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Vertical land motion along the Black Sea coast from satellite altimetry, tide gauges and GPS

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Abstract

Tide gauge records comprise of relative sea level change and vertical land motion, while satellite altimetry provides absolute sea level change in the Earth's center fixed frame. Accordingly, the difference of both observations can be used to estimate geocentric vertical land motion along the coasts. In this paper, the vertical land motion rates are investigated at 13 tide gauge sites along the Black Sea coast by analyzing differences between Tide Gauge (TG) and Satellite Altimetry (SA) observations. Furthermore, the estimated vertical motion rates are compared with those from nearby the Global Positioning System (GPS) measurements. The results show general consistence with the present geodynamics in the Black Sea coastal region. For example, our estimates support the general subsidence at Bourgas and Varna.

Keywords: Black Sea; GPS; Satellite altimetry; Tide gauge; Vertical land motion

1. Introduction

As a robust indicator of climate change, sea level change is of great interest for scientific research related to the Earth sciences (Jin et al., 2013). For almost two centuries, tide gauges have been widely used to detect sea level changes along coasts (Douglas, 2001; Dusto, 2014). Alternatively, since 1993 satellite altimetry has enabled to monitor sea level changes at regional and global scales with high accuracy (Fu and Cazenave, 2001). Different spatial and temporal sampling, measurement noise, data gap, and corrections applied to the data induce a negligible difference between sea level changes obtained from the two independent techniques (Fenoglio-Marc and Tel, 2010). However more importantly, TG measures sea surface height relative to a benchmark on the land whereas SA provides absolute sea surface height with respect to a geocentric reference frame. Therefore, TG records also contain geophysical signals related to land motion; namely, sea level rise would be added to the absolute sea level change as the land sinks (Garcia et al., 2007). Accordingly, the essential difference between SA and TG observations is geocentric vertical land motion at the TG site; that is to say, the combination of these two sea level measurements enables to assess vertical displacements at the TG sites as independent of the well-known geodetic techniques such as GPS. Several studies based on the approach of subtracting TG data relative to the coast from geocentric SA data for estimating vertical land motion have been carried out over the past 20 years (Cazenave et al., 1999; Garcia et al., 2007, 2012; Nerem and Mitchum, 2002). Recently, in order to improve vertical motion estimates, various approaches adapted from the aforesaid approach have

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been proved (Kuo et al., 2004; Ray et al., 2010; Wöppelmann and Marcos, 2012, 2016).

In order to estimate vertical land motion, although a number of studies have been conducted by making use of SA data with the long-term record from TGs along the Mediterranean Sea coast (Braitenberg et al., 2011; Fenoglio-Marc et al., 2004; Garcia et al., 2012; Yildiz et al., 2013), the studies on the Black Sea have been less due to the deficiency of available set of long-term TG records in the region. For example; along the Black Sea coast, Garcia et al. (2007) reported a land uplift rate of 3.5 ± 2.7 mm/y and 6.2 ± 1.7 mm/y for the Poti and Tuapse TG sites, respectively and a land subsidence rate of -12.3 ± 7.4 mm/y and -25.5 ± 6.1 mm/y for Bourgas and Varna TG sites, respectively from TOPEX/Poseidon and ERS-1/2 $1° \times 1°$ gridded SA data, and TG data over the 1993–2001 period. Kubryakov and Stanichnyi (2013), analyzing the differences between sea level time series of along-track of TOPEX/Poseidon and Jason-1 altimetry satellites, and TG stations along the Ukraine's Black Sea coast for the period of 1993–2005, demonstrated that coasts of the Eastern Crimea and Odessa subside with the rate of -8.8 ± 1.7 mm and -5.1 ± 3.6 mm per year, respectively.

The Black Sea is surrounded by the Eurasian plate in the north, and the African and the Arabian plates in the south (see Fig. 1). The ongoing interactions between these plates, and so the westward motion of the Anatolian block are noteworthy in terms of tectonics of the Black Sea basin. Tari et al. (2000) investigated tectonic processes of the Black Sea region using the horizontal velocities of the GPS stations around the region. They have concluded that the compressional tectonic regime is active in the eastern of the region and there is a north-south shorting at the south-east coast, whereas the southwest parts do not show an apparent seismic activity to resolve whether compressional or extensional regime is active. Results of geophysical research also show an average subsidence in the Black Sea basin by about 1 mm/y (Bondar, 2009), which exceeded in the Crimean coast (~2 mm/y), Odessa (~5 mm/y) and Poti (~6 mm/y). A considerable crust subsidence has been reported at Varna and Bourgas in Goryachkin and Ivanov (2006) (Bondar, 2009). Pashova (2002) also addressed strong irregular local subsidence in the harbour areas Varna and Bourgas. At some specific locations along the Black Sea coast, anthropogenic origins might be dominant for vertical movements, for example related to groundwater pumping, oil/gas extraction or land settlement (Garcia et al., 2012; Pashova and Yovev, 2010). On the other hand, note that according to the Glacial Isostatic Adjustment (GIA) models, the post glacial rebound effect is minimal in the Black Sea region (Garcia et al., 2007). The present-day rates of land movement because of the ongoing post-glacial rebound are mapped in Fig. 2 according to the ICE-6G_C (VM5a) model from Peltier et al. (2015).

In this study, the vertical land motion is investigated using the differences between SA and TG monthly sea level

Fig. 1. Plate boundaries in the circum Black Sea according to Bird (2003).

