RELATIVE SEA LEVEL CHANGE ALONG THE BLACK SEA COAST FROM TIDE-GAUGE OBSERVATIONS

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ABSTRACT:

Potential sea level rise poses a significant threat to low-lying areas. Considering present and future of coastal areas, scientific study of sea level rise is an essential for adapting to sea level extremes. In this study, the relative sea level change in the Black Sea were investigated using data of 12 tide-gauge and 6 GNSS stations. Results generally indicated sea level rise along the Black Sea coast. Only at Bourgas tide-gauge station, a sea level fall was detected. A significant sea level change were not determined at Sinop tide-gauge station. On the other hand, at some stations such as Poti and Sile, ground subsidence contribution to relative sea level changes were observed.

1. INTRODUCTION

Global sea level is rising, and there is evidence that rate of its rise has been accelerating especially for since early 19th century (Church et al., 2013). Increasing concentration of greenhouse gases, primarily from human contributions, are warming the atmosphere and oceans. The higher temperatures cause sea level rise by expanding ocean water, melting glaciers, and possibly increasing the rate at which ice sheets discharge water into the oceans.

Today, nearly 10% of the world population is living in coastal areas less than 10 m above sea level (Cazenave and Le Cozannet, 2014). In this sense, the possible consequences of sea level rise pose an increasing threat to coastal cities, inhabitants, infrastructure, wetlands, ecosystems, and beaches (Nicholls, 2010). It is clear that, rising sea level can affect human activities in coastal regions, cause to inundate low-lying land, contributes to coastal storms and flooding, induce shoreline erosion, and increase salt water intrusion into estuaries and nearby groundwater aquifers. Furthermore, according to high concentration scenarios global sea level are expected to rise by 45 to 82 cm by 2090 (IPCC, 2013). Eventually, rising sea level and potentially more intense storms will exacerbate possible consequences, and more frequent extreme sea level events will occur.

When sea level is referred to the Earth’s centre of mass, it is defined as “absolute sea level” whereas when it is referred to a fixed point that is used as a reference on the solid Earth, it represents “relative sea level”. Thus, if considering coastal impacts of sea level change, relative sea level is the more relevant quantity, and it has been measured using tide-gauges for the past few centuries. In this context, this study focuses on relative sea level trends in the Black Sea coast. For this aim, the sea level observations from available 12 tide gauge stations along the Black Sea coast were analysed in this study.

On the other hand, the tide gauge observations contain some geophysical (i.e., non-oceanographic) signals, as tide-gauges measure sea level relative to the adjacent land (Avsar et al., 2016; 2017; Wöppelmann and Marcos, 2016). In active tectonic and volcanic regions, or in areas subject to strong ground subsidence due to natural causes (e.g., sediment loading in river deltas) or human activities (ground water and oil/gas extraction), or in the rising land areas due to the Glacial Isostatic Adjustment (GIA); tide-gauge records are directly affected by the corresponding land motions. In order to determine absolute sea level change, the ground motions need to be removed (Woodworth and Player, 2003). The measurement of such vertical ground movements is available from Global Navigation Satellite System (GNSS) (episodic or continuous), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), absolute gravity, and/or precise levelling. In this sense poor knowledge of vertical ground motion can distort the sea level rise estimates, which in turn causes assessment of the coastal impacts deficiently. In this study, in order to determine ground motions’ contribution to relative sea level changes, the continuous GNSS data were provided from nearly co-located GNSS stations with the available tide-gauge locations.

2. RELATIVE SEA LEVEL CHANGE IN THE BLACK SEA

2.1 Tide-Gauge Records along the Black Sea Coast

Long-term sea level data are required to determine sea level changes with high accuracy. At least 50 year-records are needed to separate secular, decadal and interannual variations, and obtain more accurate trend estimations of sea level change (Douglas, 2001; Fenoglio-Marc and Tel, 2010). The existence of long-term data in many tide-gauge stations is still one of the most important reasons for using these stations in sea level measurements. Nevertheless, there are some problems in tide-gauge stations along the Black Sea coast, such as poor spatial distribution. Each station has a different data length. Moreover, most of the records suffer from data gaps and/or short data period. Note that the numbers of obtainable tide-gauge station data are limited. In this study, data of 12 tide-gauge stations on

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the Black Sea coast have been used, which have different time intervals. 7 tide-gauge stations (Poti, Batumi, Sevastopol, Tuapse, Varna, Bourgas, and Constantza) located at along the Black Sea coast have been chosen from the Permanent Service for Mean Sea Level (PSMSL) (PSMSL, 2019) and other 5 tide-gauge (Amasra, Igneada, Trabzon, Sinop, and Sile) are from the Turkish Sea Level Monitoring System (TUDES) (TUDES, 2019). Figure 1 shows the locations of all the stations in this study. An overview of the tide-gauges is given in Table 1.

