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Geodesy and Geodynamics

Sea level change along the Black Sea coast from satellite altimetry, tide gauge and GPS observations

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ABSTRACT

Sea level change affects human living conditions, particularly ocean coasts. However, sea level change is still unclear along the Black Sea coast due to lack of in-situ measurements and low resolution satellite data. In this paper, sea level change along the Black Sea coast is investigated from joint satellite altimetry, tide gauge (TG) and Global Positioning System (GPS) observations. The linear trend and seasonal components of sea level change are estimated at 8 TG stations (Amasra, Igneada, Trabzon-II, Sinop, Sile, Poti, Tuapse, and Batumi) located along the Black Sea coast, which are compared with Satellite Altimetry and GPS. At the tide gauge stations with long-term records such as Poti (about 21 years) and Tuapse (about 19 years), the results obtained from the satellite altimetry and tide gauge observations show a remarkably good agreement. While some big differences are existed between Satellite Altimetry and TG at other stations, after adding vertical motion from GPS, correlation coefficients of the trend have been greatly improved from 0.37 to 0.99 at 3 co-located GPS and TG stations (Trabzon-II, Sinop and Sile).

1. Introduction

With global warming and climate change recently, sea level change is affecting our human living conditions [1]. Sea level change contains two main causes: (1) volume change due to density changes of sea waters, and (2) mass change due to water exchange with atmosphere and land through precipitation, evaporation, river runoff and ice melting [2,3]. Thus, sea level change is not geographically uniform [4]. Therefore, accurate estimations of sea level change are important to estimate and predict its impacts on coastal and island regions. Since late 1992, satellite altimetry has nearly provided global measurements of absolute sea and lake level changes [5,6]. On the other hand, global sea level change has been measured from numerous networks of coastal tide gauges around the world since the 18th century [7]. However, as tide gauge measurements are made with respect to a local

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fixed reference level on land, the tide gauge data reflect the relative sea level change [8]. If there is vertical land motion at the tide gauge location, the tide gauge record is a combination of the local sea level change and the vertical land motion. Therefore, in order to obtain absolute coastal sea level change, the vertical land motion at tide gauge location should be added, such as from levelling and GPS observations.

The Black Sea is an inland sea and filled with salty water by sea level rise at the end of the last glacial period when it was a freshwater body [9]. Today, the Black Sea exchanges water with the Mediterranean Sea only through the Bosphorus and Dardanelles Straits. On the other hand, the north-western shelf of the Black Sea receives the discharges from the Europe's largest rivers. Using satellite altimetry data [10] reported that the Black Sea basin shows an increase in sea level with around 0–5 mm/yr from January 1993 to December 2014. Ref. [11] also pointed out that due to the cyclonic Rim Current intensification the Black Sea level was rising at 8–9 mm/yr in the coastal areas of the Black Sea basin that exceeded in the offshore by 1.5–2 times (4.5–6 mm/yr) for the period of 1992–2005. Thus, estimation of the Black sea level change has large uncertainty.

In this study, sea level changes along the Black Sea coast are estimated from tide gauge and multi-mission satellite altimetry data as well as GPS. Because of some problems in tide gauges, such as poor spatial distribution along the Black Sea, less tide gauge data and short overlapping period, we concentrate only on the analysis of sea level change at 8 tide gauge stations along the eastern and southern coasts of the Black Sea (Fig. 1). Because each tide gauge station has different data period, the satellite altimetry time series has been analyzed at the same time period (Table 1). Moreover at 3 stations with co-located GPS and TG, the sea level change is analyzed and compared.

2. Data and method

2.1. *Satellite altimetry data*

For this study, gridded daily sea level anomalies maps with spacing of 1/8° × 1/8° are provided from the French Archiving, Validation and Interpretation of the Satellite Oceanographic Data (AVISO; http://www.aviso.altimetry.fr/en/data.html).