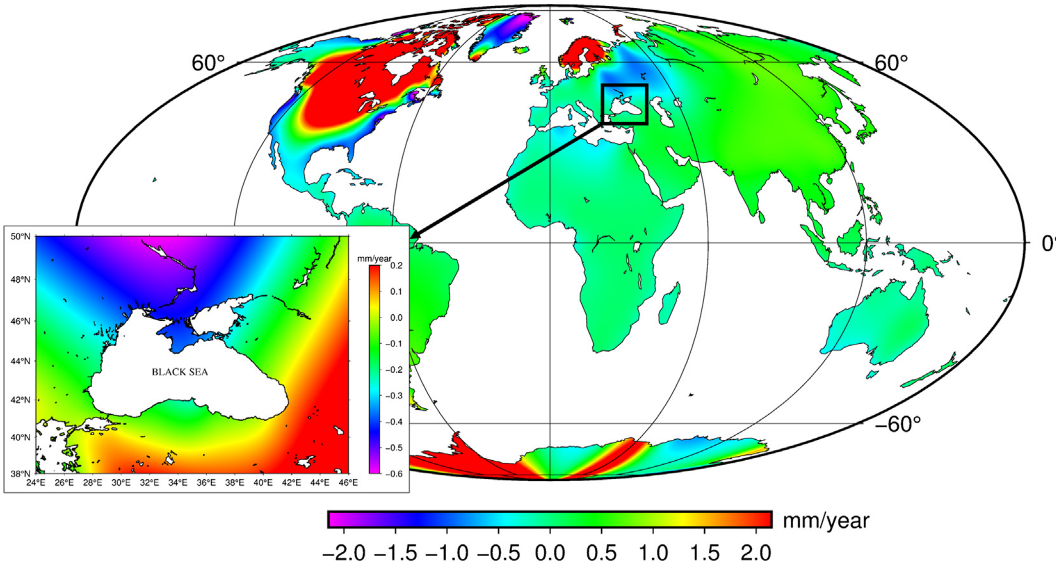

Fig. 2. Predicted present-day rate of vertical motion of the solid Earth due to GIA according to the ICE-6G_C (VM5a) model from Peltier et al. (2015) (Area surrounding the Black Sea is zoomed-in). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

time series at each TG station along the Black Sea coast. Hereby, we also reveal the contribution of changes in ground level to coastal sea level changes in the Black Sea. This study follows the same idea presented in Garcia et al. (2007), however utilizes more TG stations along the Black Sea coast, and extends the time period up to 21 years for some stations such as Poti. Prior to the computations of the difference time series, the seasonal signals are removed from the original time series as their presence can distort trend estimates of the short time series (Garcia et al., 2007; Wöppelmann and Marcos, 2012). In order to qualify the estimates, the correlation of SA and TG time series, and the Root Mean Square (RMS) of non-seasonal differences are also taken into consideration in the study. Furthermore, the estimated vertical land motion rates at the TG sites are compared with vertical velocities of the continuous or the campaign GPS stations that are neighboring to these TG stations. The GPS stations in this study are chosen by considering their proximity to the TGs.

The obtained results in this study mostly represent crustal plate movements along the Black Sea coast. In this sense, the study will contribute to interpret the Black Sea's geophysical mechanism from a different viewpoint. It is worth mentioning that the approach of SA minus TG applied in this study could lead to improvements in the assessment of vertical land motion along the Black Sea coast by verifying GPS or levelling.

2. Data and methodology

2.1. Tide gauge data

Douglas (2001) suggested that the TG records of at least 50 years are needed to determine secular sea level changes accurately. Because low-frequency sea level signals can affect the accuracy of long-term vertical land motion estimates (Wöppelmann and Marcos, 2012) or not allow to estimate a stable trend in land movement. On the other hand, the mentioned long time interval is available only for a few tide gauges along the Black Sea coast (Avsar et al., 2015). For this study, available 7 tide gauge stations (Poti, Batumi, Sevastopol, Tuapse, Varna, Bourgas and Constantza) along the Black Sea coast are chosen from the Permanent Service for Mean Sea Level - PSMSL (PSMSL, 2015). In addition, other 6 tide gauges (Amasra, Igneada, Trabzon, Sinop, Sile and Istanbul) belong to the Turkish National Sea Level Monitoring System - TUDES (TUDES, 2016). Fig. 3 shows the locations of these TG stations. The TG data provided from the PSMSL are time series of monthly averages from the Revised Local Reference (RLR) data set whereas the TUDES data are provided at 15-min intervals in the Turkish National Vertical Control Network-1999 (TUDKA-99) datum. For our analysis, the TUDES data have been simply averaged arithmetically into monthly mean values. As some TG time series contain missing observations, the data gaps in these time series (given in Table 1, column 3) have been removed. In view of the effective number of available stations along the Black Sea coast, the TG stations having the incomplete records have not been ignored for this study.

2.2. Satellite altimetry data

Standard altimetry data (gridded or along-track) have intrinsic difficulties in instrumental, atmospheric and geophysical corrections as well as land contamination in their footprint in the vicinity of coast (Cipollini et al., 2009). Various algorithms have been developed to improve the