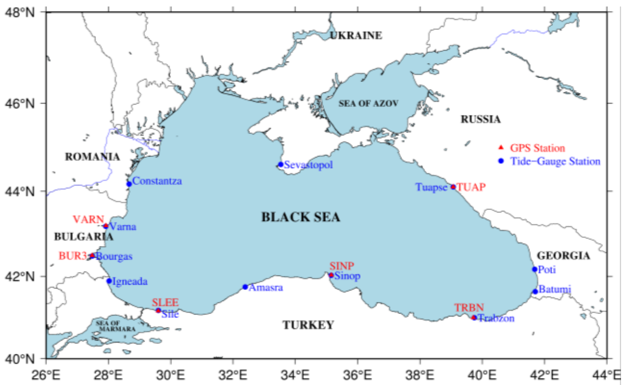
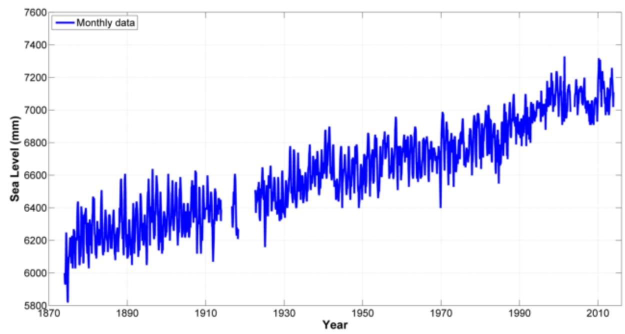


Figure 1. Data locations in the study: Tide-gauge stations (blue), GPS stations (red).

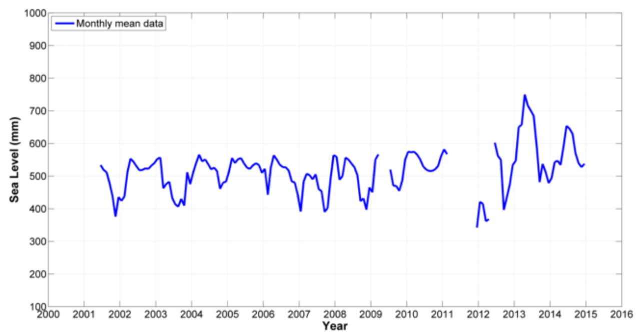
Tide-gauge station (Country)	Location		Time-span	Data gaps (%)
	Latitude	Longitude		
Poti (Georgia)	42 10 N	41 41 E	Jan. 1874 Dec. 2013	~ 5.7
Batumi (Georgia)	41 38 N	41 42 E	Jan. 1882 Dec. 2013	~ 13.4
Sevastopol (Ukraine)	44 37 N	33 32 E	Jan. 1910 Dec. 1994	~ 3.1
Tuapse (Russia)	44 06 N	39 04 E	Jan. 1917 Dec. 2011	~ 1.0
Varna (Bulgaria)	43 11 N	27 55 E	Jan. 1929 Dec. 1996	~ 4.9
Bourgas (Bulgaria)	42 29 N	27 29 E	Jan. 1929 Dec. 1996	~ 13.7
Constantza (Romania)	44 10 N	28 40 E	Jan. 1933 Dec. 1997	~ 5.0
Amasra (Turkey)	41 45 N	32 24 E	Jun. 2001 Dec. 2014	~ 9.4
Igneada (Turkey)	41 53 N	28 01 E	Jun. 2002 Dec. 2014	~ 5.3
Trabzon (Turkey)	41 00 N	39 44 E	Jul. 2002 Dec. 2014	~ 0.7
Sinop (Turkey)	42 01 N	35 09 E	Jun. 2005 Dec. 2014	0
Sile (Turkey)	41 11 N	29 37 E	Jul. 2008 Dec. 2014	0

Table 1. General information on all the tide-gauge stations used in this study.

Revised Local Reference (a common datum which is defined to be approximately 7000 mm below mean sea level, for each tide-gauge station) data from the PSMSL are the monthly averaged time series, spanning from 65 to 140 years in the period of 1874–2013. As for the TUDES data, the data have been provided at 15-minute intervals in the Turkish National Vertical Control Network-1999 (TUDKA-99) datum. In the study, the monthly averaged time series of the TUDES data have been derived at each station. The record with the longest time period among these stations extends to mid-2001 at Amasra. As an example, Figure 2 demonstrates the evolution of sea level at Poti and Amasra tide-gauges.



a) Poti



b) Amasra

Figure 2. Monthly mean sea level changes at tide-gauge stations along the Black Sea coast.

