Acta Geodyn. Geomater., Vol. 16, No. 3 (195), 245–252, 2019
DOI: 10.13168/AGG.2019.0020

journal homepage: https://www.irsm.cas.cz/acta

ORIGINAL PAPER

MODERN VERTICAL CRUSTAL MOVEMENTS OF THE SOUTHERN BALTIC COAST FROM TIDE GAUGE, SATELLITE ALTIMETRY AND GNSS OBSERVATIONS

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ARTICLE INFO

Article history:
Received 26 February 2019
Accepted 22 May 2019
Available online 29 May 2019

Keywords:
NigNET
Time Series
Noise
Velocity
Nigeria

ABSTRACT

In this study, the vertical crustal movements of the southern Baltic coast were determined based on two independent methods: tide gauge and GNSS observations. The mean sea level change trends were determined from five tide gauge observations and satellite altimetry data along the Polish coastal zone. The vertical crustal movements at nearby GNSS stations were also determined. We used the tide gauge water level data from the Permanent Service for Mean Sea Level (PSMSL) and from the Institute of Meteorology and Water Management National Research Institute, Poland (1951-2017 and 1993-2017) as well as sea level anomalies obtained from the Copernicus Marine and Environment Monitoring Service (CMEMS) (1993-2017). The time series for GNSS stations eveloped with the PPP technique obtained from Nevada Geodetic Laboratory (NGL) and last - squares approach were used for the analysis. The results provide a view of the absolute vertical crustal movements of the Polish coast. The absolute vertical crustal movements, calculated from tide gauge data and satellite altimetry for the time period between 1951-2017 – from +2.20 mm/yr ±0.42 mm/yr to +2.68 mm/yr ±0.31 mm/yr. A comparison was made, and it showed that the absolute movements determined from two data sets were different. This may be a consequence of several factors: short and incomplete time series, other unidentified movements of a GNSS station, a tide gauge of own movements, human activity, geological and hydrological factors, the method of the time series elaboration and of the data used to work out the vertical crustal movements. It is thought that the results are very significant despite the existing differences in the absolute crustal movements, because the sea level is a unique index in studies of climate impact on all changes on the Earth and crustal movements are closely linked to it.

INTRODUCTION

Vertical crustal movements are caused by geophysical processes and those resulting from human activity (Vaniček and Krakiwsky, 1986; Rovere et al., 2016). Geophysical processes include the formation and disappearance of ice sheets, changes in water levels in water bodies, sedimentation, erosion, orogeny and convection currents in the Earth mantle. Non-geophysical processes include mines, land draining and irrigation, etc.

Knowledge of vertical crustal movements is used in the economy, reference system maintenance, and scientific research comparing changes in the average sea level determined by various measurement techniques (Cazenave et al., 2002).

Methods of studying vertical crustal movements can be generally divided into direct and indirect (Liszkowski, 1976). Direct methods include observations of sea level changes on tide gauges, repeated levelling measurements, working out observations from GNSS systems, VLBI, SLR, satellite altimetry, archaeological measurements. Indirect methods include geological, geomorphological, geophysical and hydrological methods.

Vertical crustal movements can be classified into relative v_r and absolute v_h. Relative vertical crustal movements are those referring to any point (or surface) regarded as constant in time. Depending on the data used, they can form a network of vertical movements executed in a classical or non-classical manner (Kowalczyk, A. and Kowalczyk, K., 2014) and they are aligned (Kowalczyk and Rapiński, 2013; Kowalczyk and Rapiński, 2017). Absolute vertical crustal movements are defined as those referred to an ellipsoid (Kakkuri, 1987), which comprise relative vertical crustal movements, average changes of the sea level, eustatic movements and changes of the geoid in time. Absolute crustal movements, understood as geocentric crustal movements (Blewitt, 2003), are determined from direct GNSS measurements, as well as from combinations of measurements from tide gauge stations and satellite altimetry (Wöppelmann and Marcos, 2016). The vicinity of a GNSS station relative to the tide gauge

Cite this article as: Kowalczyk K, Pajak K, Naumowicz B: Modern vertical crustal movements of the southern Baltic coast from tide gauge, satellite altimetry and GNSS observations. Acta Geodyn. Geomater., 16, No. 3 (195), 245–252, 2019. DOI: 10.13168/AGG.2019.0020

station and the proximity of the point at which changes in the sea level were determined from altimetric data is a necessary condition.