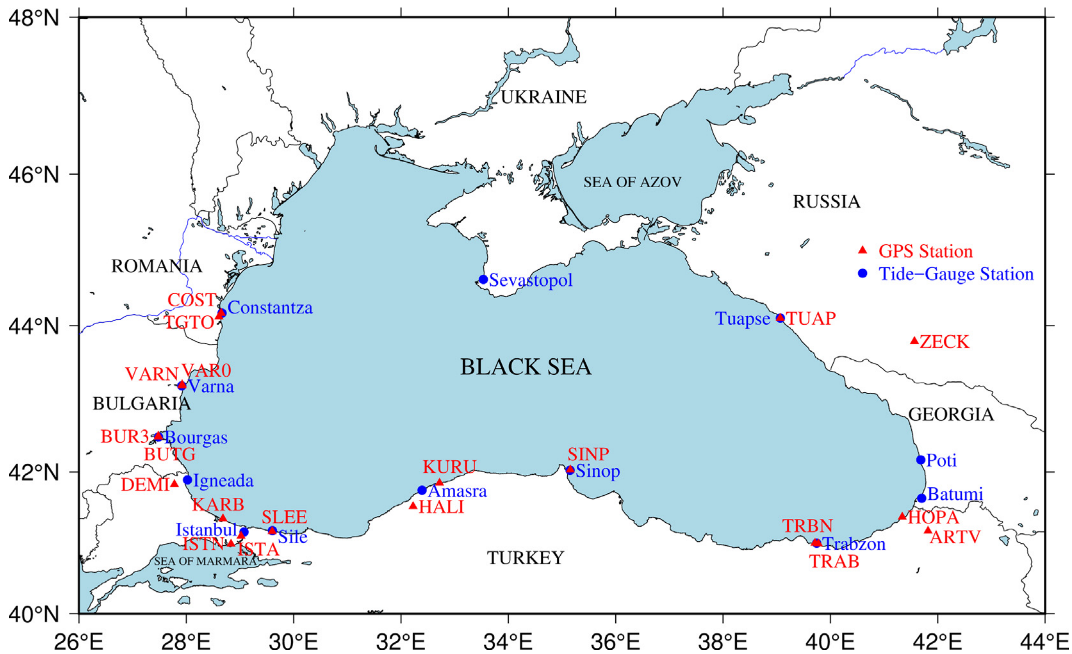

Fig. 3. Data locations used in the study. TG and GPS stations are indicated by blue dots and red triangles, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
An evaluation of TG and SA data on the basis of tide gauge stations along the Black Sea coast over the common time-span.

Tide gauge station (Country)	Common time-span	Gaps (%)	Distance (km)	Correlation	RMS (cm)
[1]Poti (Georgia)	1993–2013	5.2	2.4	0.69	7.0
[1]Batumi (Georgia)	1993–2013	31.8	6.2	−0.27	14.7
[1]Sevastopol (Ukraine)	1993–1994	0	6.8	0.70	5.7
[1]Tuapse (Russia)	1993–2011	1.3	4.2	0.89	4.8
[1]Varna (Bulgaria)	1993–1996	16.7	2.4	0.66	6.0
[1]Bourgas (Bulgaria)	1993–1996	10.4	7.2	0.66	6.0
[1]Constantza (Romania)	1993–1997	8.3	3.3	0.71	4.5
[2]Amasra (Turkey)	2001–2012	9.4	7.9	0.70	6.1
[2]Igneada (Turkey)	2002–2014	5.3	7.9	0.86	6.6
[2]Trabzon (Turkey)	2002–2014	0.7	8.6	0.88	6.2
[2]Sinop (Turkey)	2005–2014	0	6.0	0.82	6.8
[2]Sile (Turkey)	2008–2014	0	5.5	0.88	7.2
[2]Istanbul (Turkey)	2011–2014	0	3.3	0.88	5.0

[1] and [2] refer the stations from PSMSL and TUDES, respectively.

altimeter signal near the coast, and the outputs have been released as coastal altimetry datasets (Anzenhofer et al., 1999; PODAAC, 2016). Yildiz et al. (2013) used along-track, gridded and coastal altimetry products to estimate vertical land motion along the southwestern of Turkey and compared their results by considering the distance to the TGs, the correlation and the RMS of the differences between SA and TG time series. The results indicated that the gridded altimetry data provide the best agreement with TG data due to their smoother variability both in space and time than the along-track data. Moreover, Yildiz et al. (2013) asserted that the making use of the coastal altimetry data did not improve the vertical land motion estimates importantly.

The grid data enable to more acceptable sampling achieved by pooling measurements in a given range of latitudes and longitudes in comparison to the along-track data (Woolf and Tsimplis, 2002). Accordingly, the altimetry data set preferred in this study is daily sea level anomalies maps at $0.125° \times 0.125°$ grids provided by the French Archiving, Validation and Interpretation of the Satellite Oceanographic Data - AVISO (AVISO, 2015). Necessary geophysical (solid earth, ocean and pole tides, ocean tide loading effect, sea state bias, and inverse barometer response of the ocean) and atmospheric (ionosphere, and dry/wet troposphere effects) corrections have been applied to the data set by the data center (SSALTO/DUACS User Handbook, 2014). It should be noted that from May 2015, the Copernicus Marine and Environment Monitoring Service - CMEMS (CMEMS, 2016) is taking over the processing and distribution of these products. More details can be seen at AVISO and CMEMS web sites.

The altimetric data set, a merged solution from the multi mission, covers nearly 22-year from January 1993 to December 2014. There are 3249 altimetric grid points in the Black Sea when excluding the Sea of Azov. For this study, we have used altimetry observations at the closest points to the TG sites. Each point can be as far as roughly 9.8 km to the corresponding tide gauge. The distances between the tide gauges and the altimetric points are given in Table 1 (column 4). In the altimetric grid points, monthly averages have been computed from the daily sea level anomalies to make them consistent with the TG data.

Wöppelmann and Marcos (2012) pointed out that the overlapping period of both data type is of major importance for a reliable estimate of vertical land motion rate. In order to investigate vertical land motion at the TG sites, they employed TG data which were contemporary to SA data for at least 8 years by testing the different overlapping periods' stabilities, whereas Cazenave et al. (1999) used about 5-year common data period. Wöppelmann and Marcos (2012) asserted that the short overlapping periods cause larger rate uncertainties. In this study, we have used available TG data beginning from January 1993, corresponding to SA data (Table 1, column 2). Thus, short overlapping periods are assessable for some TGs (Sevastopol - ~2 years, Varna - ~4 years, Bourgas - ~4 years and Constanza - ~4 years). Also, data from the Istanbul station have been provided since only June 2011. Actually, the estimated vertical land motion rates in such studies are limited by the short-term (interannual and decadal) variability of observed sea level signal. This is because, short TG records with not sufficiently long altimetry time series are mostly obtainable for vertical land motion analysis. Nevertheless, many studies (Cazenave et al., 1999; Garcia et al., 2007; Nerem and Mitchum, 2002) demonstrated that the combination of available TG and SA data can provide worthwhile results for vertical land motion estimation.