2.2 Analysis of Tide-Gauge Data

Sea level measurements from the TUDES network along the Black Sea coast are not long-term (< 20 years) while the tide-gauge time series provided from the PSMSL have an enough period for long-term trend estimation. In addition, some sea level time series contain the missing observations. For example, nearly 13.4% of the records at the Batumi and nearly 13.7% of the records at Bourgas are void (see Table 1). Although the data of some tide-gauge stations are short-term, the time series of sea level change for all the stations have indicated a trend and seasonal fluctuations. Therefore, the following equation was used in the analysis of the sea level time series from the tide-gauge stations along the Black Sea coast (Feng et al., 2013):

$$M(t) = M(t_0) + v(t - t_0) + \sum_{k=1}^{2} A_k \cos(\omega_k (t - t_0) + \varphi_k) + \varepsilon(t) \quad (1)$$

where $M(t)$: sea level time series
t: time, t_0: beginning time
$M(t_0)$: mean sea level at t_0
v: rate of sea level change (linear trend)

$k = 1$ annual signal, $k = 2$ semi-annual signal
A: amplitude
ω: angular frequency
φ: phase
$\varepsilon(t)$: unmodelled residual term.

The seasonal variation of sea level time series can be expressed as the sum of a number of sine and cosine terms as in Equation (1). Here, in order to examine the long-term variability of the sea level time series, the seasonal components have been removed from the monthly values by simple subtraction of the estimates obtained by least squared fitting of seasonal sinusoids with annual and semi-annual periods. And the relative sea level change trends have been estimated for each station. In the evaluation, the data gaps that result from due to reasons such as equipment failure, power failure, etc., in the stations, have been excluded. However, the data with less than 4 consecutive missing months have been used through linearly interpolating. According to this, the linear variation with time of observed sea level in the tide-gauge stations are given in Table 2.

Tide-gauge	Time-span	Trend (mm/year)
Poti	Aug. 1922 - Dec. 2002	7.01 ± 0.12
Batumi	Jan. 1925 - Dec. 1996	3.52 ± 0.15
Sevastopol	Sep.1944 - Dec. 1994	1.56 ± 0.22
Tuapse	Jan. 1943 - Dec. 2011	2.92 ± 0.14
Varna	Jan. 1926 - Nov. 1961	1.53 ± 0.48
Bourgas	Feb. 1981 - Jan. 1996	-7.52 ± 1.33
Constantza	Jan. 1945 - Dec. 1979	3.02 ± 0.46
Amasra	Jun. 2001 - Feb. 2011	3.43 ± 1.42
Igneada	Jun. 2002 - Dec. 2014	6.94 ± 2.18
Trabzon	Jul. 2002 - Dec. 2014	2.33 ± 1.75
Sinop	Jun. 2005 - Dec. 2014	0.43 ± 2.88
Sile	Jul. 2008 - Dec. 2014	5.03 ± 4.84

Table 2. Trends of relative sea level changes at the tide-gauge stations along the Black Sea coast (The longest data periods of the tide-gauges were used for the analysis).

As an example, the trend, and curve fitting model with Equation (1) of the Amasra tide-gauge data are represented in Figure 3.

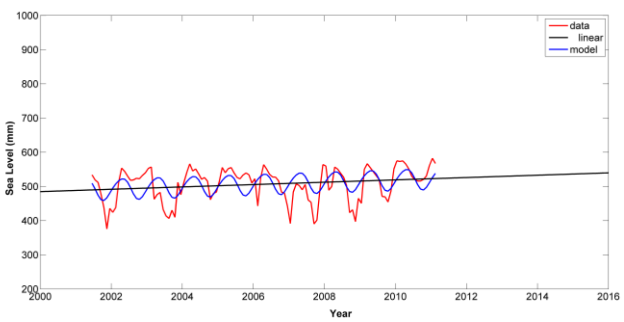


Figure 3. Trend and curve fitting model of ~ 10-year sea level time series at Amasra tide-gauge station.

The trend of each tide-gauge station have been derived from the varying record lengths considering the data gaps. Accordingly, the results in Table 2 show that rate of the relative sea level varies from coast to coast. Consequently, nearly all the tide-gauge stations (except for Bourgas) indicated the rising sea levels. The distribution of the data gaps in Bourgas sea level time series did not allowed a reliable trend estimate for this station, despite the interpolation. In addition, the Sinop station showed no significant sea level change. The non-significant results may be related to the short records, since trend estimations are sensitive to the record length. At the Poti station a highly sea level trend of 7.01 ± 0.12 mm/year were calculated. This relative sea level rise may be resulted from the subsidence at the Poti coast as mentioned in Ginzburg et al., (2011).