In each of the data sets mentioned above, altitude changes in time (crust or sea level) are worked out by analysing a time series (Bogusz and Klos, 2015; Bos et al., 2013; Rapiński and Kowalczyk, 2016). The time of functioning and type of measurement and accuracy are different for each of the data sets (Wöppelmann and Marcos, 2016).

The following formula shows the relationships between vertical movements from tide gauge, GNSS and altimetric observations:

$$v_{al} = v_h + v_r + v_m \tag{1}$$

Which, after transformation, yields a formula used to calculate the absolute vertical crustal movements in the coastal zone:

$$v_h = v_{al} - v_r - v_m \tag{2}$$

where:

v_{al} – change of the sea level determined from altimetric data – referred to the ellipsoid

v_h – absolute vertical crustal movement determined from GNSS data – referred to the ellipsoid

v_r – relative vertical crustal movement between a benchmark(-s) in the vicinity of and the tide *gauge station*

v_m – the relative change of the mean sea level determined at a from the tide gauge observations.

The following two solutions are assumed in the above relationship:

- a permanent station at which absolute crustal movements v_h are determined shows a different vertical movement than a tide gauge lath (mainly because of the tectonic or geological structure); in such a case, the relative crustal movement between them has to be determined (usually from repeated levelling measurements),
- a permanent station at which absolute vertical crustal movements v_h are determined is situated in the immediate vicinity of a tide gauge; $v_r = 0$, and formula (2) then has the following form:

$$v_h = v_{al} - v_m \tag{3}$$

For this paper, the absolute vertical crustal movement determined from tide gauge data and satellite altimetry will be marked as (v_h), absolute vertical movement determined from GNSS data will be marked as v_{hGNSS}.

The determination error σv_h is:

$$\sigma v_h = \sqrt{\sigma v_{al}^{'2} + \sigma v_m^{'2}} \tag{4}$$

A positive vertical movement of the crust on which a tide gauge is founded, decreases the readouts of the sea level, whereas a negative movement increases them. These considerations are consistent with Wöppelmann and Marcos (2016), Grgić et al. (2017) and Bitharis et al. (2017).

The principal scientific objective of this paper is to determine the absolute vertical crustal movements of the northern part of Poland based on tide gauge data, satellite altimetry and comparison with results from GNSS data. An additional scientific objective is to determine the practical relationships between these vertical crustal movements and those determined from data acquired from the neighbouring GNSS stations. This study was taken up since there are no studies of this kind for this part of Europe (Xu et al., 2015; von Schuckmann et al., 2018).

The tide gauge data (metric data) were obtained from the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB, Poland) and from the PSMSL (Permanent Service for Mean Sea Level) database. The data from GNSS permanent stations were obtained from Nevada Geodetic Laboratory. We used the sea level anomalies obtained from the Copernicus Marine and Environment Monitoring Service (CMEMS). Tide gauge data and those from satellite altimetry were extended up to 2017 when compared to the data used in other papers (Kowalczyk, 2005; Pajak and Kowalczyk, 2018, 2019).