2.3. GPS data

Global Positioning System (GPS) is a commonly used geodetic technique due to its high precision to monitor land motions (Jin et al., 2007). For comparison, we have analyzed the measurements from total 20 GPS stations which are co-located at or close to a TG station along the Black Sea coast (Fig. 3; Table 2). The vertical displacement time series of 4 GPS stations (TUAP, VARN, BUR3 and TGTO) in the Black Sea region have been obtained from the Nevada Geodetic Laboratory - NGL (NGL, 2017). 7 GPS stations (ARTV, KURU, TRBN, SINP, SLEE, ISTN and KARB) from the Turkish National Permanent Real Time Kinematic Network - TUSAGA-Active (TUSAGA, 2016), 3 GPS stations (ZECK, TRAB and ISTA) from the International GNSS Service - IGS Network (IGS, 2017) and also 1 GPS station (COST) from the EUREF Permanent Network - EPN (EPN, 2016) data have been processed using the GAMIT/GLOBK scientific software package (Herring et al., 2015). Data belong to continuous GPS stations around the Black Sea, which are processed in this study, vary from 2000 to 2017 (Table 2, column 4). So, in addition to these continuous GPS stations, we utilized the GPS campaign measurements from 1991 to 1998 around the Black Sea, which were provided from the collaborated study between Istanbul Technical University (ITU), Massachusetts Institute of Technology (MIT) and Joint Institute of Physics of the Earth (Tari et al., 2000): HOPA, VAR0, BUTG, HALI and DEMI. However, the data belong to early 90s could not be included in the processing due to lack of precise orbit information.

In the GAMIT phase of evaluations while applying loose constraints to estimate coordinates and atmospheric parameters, the global permanent sites (15 stations from the IGS) have been used to establish the link between regional and global networks. The final product of IGS as precise orbit, tidal and non-tidal atmospheric pressure loading (ATML) with the Earth's center of mass frame (CM) (Tregoning and van Dam, 2005) have been preferred in the GAMIT software. Zenith delay unknowns have been computed based on the Saastamoinen troposphere model with Vienna mapping function (VMF1) (Boehm et al., 2006). The second- and third-order of the ionospheric effects were neglected in the processing. For ocean loading, FES2004 model has been used which is already proven to be most accurate in the Black Sea region (Gurbuz and Jin, 2016).

2.4. Methodology

In order to estimate vertical land motion at the TG sites along the Black Sea coast, the approach implemented in this study is based on the classical approach using the difference time series for altimetry minus tide gauge. We follow a similar notation in Garcia et al. (2007); that is, TG(t) and SA(t) denote the sea level time series of tide gauge records, and satellite altimetry measurements at the closest available point to tide gauge site, respectively. As previously noted, when forming the difference between SA(t) and TG(t) for a common observation period, apart from the deviations caused by measurement noise, data gaps because of power outages, instrumental drifts or calibration errors, the only existing would be geocentric vertical land motion at the TG site. In here, for comparison of two time series, we also ignore the distance – given in Table 1 – between the locations of TG and corresponding point of the altimetry grid (Garcia et al., 2007; Yildiz et al., 2013).

Sea level time series exhibit strong seasonality as well as a linear trend. So, we have used a model including seasonal components (annual and semi-annual harmonics) and linear trend to adjust time series by least squares method (Avsar et al., 2016; Feng et al., 1978; Pugh, 1996).

$$M(t) = a + bt + \sum_{k=1}^{2} A_k \sin(\omega_k (t - t_0) + \phi_k) + \varepsilon(t) \quad (1)$$

Table 2
Linear trends of the vertical land motions at the TG sites along the Black Sea coast from altimetry minus tide gauge and GPS time series (The closest GPS stations to the TG stations are considered).

TG station	GPS station	Time-span		Distance (km)	Vertical land motion (mm/year)		GIA (mm/year)
		TG(t)	GPS(t)		SA(t) - TG(t)	GPS(t)	
Poti	[1]ZECK	1993–2013	1997–2013	186.7	−0.7 ± 0.6	−1.6 ± 0.5	0.02
Batumi	[4]HOPA	1993–2013	1994–1998	41.9	11.2 ± 1.4	14.6 ± 5.5	0.04
	[3]ARTV		2010–2014	51.9		−0.8 ± 0.1	
Tuapse	[5]TUAP	1993–2011	2015–2017	0.05	−1.0 ± 0.4	−1.7 ± 0.5	−0.15
Varna	[4]VAR0	1993–1996	1996–1998	0.7	−30.7 ± 7.5	−16.8 ± 8.3	−0.14
	[5]VARN		2005–2017	2.1		−1.1 ± 0.1	
Bourgas	[4]BUTG	1993–1996	1996–1998	0.08	−11.5 ± 6.9	−6.5 ± 2.4	−0.08
	[5]BUR3		2009–2014	1.5		4.2 ± 0.2	
Constantza	[2]COST	1993–1997	2010–2014	0.9	7.3 ± 4.2	6.9 ± 1.8	−0.18
	[5]TGTO		2009–2010	7.1		2.3 ± 0.03	
Amasra	[4]HALI	2001–2012	1994–1998	28.6	0.5 ± 1.4	5.2 ± 1.8	−0.15
	[3]KURU		2010–2014	29.2		−5.3 ± 0.9	
Igneada	[4]DEMI	2002–2014	1992–1998	21.4	−4.8 ± 1.0	−6.3 ± 0.5	−0.11
Trabzon	[3]TRBN	2002–2014	2009–2014	2.8	−2.7 ± 0.8	−1.9 ± 0.3	−0.05
	[1]TRAB		1999–2007	2.8		−0.3 ± 0.01	
Sinop	[3]SINP	2005–2014	2010–2014	0.8	6.6 ± 1.5	6.2 ± 2.5	−0.26
Sile	[3]SLEE	2008–2014	2009–2014	1.2	−1.3 ± 2.3	−3.0 ± 0.6	−0.11
Istanbul	[3]ISTN	2011–2014	2011–2014	27.6	16.1 ± 5.8	25.7 ± 3.6	–
	[3]KARB		2009–2011	38.7		−0.8 ± 0.2	
	[1]ISTA		2011–2014	7.7		4.2 ± 0.1	