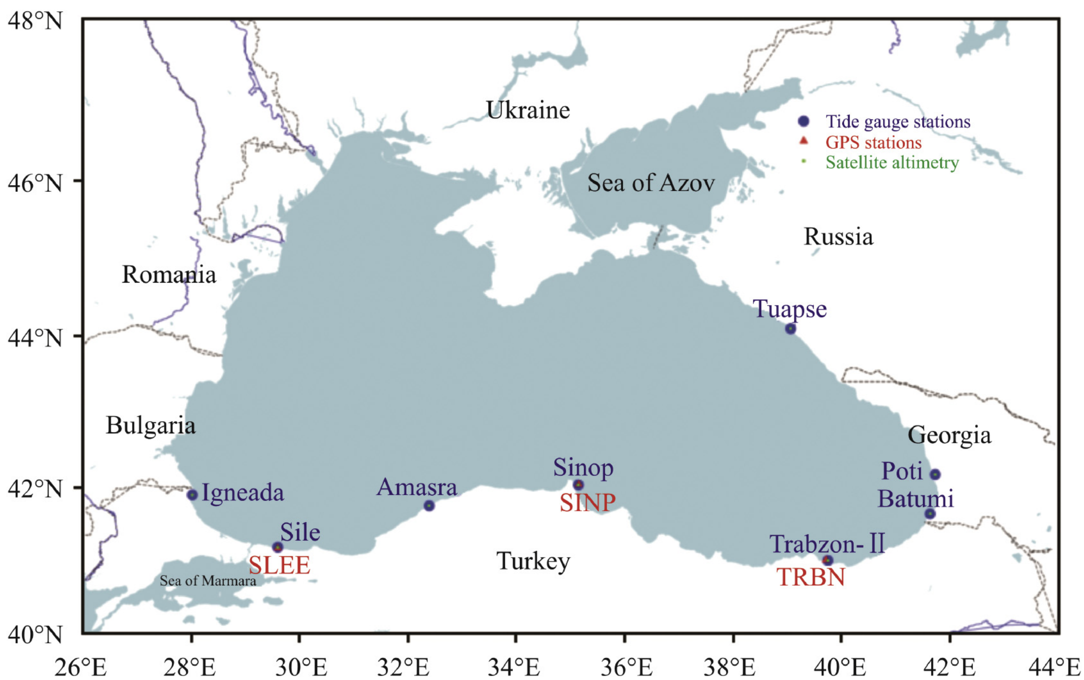

Fig. 1 – The locations of observation stations used in the study.

Table 1 – Trends of sea level change from satellite altimetry and tide gauge data at the same observation period.

Tide gauge station	Location		Distance (km)	Time span	Trend (mm/yr)	
	Latitude	Longitude			Satellite altimetry	Tide gauge
Poti	42°10″N	41°41″E	2.4	Jan. 1993–Dec. 2013	3.45 ± 0.78	4.13 ± 0.78
Tuapse	44°06″N	39°04″E	4.2	Jan. 1993–Dec. 2011	3.42 ± 0.86	4.30 ± 0.88
Batumi	41°38″N	41°42″E	6.2	Sep. 2003–Dec. 2013	1.38 ± 2.29	3.47 ± 2.56
Amasra	41°45″N	32°24″E	7.9	June 2001–Dec. 2012	0.95 ± 1.72	0.07 ± 1.45
Igneada	41°53″N	28°01″E	7.9	July 2002–Dec. 2014	2.19 ± 1.66	6.74 ± 2.08
Trabzon-II	41°00″N	39°45″E	8.6	July 2002–Dec. 2014	−0.38 ± 1.65	2.33 ± 1.76
Sinop	42°01″N	35°09″E	6.0	June 2005–Dec. 2014	7.05 ± 2.48	0.43 ± 2.88
Sile	41°11″N	29°36″E	5.5	July 2008–Dec. 2014	3.61 ± 4.57	5.03 ± 4.84

This data set is a product of combined data from several altimetry missions. It spans the period from January 1993 to December 2014. The altimetric measurements have been corrected for atmospheric effects (ionospheric delay and dry/wet tropospheric effects) and geophysical processes (solid, ocean, and pole tides, loading effect of the ocean tides, sea state bias, and the Inverted Barometer response of the ocean). Detailed information of the corrections can be found at the AVISO website. In order to compare with tide gauge (+GPS) results, we have computed the monthly altimetry time series using the daily data at the closest grid points to the tide gauge location. Considering the grid interval, the altimetric points are chosen with less than 10 km to the tide gauges (Table 1). Fig. 1 shows the locations of all the data used in this study.