SATELLITE ALTIMETRY AND TIDE GAUGE

Observations of the Baltic Sea level have been conducted for several hundred years. There are a number of tide gauge stations installed along its coast which have been analysed from the scientific, research and practical perspective by many scientific institutions (e.g. The 2nd Edition of the Copernicus Marine Service Ocean State Report (OSR) published online: 08 September 2018) and as part of various research projects (Kryński and Zanimonskiy, 2004). Such observations in the Polish part of the Baltic Sea have been carried out since 1810 (Swinoujscie) and have been conducted by the Institute of Meteorology and Water Management, as well as in other studies (Łyszkowicz, 1995; Kowalczyk, 2005; Wöppelmann et al., 2000; Pajak and Kowalczyk, 2018, 2019; Łyszkowicz and Bernatowicz, 2018). They concern the changes in the average Baltic Sea level and the change of its rate. Observations from tide gauge stations are shared as time series with daily, monthly and annual average values. These series should not contain any outlying data, effect of seasonality or any data non-continuity. The current study uses monthly average Baltic Sea levels at five tide gauge stations: Swinoujscie, Kolobrzeg, Ustka, Wladyslawowo and Gdansk, during the periods of 1951-2017 and 1993-2017.

Since the early 1990s, sea level has measured by altimeter satellites. Contrary to tide gauges, which provide sea level relative to the Earth crust, satellite

Table 1 Trends in time series from satellite altimetry and tide gauge data and the correlations between the corresponding time series with trends removed (sea level anomaly or tide gauge water level) at the same observation period (1993-2017 and 1951-2017).

Name of station	Time span	Trend (mm/yr)	Time span	Trend (mm/yr)	Time span	Trend (mm/yr)	Correlation coefficient
	Satellite altimetry		Tide gauge				
Swinoujscie	**1993-2017**	**4.53 ± 0.29**	1993-2017	3.94 ± 0.24	**1951-2017**	**1.85 ± 0.10**	0.87
Kolobrzeg	**1993-2017**	**4.37 ± 0.35**	1993-2017	3.41 ± 0.32	**1951-2017**	**1.73 ± 0.10**	0.92
Ustka	**1993-2017**	**4.42 ± 0.38**	1993-2015	3.80 ± 0.42	**1951-2015**	**1.82 ± 0.12**	0.94
Wladyslawowo	**1993-2017**	**4.52 ± 0.40**	1993-2017	2.10 ± 0.41	**1951-2017**	**2.11 ± 0.13**	0.94
Gdansk	**1993-2017**	**4.53 ± 0.40**	1993-2017	1.52 ± 0.36	**1951-2017**	**2.33 ± 0.12**	0.94

altimetry measures sea level variations relative to the centre of the Earth's mass. As a result, satellite altimetry measurements of sea level are made in an absolute reference system and do not need to be corrected for VLM. We used the altimetric observations to estimate the trend and the annual and semi-annual variations in the Baltic Sea level.

Although satellite altimetry is designed to study the open ocean, this technology is now used over continental water bodies such as lakes, inland seas, flooding plains or rivers. In this paper, gridded daily sea level anomalies (SLA) at a resolution of 0.25 × 0.25 degrees and ranging from January 1993 to December 2017 were used.

The sea level anomaly (SLA) is the anomaly of the signal around the mean component. It is determined from the SSH (sea surface height) and MSSN (mean sea surface) (Taburet et al., 2019):

$$SLA_N = SSH - MSS_N \tag{5}$$

The data set from the altimetric measurements has 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), (Fu et al., 2013). To produce SLA in delayed-time (REPROCESSED), the system uses the Geophysical Data Records which are computed from a Precise Orbit Ephemeris (POE) and are delivered within two months depending on the mission. The system acquires and then synchronizes altimeter data and auxiliary data; each mission is homogenized using the same models and corrections (Taburet et al., 2019).

DETERMINATION OF CHANGES IN THE SEA LEVEL OF THE SOUTHERN BALTIC

The tide gauge and satellite altimetry time series were analysed in the same time period. In order to analyse velocity, the linear trend estimation was calculated for the tide gauge and SLA time series (Stammer et al., 2013). Additionally, at each station, the correlation coefficient between the satellite altimetry and the tide gauge data were computed in all of the analysed locations. Table 1 presents the trend and correlations in all of the analysed locations.