[1], [2], [3], [4] and [5] refer the GPS data from IGS, EUREF, TUSAGA-Active, Tari et al. (2000) and Nevada Geodetic Laboratory, respectively.

where $M(t)$ is a sea level time series, t is time, t_0 is 1 January 1993, a and b are constant and trend, respectively. The third term in Eq. (1) represents the seasonal components where $k = 1$ and $k = 2$ for annual and semi-annual variations, respectively; A_k is amplitude, ω_k is angular frequency and ϕ_k is phase. $\varepsilon(t)$ stands for un-modelled residual term.

The trend estimates of vertical land motion are strongly affected by the seasonal signals. Therefore, the original time series of SA and TG should be isolated from such signals. Here, the seasonal signals have been removed from both time series by simple subtraction of the estimates obtained by least squared fitting of seasonal sinusoids with annual and semi-annual periods as mentioned in Garcia et al. (2007) and Wöppelmann and Marcos (2012). And the non-seasonal differences between SA(t) and TG(t) have been computed for each tide gauge. Fig. 4a and b depict correlation between the non-seasonal SA(t) and TG(t), and histogram of their differences, respectively by considering all SA and TG observations used in this study. Furthermore, the correlation between both non-seasonal time series, and the RMS of difference time series are also given in Table 1 (column 5 and column 6) separately for each TG site. It is clear from Table 1 and Fig. 4a that despite of several possible error sources mentioned before, TG and SA data are in good agreement except for Batumi. The RMS value of differences is 14.7 cm and the correlation coefficient is -0.27 between SA(t) and TG(t) at the Batumi station. It is very likely that this case is related to nearly 7-year gaps in the records of the Batumi station. Fig. 4a shows a correlation of 0.59 (a moderate linear relationship) for all the data. Accordingly, the data are somewhat scattered in a wider band; however the correlation coefficient is 0.76 (a strong linear relationship) without the Batumi data. Although the TG data of Tuapse show the best agreement with the SA data among all the TGs, the TUDES tide gauges exhibit better statistics than the PSMSL tide gauges in terms of the correlation coefficient. According to Fig. 4b, the differences have an approximately normal distribution with a mean of 33 mm, and most of them fall in range of −25 to 100 mm. It is worth mentioning again that the discrepancies of SA(t) and TG(t) may result from the instrumental factors (measurement noise, power outages, drifts, etc.), the data processing methodology (different corrections applied for SA and TG data, interpolation for deriving altimetric grids, etc.), and the different spatial and temporal sampling from both techniques. Nevertheless, the influence of differences due to such factors on vertical land motion estimates is in any case small in magnitude (Garcia et al., 2007).

As can be seen from Table 1, the common period of TG and SA data is very short for Sevastopol. Thus, this station was discarded from the analysis despite its agreement with high correlation. Eventually, a linear regression has been applied to derive the rates of change of non-seasonal differences, and their standard errors at all the TGs. Consequently, the linear trend computed for each TG site is given in Table 2 (column 6). Here, a positive trend represents land uplift while a negative trend represents land subsidence (Cazenave et al., 1999; Garcia et al., 2007).

3. Results and discussion

Generally, TG(t) and SA(t) show similar temporal behaviors in sea level fluctuations for TG sites along the