2.3 Assessment of Vertical Velocities of GNSS Stations

Unfortunately, in order to monitor ground motions at the tide-gauge stations along the Black Sea coast, the number of the GNSS receivers/stations attached directly to the tide-gauge or located nearby are very sparse. So, we have the vertical rates of only 6 GNSS stations nearly co-located with the tide-gauge stations in this study (see Figure 1).

The vertical displacement time series of 3 stations (TUAP, VARN and BUR3) of these GNSS stations were provided from the Nevada Geodetic Laboratory (NGL) (NGL, 2019). Other 3 stations (TRBN, SINP and SLEE) are continuous GNSS stations from the Turkish National Permanent Real Time Kinematic Network (TUSAGA-Active) (TUSAGA, 2019). Their data varying from 2009 to 2014 had been processed using the GAMIT/GLOBK software in Avsar et al., (2017). The obtained GNSS time series have been analysed by using Equation (1), and thus the vertical ground motions at these 6 GNSS stations have been estimated. Accordingly, for the Tuapse, Varna, Bourgas, Trabzon, Sinop and Sile tide-gauge locations, the GNSS-derived vertical velocities are presented in Table 3 along with the distances between the tide-gauge and related GNSS stations.

Tide-gauge station	GNSS station	Time-span		Distance (km)	Vertical velocity (mm/year)
		Tide-gauge	GNSS		
Tuapse	TUAP	1943 2011	2015 2017	0.05	-1.7 ± 0.5
Varna	VARN	1926 1961	2005 2017	2.1	-1.1 ± 0.1
Bourgas	BUR3	1981 1996	2009 2014	1.5	4.2 ± 0.2
Trabzon	TRBN	2002 2014	2009 2014	2.8	-1.9 ± 0.3
Sinop	SINP	2005 2014	2010 2014	0.8	6.2 ± 2.5
Sile	SLEE	2008 2014	2009 2014	1.2	-3.0 ± 0.6

Table 3. Vertical ground motions at the tide-gauge locations along the Black Sea coast.

The results in Table 3 show land subsidence motions at Tuapse, Varna, Trabzon and Sile locations. On the other hand, land uplift motions have been seen at Bourgas and Sinop locations. As mentioned in Garcia et al., (2007), vertical motions of the land in coastal areas masquerade as an apparent sea level change, namely, an apparent sea level rise would be added to the absolute sea level motion as the land sinks, and conversely. Accordingly, especially for Sile, the high relative sea level rise may result from the land subsidence. Here, the time-span of GNSS time series does not exactly coincide with those of tide-gauges. Nevertheless, the GNSS-derived estimates can give information on the recent ground motions along the Black Sea coast.

3. CONCLUSIONS AND SUGGESTIONS

Since tide-gauge measurements are made with respect to a local fixed reference level on land, the tide-gauge data reflect the relative sea level change. If there is a vertical ground motion at that tide-gauge location, the tide-gauge record is a combination of local sea level change and vertical ground motion at the location. Therefore, in order to obtain absolute coastal sea level change, the vertical land motion should be added via the GNSS observations.

However, most of available tide-gauge data along the Black Sea coast are not up to date. Nevertheless, in this study by using the available data coastal sea level changes in the Black Sea were assessed, and generally seen a rise in the relative sea level. The results showed that at some tide-gauge locations, there were significant vertical movements. For example, at the Poti and Sile locations, the relative sea level rises implying the significant land subsidence was observed. The GNSS measurements at the SLEE station support this finding.

If the relative contribution of local ground movement to the sea level change are revealed, it enables to detect climate-related regional sea level change in the Black Sea. For this purpose, a regional network of tide-gauge stations having a suitable spatial distribution along with co-located continuous GNSS stations along the Black Sea coast should be established.

The observed rise rates along the Black Sea coast may be significant for coastal erosion threat. At present, coastal erosion is a major challenge in the Black Sea coastline, especially for alluvial areas. The results of this study show that accurately modelling of sea level changes depending on time and location in the Black Sea is crucial for risk assessments related to sea level rise and planning of coastal area use. Local, regional and national patterns of potential consequences of sea level rise should be assessed, and coastal vulnerabilities should be identified. The implications of sea level rise should be considered for population location, economic, infrastructure, and construction planning. The necessary precautions for reducing effects of sea level rise should be implemented for all coastal areas.

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