We compared the sea level change time series from the tide-gauge stations to the altimetric grid points closest to those tide gauge stations (the distance was a maximum of 20 km).

The mean correlation coefficient between the corresponding time series with trends removed from satellite altimetry and tide gauges is 0.92 (1993-2017). Figure 1 shows the correlations between the satellite altimetry and tide gauge results (1993-2017).

The annual amplitude at five locations is from 4.61 ± 0.95 cm to 6.16 ± 1.20 cm and the annual phase is from -0.77 to -1.00 from the satellite altimetry. The amplitude of the annual variation generally increases from west to east. The tide gauge results show that the annual amplitude is from 3.02 ± 0.97 cm to 5.74 ± 1.13 cm and the annual phase is from -0.72 to -1.54. The annual amplitude of the tide gauge results is smaller than the satellite altimetry results. For the annual phase, the tide gauge results have smaller deviations in comparison with the satellite altimetry results. Two independent observations of the sea level variations along the Polish coast have a good agreement both on annual amplitude and annual phase, although the semi-annual amplitude and semi-annual phase differ from the data obtained from satellite altimetry and tide gauges.

The semi-annual amplitude of the tide gauge results is higher than the satellite altimetry results. For the semi-annual phase, the differences between tide gauge and altimeter data were considered small.

The annual and semi-annual cycles of sea level variations measured by altimetry reach the maximum values almost at the same month as the sea level variations obtained from tide gauge data.

The satellite altimetry and tide gauge time series and the fitted seasonal curves (function model) are shown in Figure 2.

ABSOLUTE VERTICAL CRUSTAL MOVEMENTS USING DATA FROM GNSS STATIONS

Twelve permanent stations in the north of Poland, at various distances from the Baltic coast, were analyzed (Table 3). The vertical velocities of the GNSS stations in the IGS08 reference frame were calculated in the Nevada Geodetic Laboratory using daily solutions of the PPP from 2004 to the end of