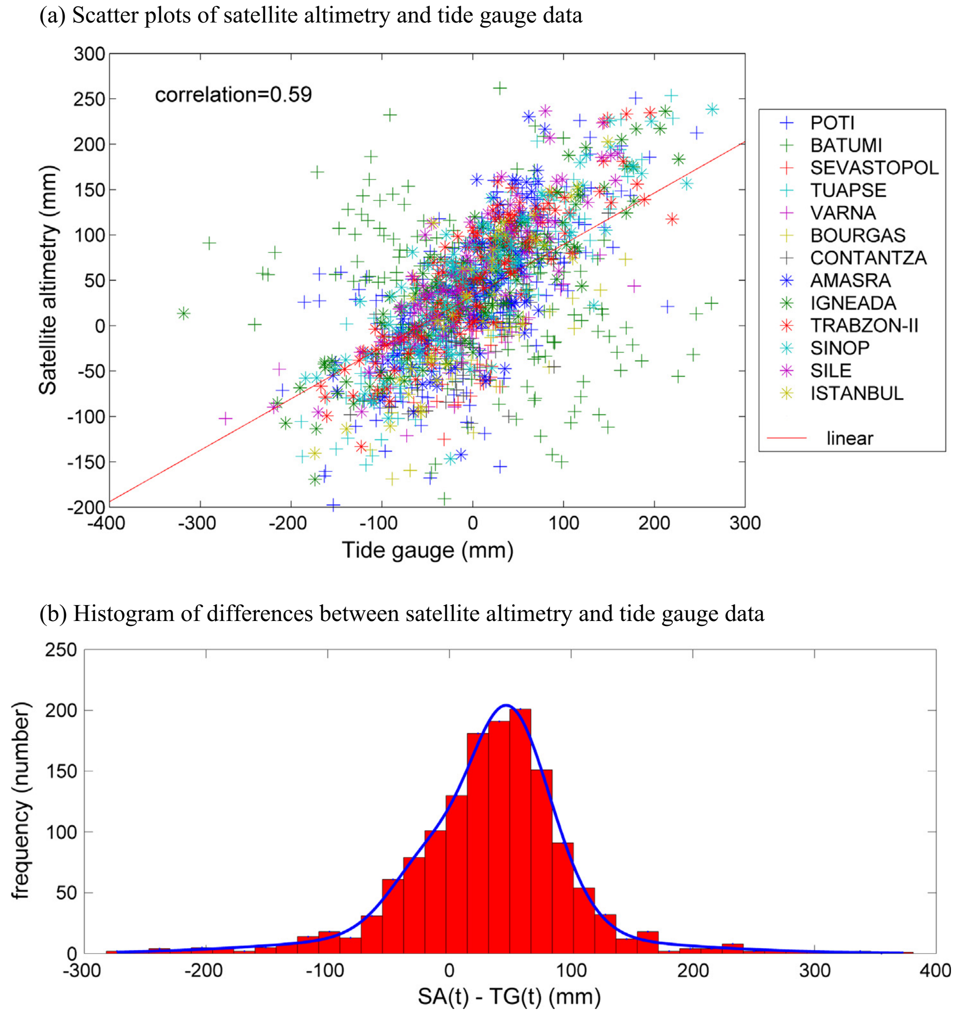

Fig. 4. For non-seasonal SA(t) and TG(t) time series at 13 tide gauge stations along the Black Sea coast. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Black Sea coast (Avsar et al., 2016). However, when examining long-term behavior of the sea level signal, some discrepancies have revealed. These discrepancies are mostly related to vertical land motions at the TG sites. As the examples of the comparison, in Fig. 5a and b, the original time series for both observations (at the top), the remaining time series after removal of the seasonal signal (in the middle), and the difference time series with their regression lines (at the bottom) are shown for the Tuapse and Sinop stations, respectively.

The results in Table 2 show land subsidence motions at Poti, Tuapse, Varna and Bourgas from the PSMSL tide gauges, and Igneada and Trabzon from the TUDES tide gauges. On the other hand, land uplift motions are seen at Batumi and Constantza from the PSMSL tide gauges, and Sinop and Istanbul from the TUDES tide gauges. Also, the trends of vertical land motions at Amasra and Sile indicate the values statistically indistinguishable from zero within 1 standard deviation. It means no significant motions for both sites. At the TG stations (Varna, Bourgas, Constantza and Istanbul), which have overlapping time-span with the SA period less than 5 years, the standard errors of vertical land motion rates are larger. Note again that the TG record in Batumi contains 32% data gaps. This lack mainly distorts the trend estimation of vertical land motion at this site. All the trend estimates of vertical land motion along the Black Sea coast are also illustrated in Fig. 6 for sensing their spatial distributions.

For the 1993–2001 period, we have found similar results to Garcia et al. (2007) using $0.125° \times 0.125°$ gridded satellite altimetry data: 2.98 ± 2.53 mm/y at Poti, and 4.05 ± 1.20 mm/y at Tuapse. However, the results for longer data period indicate land subsidence rates at the Poti station (Blagovolin et al., 1975; Bondar, 2009).

The estimates of vertical land motion along the Black Sea coast have been compared with the GPS derived vertical displacement rates. As mentioned above, this comparison has included the time series, denoted by GPS(t), from 15 continuous GPS stations and 5 GPS campaign stations in the Black Sea region. As an example, the GPS monthly vertical position time series for the SINP station is seen at the bottom of Fig. 5b. The distances between