2.2. Tide gauge data

In this study, 5 tide gauge stations (Amasra, Igneada, Trabzon-II, Sinop, and Sile) along the southern Black Sea coast are selected from the Turkish Sea Level Monitoring System (TUDES; http://www.hgk.msb.gov.tr/english/u-12-turkish-sea-level-monitoring-system–tudes-.html). The TUDES data are provided at 15-minute intervals in Turkish National Vertical Control Network-1999 (TUDKA-99) datum. The record with the longest time period among these stations extends to mid-2001 at Amasra. In addition, we have also analyzed 3 tide gauge stations (Poti, Batumi, and Tuapse) with long-term data from the Permanent Service for Mean Sea Level (PSMSL; http://www.psmsl.org/data/) database. The Revised Local Reference (RLR) data from the PSMSL are the monthly averaged time series, spanning from 10 to 21 years in the period of 1993–2013. This study does not include the western and northern Black Sea coast because of the short time series of available tide gauges for the altimetry period. In addition, some time series contain several missing observations. For example, although the Batumi station has sea level record of 21-year, its 32% is invalid. Thus, at this station only 10-year record is useful for present study. General information on all the tide gauges in this study and their studied data period corresponding the altimetry period are given in Table 1.

2.3. GPS data

Generally, continuously operating GPS stations co-located with tide gauge stations [12,13], or episodic GPS and precise levelling measurements (like at TUDES) are used to monitor the vertical land motions at the tide gauge sites. A number of studies have utilized nearby GNSS (Global Navigation Satellite Systems) stations from national or international networks [14] or DORIS (Doppler Orbitography and Radio-positioning Integrated by Satellite) observations [15] to observe vertical land motions. In this study, to estimate absolute sea level changes from the tide gauges, three available GPS data with co-located TG stations are also used from January 1st 2010 to December 31st of 2014 (TRBN, SINP, and SLEE) from the Continuously Operating Reference Station-Turkey (CORS-TR) Network. Using the IERS (International Earth Rotation Service) solid Earth tide and pole tide model, and a 10° elevation cut-off angle, the vertical coordinates of GPS stations are obtained using the GAMIT/GLOBK software [16].

Since the Glacial Isostatic Adjustment (GIA) effect is minimal in the Black Sea region [17,18], it is negligible for this study.

3. Results and analysis

The monthly time series of sea level measurements from the satellite altimetry and 8 tide gauge stations (+available 3 GPS stations) are used to estimate the sea level change along the Black Sea coast. For example, the time series at the Sinop tide gauge site are depicted in Fig. 2. As we can see, the time series of satellite altimetry and tide gauge (+GPS) present show almost similar behaviour in the sea level change. All the time series have a seasonal signal (annual plus semi-annual) and a trend as mentioned in [19], which can be expressed as follows [20]:

$$SLC(t) = a + bt + \sum_{k=1}^{2} c_k \sin[\omega_k(t - t_0) + \varphi_k] + \varepsilon(t) \quad (1)$$

where $SLC(t)$ is the sea level change time series, t is time, t_0 refers to January 1993, a and b are the constant and the trend, respectively, c_k, ω_k and φ_k are the amplitude, the frequency and the phase, respectively, $k = 1$ and $k = 2$ are for the annual variation and the semi-annual variation, respectively, and $\varepsilon(t)$ is the un-modelled residual term. Here, in order to estimate the trend and the seasonal components, the least squares method is used.

The linear trends of satellite altimetry and tide gauges time series are shown in Table 1 and Fig. 3 for each station. The results for the stations with long-term records such as Poti and Tuapse have a good agreement. At some stations like Amasra the linear rates of both observation data are not statistically significant with a correlation coefficient of −0.08 between altimetry and tide gauges time series. It may result from the short time span or the data gaps. According to Ref. [21], sea level trends obtained from tide gauges records of shorter than about 50–60 years are corrupted by interdecadal sea level variation. In addition, Ref. [22] have stated that coastal sea level has much more short-term variability than the global sea level, and tide gauge records have considerable interannual and annual variability. Moreover, the seasonal variation of sea level is also significant [23]. Seasonal components of sea level change

