

$$\sigma^2 = \frac{\left\{n(n-1)(2n+5) - \sum_{j=1}^{p} t_j(t_j-1)(2t_j+5)\right\}}{18} \quad \text{(Eq.2)}$$

where p is the number of linked groups in the dataset, and t_j is the number of data points in the j^{th} linked group. The S statistic is approximately normally distributed, provided the following Z transform is given in Equation 3.

$$Z = \begin{cases} \frac{S-1}{\sigma}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sigma}, & S < 0 \end{cases} \quad \text{(Eq.3)}$$

The S statistic is closely related to Kendall's τ, which has the following expression.

$$\tau = S/D \quad \text{(Eq.4)}$$

$$D = \left[\frac{1}{2}n(n-1) - \frac{1}{2}\sum_{j=1}^{p} t_j(t_j-1)\right]^{1/2} \left[\frac{1}{2}n(n-1)\right]^{1/2}$$

where x_i and x_j are ordinal data values, n is the number of recorded data.

Sen's slope is used to determine the magnitude of the trend in the time series that is not serially auto-correlated. He proposed this approach through regression coefficient estimates based on Kendall's τ (Sen, 1968). Later, Hirsch et al. (1982) expanded Sen's Slope Method through a nonparametric median-based slope estimation. The equation of the slope estimation is given as follows.

$$\beta = Median\left[\frac{x_j - x_k}{j-k}\right] \quad \text{(Eq.5)}$$

where $1 < k < j < n$ and β are the median of all possible pair combinations for the entire data set. The intersections are calculated for each time step *t* as,

$$a_t = X_t - (\beta * t) \quad \text{(Eq.6)}$$

The corresponding intersection is also the median of all intersections. Simply analyzing the trends and ignoring the change-point or vice versa can mislead calculations. Therefore, examining both possibilities allows better predictions for future projections (Sharma et al., 2016).

Change-Point Analysis

A change-point analysis is performed on time-ordered data to detect any sharp change in mean and variance. The number of changes is determined, and the time of each change is estimated. In addition, confidence levels for each change are provided in addition to confidence intervals for the time of each change (Chen and Gupta, 2000).

The change-point analysis is essential in investigating whether there is a sudden change in the time series and determining the change-points, if any. A change-point may occur due to changes in extreme value data, such as floods or droughts. Many methods are applied for change-point analysis, from nonparametric to fuzzy methods and all Bayesian approaches (Salarijazi et al., 2012).

Linear Regression

Simple linear regression is an approach used to model the relationship between a dependent variable and independent variables. In this study, simple linear regression and multiple linear regression are calculated using one and two independent variables. The simple and multiple linear regression equations are given as follows.

$$y_i = \beta_0 + \beta_1 * x_{i1} \quad \text{(Eq.7)}$$

$$y_i = \beta_0 + \beta_1 * x_{i1} + \beta_2 * x_{i2} \quad \text{(Eq.8)}$$

where y_i is the dependent variable, x_{i1} and x_{i2} are independent variables, β_0 is the intercept, and β_2 and β_1 are slope.

Sea Level Differences

The Marmara and Black Sea balance may change due to external and internal effects. Therefore, the value of the other station is subtracted from the water level values of all stations to obtain the temporal change of the sea-level difference using the following expression.

$$\Delta y_{ij} = y_i - y_j \quad \text{(Eq.9)}$$

where, i is Istanbul and Sile stations, j is Sile, Yalova stations.

Results

In light of all the previous sections, calculations are achieved by writing code using packages in the R program such as trend (URL-2), Kendall (URL-3), and changepoint (URL-4).

Trend analysis

The trend analysis of the three SWL measurements is calculated and given in Table 2. It is well-known that there is a trend if the p-value is less than 0.05. Sile station has the minimum p-value, which represents the statistically significant trend.

Kendall's tau value may vary between -1 and 1, and a positive (negative) value indicates an increasing (decreasing) trend. In addition, the magnitude of tau represents the strength of the trend. The highest tau value is calculated at the Şile station.

The slope of the trend is calculated, and Sen's slope is given in Table 2. Daily sea level data, measured at three TUDES stations, have no slope.