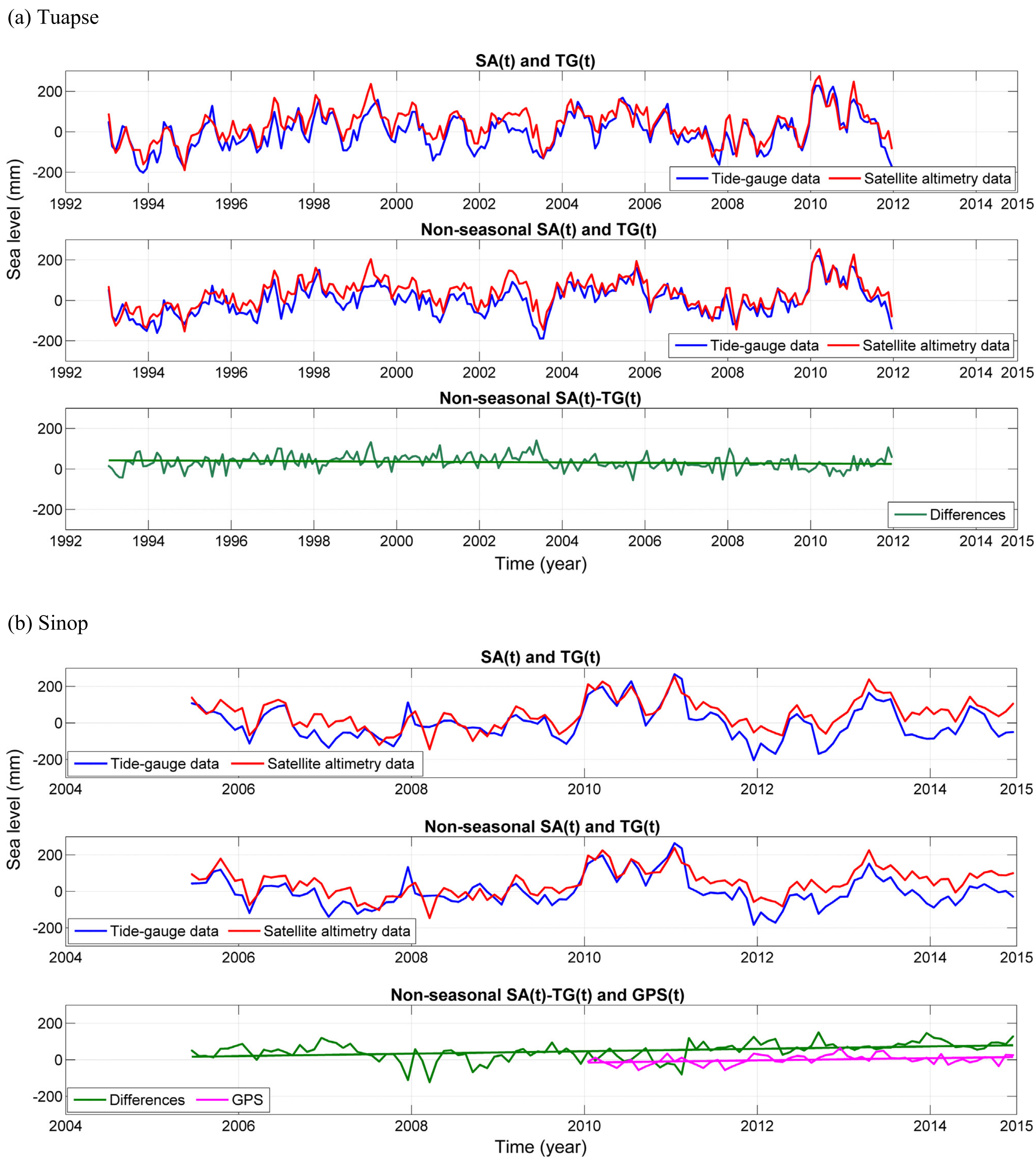

Fig. 5. Original time series (top), non-seasonal time series (middle), and non-seasonal difference time series and the fit with linear regression (bottom) at Tuapse and Sinop TG sites (The vertical displacement time series at SINP TUSAGA-Active station and its linear fit are also seen at the bottom of the Figure). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

TG and nearby GPS stations are given in Table 2 (column 5). Accordingly, 8 TG stations are located in less than 10 km from a GPS station (can be regarded as co-located). In general, the time-span of GPS(t) does not exactly coincide with the overlapping duration between SA(t) and TG(t) (Table 2, column 3 and column 4). This fact can be lead some discrepancies between both trend estimates for vertical land motion (Garcia et al., 2012). In addition to this, the distance between both stations, several geophysical corrections applied to GPS, TG and SA data, the short time-spans of these datasets, etc. no doubt influence estimates. Nevertheless, the SA-TG derived estimates are in good agreement with the rates from GPS measurements especially at Tuapse, Constantza, Igneada, Trabzon and

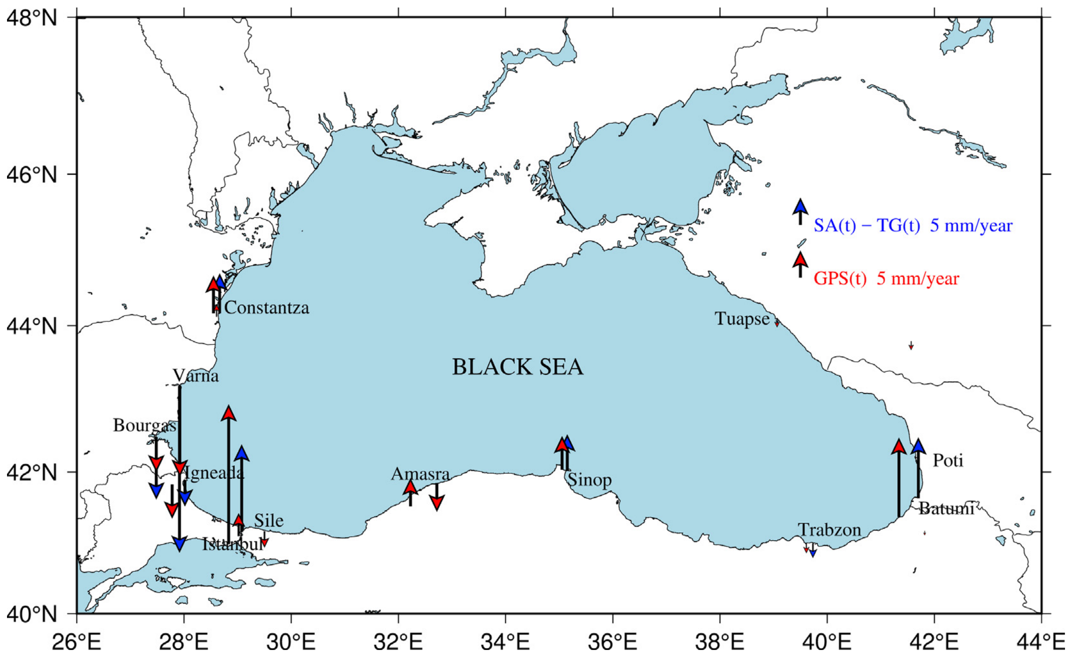

Fig. 6. Vertical land motion at TG sites along the Black Sea coast derived from Alt(t)-TG(t) and the corresponding GPS(t). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Sinop TG sites (see Table 2, column 6 and column 7; Fig. 6). The estimates for Poti and Batumi stations, despite their longer distance than 50 km from a GPS station, are consistent with the GPS rates. At most of TG sites, both estimates indicate a land motion in same direction. However, unlike the trend of SA(t)-TG(t), the trend of GPS(t) shows a significant subsidence motion at Sile. For this TG site, the larger uncertainty of the estimate from altimetry minus tide gauge can be caused by the higher RMS value of differences between SA and TG data (see the last column in Table 1). Fig. 7 also demonstrates the difference of both rates at the co-located TG sites.