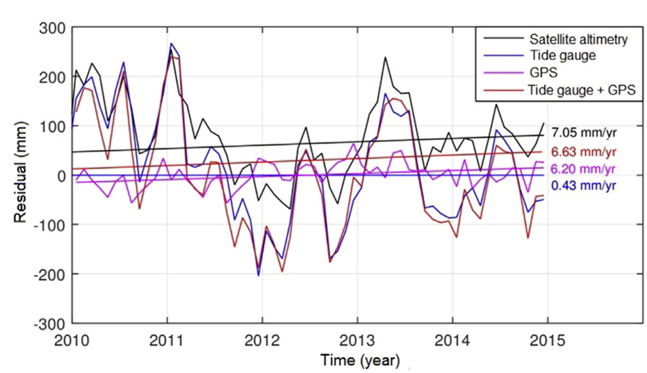

Fig. 2 – Sea level change time series at SINOP station from satellite altimetry (black), tide gauge (blue), and tide gauge + GPS (red), and GPS vertical motion (pink).

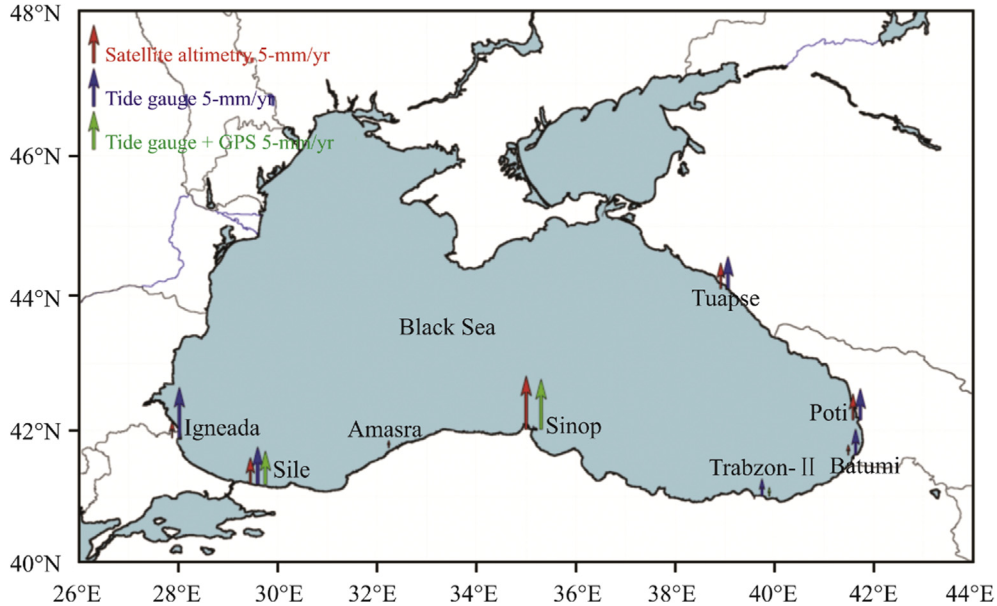

Fig. 3 – Trends along the Black Sea coast.

along the Black Sea coast are given in Table 2. Accordingly, the results are generally in good agreement with each other. Along the Black Sea coast, the average annual amplitude of sea level variations is about 35.44 mm from the satellite altimetry, and 55.72 mm from the tide gauges. The annual cycles of sea level variations measured by the altimetry reach the maximum values almost a month later than the sea level variations obtained from tide gauge data. The correlation coefficient between the seasonal components of two time series is 0.45 and 0.48 for the annual amplitude and the annual phase, respectively.

Since the tide gauge record contains changes of the ground level at a tide gauge site, while GPS can measure vertical land motions. Here, the vertical land motions at 3 co-located tide gauge sites along the southern Black Sea coast are estimated from nearby GPS stations and added to the results obtained from the tide gauge data. For Trabzon-II, Sinop and Sile stations, the trend of sea level change from tide gauge + GPS are presented in Table 3 along with those computed from the satellite altimetry. The results derived from the satellite altimetry, tide gauge, and tide gauge + GPS are also shown in Fig. 3. It is clearly seen that the results of satellite altimetry and tide gauge + GPS have a better agreement.