Table 2. Trend Analysis (Mann-Kendall and Sen's slope) for the three TUDES Stations

	Parameter	Istanbul	Sile	Yalova
Mann-Kendall	z	-2.35	-16.17	-6.42
	p-value	0.0188	$2.2*10^{-16}$	$1.4*10^{-10}$
	S	$-4.8*10^{5}$	$-3.4*10^{6}$	$-1.4*10^{6}$
	varS	$4.2*10^{10}$	$4.5*10^{10}$	$4.5*10^{10}$
	tau	$-1.9*10^{-2}$	$-1.3*10^{-1}$	$-5.2*10^{-2}$
	trend	decrease	decrease	decrease
	H_0	reject	reject	reject
Sen's slope	Intercept	0.521	0.649	0.386
	X	0	0	0
Conf. int. 0.025	Intercept	0.383	$4.56*10^{-1}$	0.177
	X	0	$-5.41*10^{-7}$	0
Conf. int. 0.975	Intercept	0.656	0.833	0.590
	X	0	0	0

Change-point analysis

The change-point times are given in Table 3, and there is no change in the means of the three stations. There are changes in the variance, most of which result from filling the gap with the station average value. The measured values come after the assigned mean values of the station as the change-point in variance.

Table 3. Change-point in mean and variance in the three TUDES stations

Change in	Istanbul	Sile	Yalova
mean	No	No	No
variance	26.06.2011	01.06.2009	27.05.2009
	26.09.2011	20.08.2009	15.12.2009
	21.07.2013	17.01.2018	28.12.2010
	01.06.2020	30.06.2018	25.09.2011
	11.06.2021	01.09.2022	27.03.2012

Linear Regression

The simple and multiple linear regression equations are established, assuming that the Istanbul station is dependent and the rest of the stations are independent variables. Moreover, the SLR for the Sile and Yalova stations is identified.

The determination coefficient values are calculated, and the highest value is obtained for the multiple linear regression equation among Istanbul and the rest of the stations as 0.567.

Table 4. Linear regression equations for the TUDES stations: Istanbul (dependent). The others are independent parameters, p-value $<2.2*10^{-16}$, and significant equals to 0.001.

Linear Regression Equation	R^2
Istanbul = 0.5382 * Sile + 0.1725	0.553
Istanbul = 0.2161 * Yalova + 0.4366	0.107
Sile = 0.2638 * Yalova + 0.5436	0.084
Istanbul=0.5126*Sile+0.0809*Yalova+0.158	0.567

Sea Level Differences

The temporal variation of the difference between all stations is calculated and given in Figure 4. The reason for the change corresponding to the years 2010-2011 period is that the value of the Istanbul station is equalized to the station's average due to the missing value, so the change is not taken into account (Figure 4).

Discussion and Conclusion

In this section, the results of trend change-point analyses are evaluated in addition to the differences of station data concerning each other by means of linear regression analysis.

The effective mechanisms of the strait flow are the net amount of freshwater entering the Black Sea, barometric pressure differences, wind speed, and direction (Özsoy et al., 2000). The top layer current waters, with a volume of approximately 230 $km^{3,}$ is renewed every 4-5 months, whereas the bottom layer waters, with a volume of approximately 3,378 $km^{3,}$ every 6-7 years (Beşiktepe et al., 1994; Oğuz et al., 1990). Therefore, the measurement results may have a single lag time or even more.

The MK test yielded a decreasing trend at all stations but no decreasing trend in Sen's slope (Table 2). This is because the MK calculation is based on the sign of the difference in time series, whereas Sen's slope estimate is the median of all two-point slopes. Sen's slope fails to capture many large downward slopes, while the MK can calculate the decreased trend.

Sea level values at Sile station have a significant and strong decreasing trend. The important freshwater resources of the Black Sea are the Tuna, Dnieper, and Dniester rivers in the northwest (Oğuz et al., 1990). The flow of the Tuna River has a significant impact on the water level and oceanographic regime of the Black Sea, which is thought to be also controlled by the SoI flow on a time scale (Beşiktepe et al., 1994; Ozturk and Altas, 2021). Moreover, many hydroelectric facilities and reservoirs operate at full capacity, leading to a decrease in annual flow rates (Tolmazin, 1985). Similarly, the amount of water from Sile and its surroundings to the Black Sea is decreasing due to the Melen water project that transports water to Istanbul, which may be the reason for the decreasing trend.

Most of the dates found in the change-point analysis in the time series indicate the changing time series due to the average value assigned to replace the missing data (Table

3). In other words, 2011, since there was no data at Istanbul station, it was filled with the average value, so the change-point here is not interpreted. Although this situation does not give the necessary clue to explain the time of change, it is still essential to show the success of the method for change-point detection.

The highest coefficient of determination of the linear regression is 0.537 when all stations are used together (Table 4). This shows that all stations are interacting with each other at different rates. The second highest value of the determination coefficient is found between Istanbul and Sile stations, and the largest cross-correlation coefficient was also obtained at these two stations at the zero-lag time (Figure 3). Moreover, when the difference between the two stations is taken, a nearly horizontal line is obtained (Figure 4).