In addition, this study includes GIA-related land motion in the Black Sea region. In order to clarify whether it contributes to the determined motion at each TG site significantly, we have used the ICE-6G_C (VM5a) model

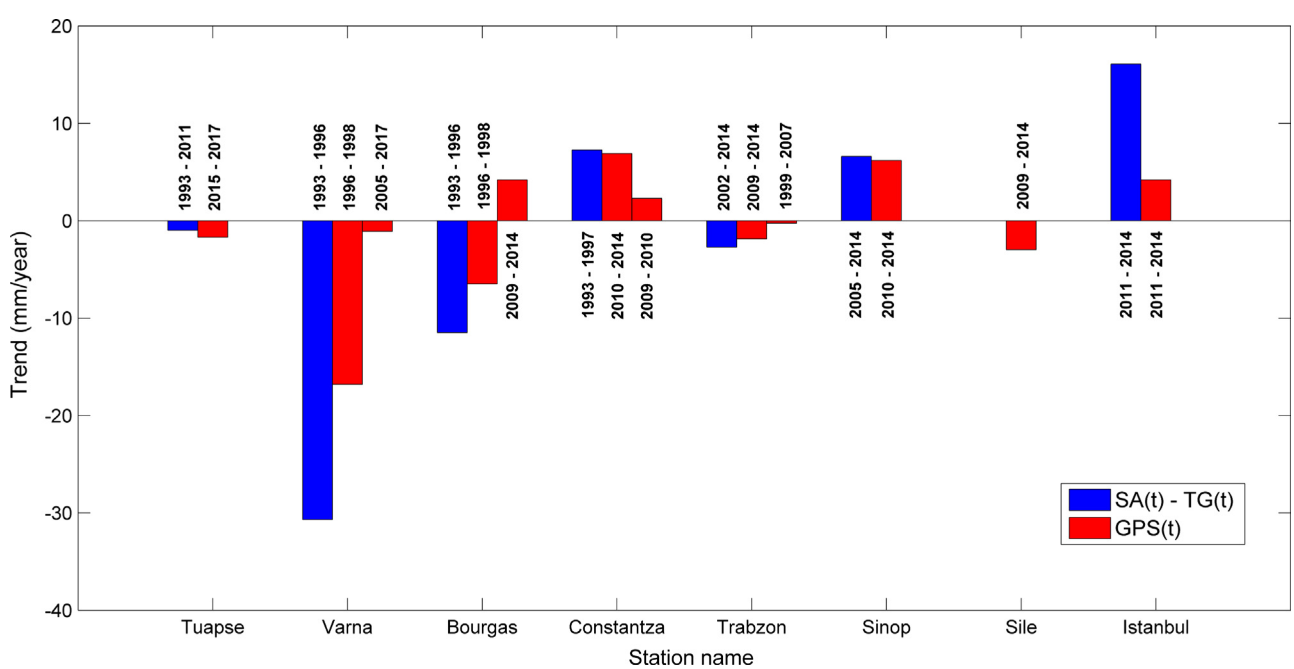

Fig. 7. Trend estimates from SA(t)-TG(t) and GPS(t) at the TG stations nearly co-located (distance < 10 km) with the GPS stations (According to SA(t)-TG(t), the Sile station shows no significant vertical land motion). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

(Peltier et al., 2015). According to this model, the vertical motion due to GIA is relatively small (see the last column in Table 2, and Fig. 2) in the circum Black Sea. So, GIA effect in the region can be negligible. Nevertheless, it is noteworthy that at the Tuapse TG site, the GIA effect is in charge of around 15% of the estimated vertical land motion.

4. Conclusions

The main purpose of this study is to estimate the vertical land motion at 13 TG sites along the Black Sea coast from combination of satellite and in-situ sea level data. Furthermore, these estimates have been compared with the calculated vertical velocities of the co-located or near GPS stations. As according to the GIA model the post-glacial rebound effect in the Black Sea region is minimal, and unless a displacement due to anthropogenic causes is occurred, the estimated vertical motions in this study mainly signify a tectonic uplift or subsidence. Accordingly, of 12 TG stations along the Black Sea coast (except for Sevastopol), 10 (Poti, Batumi, Tuapse, Varna, Bourgas, Constantza, Igneada, Trabzon, Sinop and Istanbul) indicate significant vertical land motion, whereas no significant trends have been found in the other 2 TGs (Amasra and Sile) from altimetry minus tide gauge. The estimated trends, showing strong spatial variability, range from −30.72 to 16.08 mm/y. These trend estimates exhibit a good agreement with the GPS-derived estimates. However, for the nearly same period of SA-TG, a land subsidence movement is determined at the Sile TG site from GPS. At nearby Amasra TG site, the GPS results show uplift over the period 1994–1998 and subsidence over the period 2010–2014 at the same rates. Most results of this study also agree with those inferred from the geological research.

On the other hand, the different corrections for both sea level data can trigger inconsistency between SA and TG, and eventually the difference time series (SA(t)-TG(t)) can be influenced. Anomalous trends may also arise from instrumental drifts or calibration errors. These effects are significant especially for short-term estimates. Since the overlapping periods of TG and SA data are not sufficiently long for some stations (Varna, Bourgas, Constantza and Istanbul) in this study, the vertical land motion estimates may be distorted. However, in future, it will be possible to obtain more reliable vertical motion rates from longer sea level time series in the Black Sea. In this sense, this study can be evaluated as a pioneer providing the first vertical land motion estimations from SA-TG at most TG sites along the Black Sea coast. A coastal altimetry data set of good quality, properly reflecting onshore specificities of the Black Sea, can be considered an alternative for such studies in the future.

Overall, this study allows to assess vertical land motion at the TG sites along the Black Sea coast using sea level time series. Here, the relative contribution of local land movement to the Black Sea level change is revealed. Thus, this study will also enable to detect climate-related regional sea level change in the Black Sea.

The results confirm that in order to monitor vertical land movements along the coasts, even though not directly observing this, the combination of SA and TG measurements can provide a valuable information. We suggest that a regional network portal of TG stations having a suitable spatial distribution with co-located continuous GPS stations along the Black Sea coast should be established for this purpose, which will also contribute to investigate absolute sea level changes.

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