Table 3 – Linear rates of sea level change from satellite altimetry and tide gauge + GPS time series at 3 tide gauge stations along the southern Black Sea coast.

Tide gauge station	Trend (mm/yr)	
	Satellite altimetry	Tide gauge + GPS
Trabzon-II	−0.38 ± 1.65	1.21 ± 1.78
Sinop	7.05 ± 2.48	6.63 ± 3.81
Sile	3.61 ± 4.57	4.44 ± 4.85

Their relationships are further analyzed (Fig. 4). The correlation between satellite altimetry and tide gauge + GPS has much improved. Fig. 5 shows the differences between the trends obtained from the satellite altimetry, the tide

Table 2 – Seasonal components of sea level change from satellite altimetry and tide gauge.

Tide gauge station	Satellite altimetry				Tide gauge			
	Annual		Semi-annual		Annual		Semi-annual	
	Amplitude (mm)	Phase (°)	Amplitude (mm)	Phase (°)	Amplitude (mm)	Phase (°)	Amplitude (mm)	Phase (°)
Poti	30.70 ± 6.68	−33.83 ± 0.17	23.65 ± 6.68	−44.67 ± 0.28	45.97 ± 6.86	−44.65 ± 0.15	17.22 ± 6.87	−76.77 ± 0.40
Tuapse	42.76 ± 6.71	3.47 ± 0.01	19.50 ± 6.70	−64.21 ± 0.34	55.75 ± 6.85	−31.93 ± 0.09	26.80 ± 6.83	−78.81 ± 0.25
Batumi	43.52 ± 9.62	22.74 ± 0.12	26.24 ± 9.62	80.35 ± 0.37	90.08 ± 10.87	−46.46 ± 0.12	14.37 ± 10.75	71.98 ± 0.75
Amasra	24.59 ± 8.15	−44.89 ± 0.33	20.44 ± 8.11	76.50 ± 0.40	27.40 ± 6.78	−43.90 ± 0.24	9.30 ± 6.57	69.17 ± 0.72
Igneada	23.16 ± 8.59	−37.91 ± 0.32	11.54 ± 8.50	62.00 ± 0.74	52.11 ± 10.89	−66.09 ± 0.27	22.54 ± 10.88	16.59 ± 0.49
Trabzon-II	22.46 ± 8.44	−16.91 ± 0.16	22.46 ± 8.43	−57.83 ± 0.38	62.65 ± 8.99	−48.58 ± 0.15	27.27 ± 9.01	−77.18 ± 0.33
Sinop	33.41 ± 9.73	−36.02 ± 0.24	26.50 ± 9.68	72.16 ± 0.37	49.04 ± 11.26	−60.82 ± 0.28	29.52 ± 11.27	47.94 ± 0.38
Sile	62.92 ± 12.84	−23.86 ± 0.12	22.90 ± 12.84	70.87 ± 0.56	62.74 ± 12.66	−51.00 ± 0.20	22.84 ± 12.66	48.96 ± 0.55