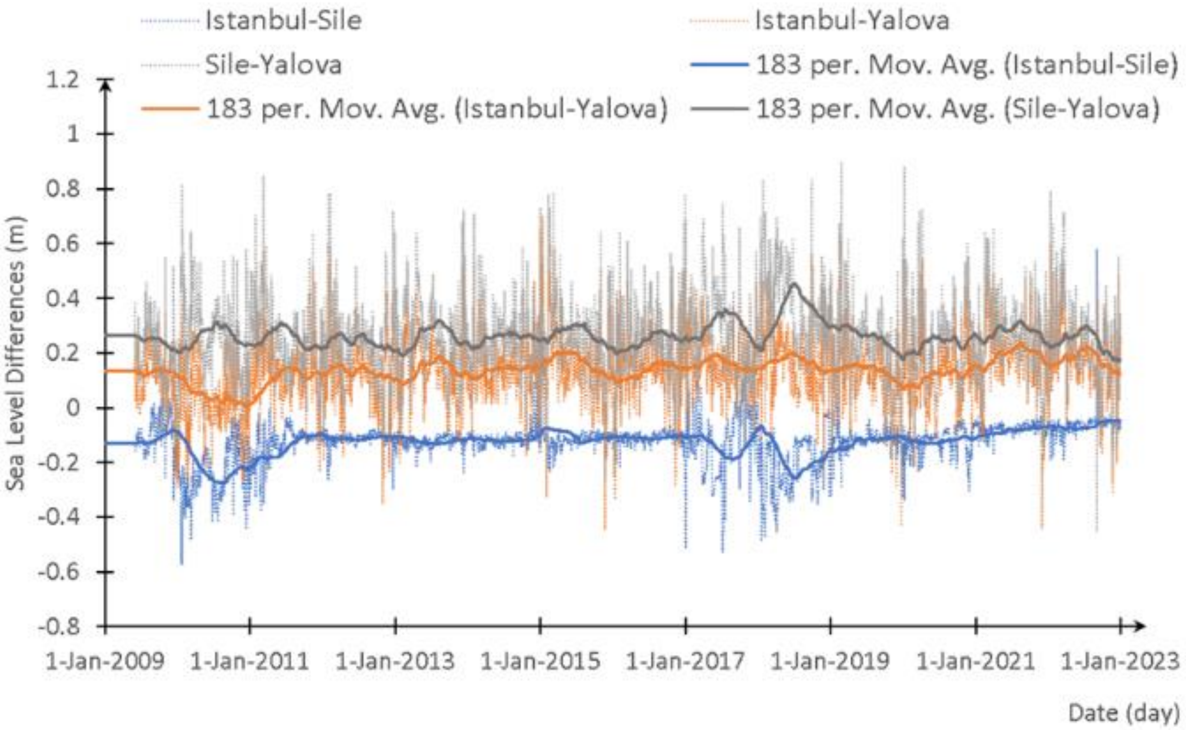

Fig. 4. Time series of the sea level difference between Istanbul and other stations.

At the Istanbul station, the sea level values are generally smaller than the values at the Sile station and larger than the values at the Yalova station (Figure 1).

Therefore, while the difference between Istanbul and Sile stations in sea level is negative, the difference between Istanbul and Yalova stations is positive (Figure 4). The fluctuation in the station differences in the 2010-2011 period is due to the filling of the missing data with the average value of the station. On the other hand, the fluctuation in the differences during the 2017-2018 period may be due to excessive precipitation, also defined as the change-point (Table 3). Sea level measurement values also include meteorological swell and tidal components. There is a tidal effect since Yalova station sea level values have a sinusoidal component. It is understood that hydro-meteorological events influence Sile station's sea level values.

The sea level stations are measured simultaneously, including meteorological parameters such as air pressure, temperature, wind direction, and strength, which significantly affect sea level changes (UNESCO, 1997). Since there are many gaps in the time series of meteorological parameters at the three stations, they are filled with the mean value in this study. As in many scientific studies, the success of analyzing sea level change depends on careful measurements over a long period (Pugh, 1988). Similarly, southerly wind causes the top layer to be trapped and even further pushes the waters sent to the SoI by the Sea of Marmara. Thus, the flow below the blocked top surface causes a three-layer flow formation. This flow blocked in the upper layer is balanced by reducing the water level difference at both ends (Oğuz et al., 1990). Therefore, the difference between Sile and Yalova may change with these parameters (Figure 4).

The sea and straits have their properties due to the complex geometry of the SoI, which is very effective on the current structure (Yüksel et al., 2018).
The morphological features, bathymetry, and balance of the straits determine their character, and it is impossible to predict this accurately without long-term observed data, so complete and accurate measurement data is essential for the accuracy of the management. Long-term data is also needed to understand the effects of climate change. With the help of these data and analyses, the vulnerabilities of the straits can be determined.

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