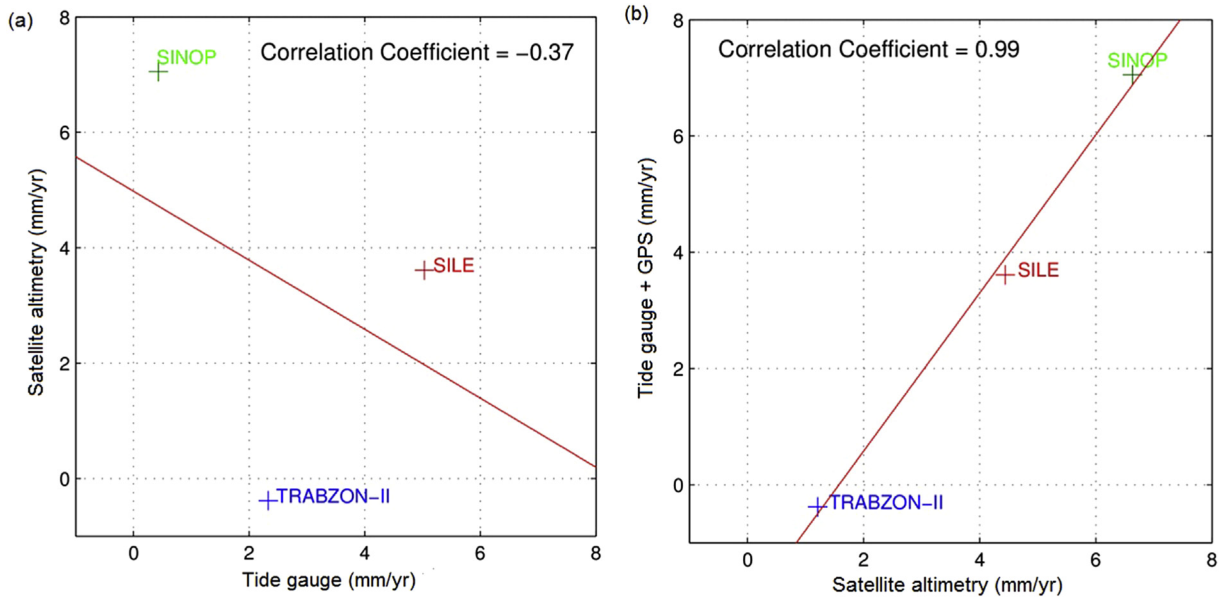

Fig. 4 – Correlations between the trends of (a) Satellite altimetry and tide gauge time series, (b) Satellite altimetry and tide gauge + GPS time series, at TRABZON-II, SINOP and SILE stations.

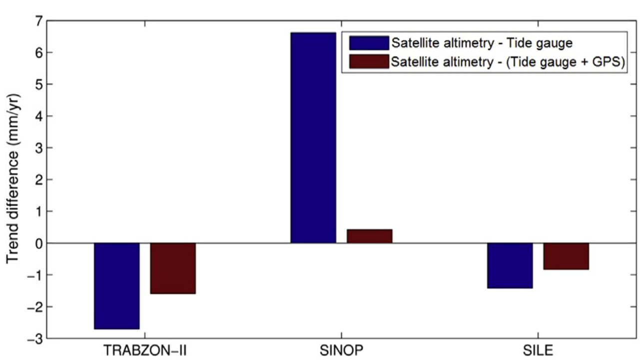

Fig. 5 – Comparison of the trend differences from satellite altimetry, tide gauge, and tide gauge + GPS at 3 tide gauge stations along the southern Black Sea coast.

gauge and tide gauge + GPS. When including GPS vertical motion, the tide gauges' results are much closer to the satellite altimetry results for all of 3 stations. Especially for Sinop station, the trend difference between satellite altimetry and tide gauge + GPS is much smaller than that difference between satellite altimetry and tide gauge. These results reveal that the vertical land motion varying at TG stations should be taken into account to get the absolute sea level change when using tide gauges data.

4. Conclusion and discussion

In this paper, sea level change along the Black Sea coast is estimated from 8 tide gauges selected from the TUDES and the PSMSL, and nearly co-located altimetric grid point data as well as three co-located GPS observations. The seasonal variations agree well at most stations, while the satellite altimetry does not exactly coincide with the tide gauges' results. When the vertical velocities from the GPS observations are added into TG results, the estimations obtained from satellite altimetry and tide gauges measurements have a better agreement.

Satellite altimetry measurements may lose the accuracy close to the coasts. The distinct temporal and spatial samplings of both techniques may cause differences for the coastal sea level change. Furthermore, although the GIA vertical displacement along the Black Sea coast is minimal, the uncertainty of the GIA model is still an error source of the trend estimations from the GPS and tide gauges. In addition, the measurement and modelling errors and systematic errors in satellite altimetry, tide gauges and GPS observations affect the sea level change estimations. In the future, more and longer co-located GPS and TG observations are expected to better quantify the sea level change along the Black Sea coast.

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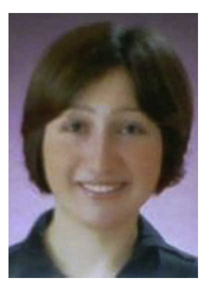

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