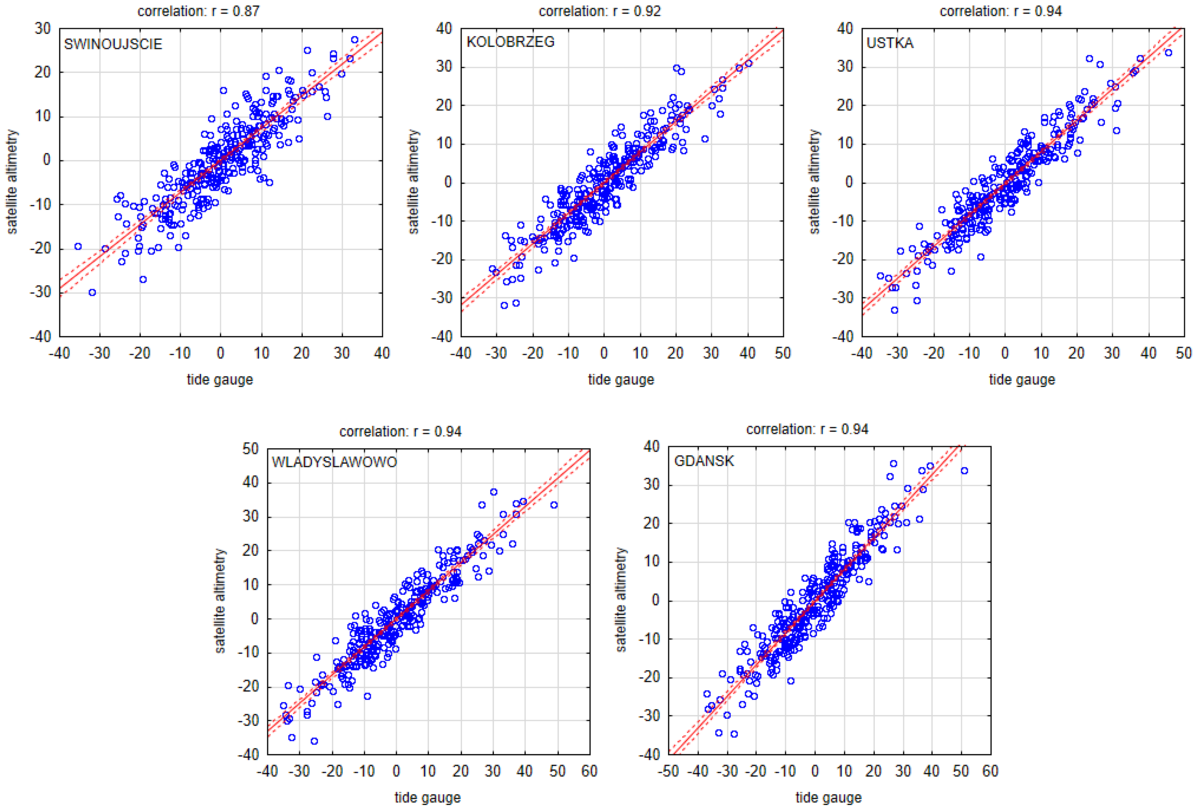

Fig. 1 Correlation coefficients between the satellite altimetry and tide gauge results (blue open circles - plot of the data dispersion and area marked by the dashed red lines – 95 % confidence interval of the regression line).

Table 2 Results of the satellite altimetry (SA) and tide gauge (TG) time series fitting, determined for the period 1993-2017.

Location	Annual amplitude (cm)		Annual phase (month)		Semi-annual amplitude (cm)		Semi-annual phase (month)	
	SA	TG	SA	TG	SA	TG	SA	TG
Swinoujscie	4.61±0.95	3.02±0.97	-1.00	-1.54	2.29±0.68	3.03±0.64	1.46	1.36
Kolobrzeg	5.47±1.08	4.33±0.85	-0.88	-0.86	2.82±0.81	3.53±0.79	1.42	1.13
Ustka	5.98±1.17	5.03±0.98	-0.78	-0.82	3.13±0.89	4.11±0.94	1.41	1.17
Wladyslawowo	6.04±1.18	5.74±1.13	-0.82	-0.72	3.46±1.03	4.42±0.94	1.46	1.06
Gdansk	6.16±1.20	4.72±0.95	-0.77	-0.94	3.42±0.96	4.21±0.94	1.40	1.13

2018. An analysis of the time series (Fig. 3) was performed with original software (Rapiński and Kowalczyk, 2016; Kowalczyk and Rapiński, 2017) and the Statistica software package.

In order to verify the correctness of the velocity calculation, the relative vertical movements between the GNSS stations were calculated and compiled with the results from the precise leveling (Kowalczyk, 2005). This approach allows the elimination of some of the factors that are involved with absolute vertical velocity e.g. Santamaria-Gómez et al. (2014), Tretyak and Dosyn (2016), Kowalczyk et al. (2014). As the reference GNSS station, the WLAD station with a velocity equal to 0.79 mm/yr was chosen. In Łyszkowicz and Bernatowicz (2018) this velocity in the WLAD station is 0.99 mm/yr, while in the work of Tretyak and Dosyn (2014) the velocity is 0.83 mm/yr. Table 3 shows the results for WLAD station with a velocity 0.79 mm/yr and 0.99 mm/yr.

ABSOLUTE VERTICAL CRUSTAL MOVEMENTS USING DATA FROM TIDE GAUGE STATIONS AND SATELLITE ALTIMETRY

In five (Table 4) points of the Polish Baltic Sea coast, the absolute vertical crustal movements v_h (Table 5) were calculated.

The use data from Table 1 and the eq. (3 and 4).

Vertical velocity v_h are:

- tide gauge data (1951-2017) from +2.20 mm/yr ±0.42 mm/yr to +2.68 mm/yr ±0.31 mm/yr,
- tide gauge data (1993-2017) from +0.59 mm/yr ±0.38 mm/yr to +3.01 mm/yr ±0.54 mm/yr.

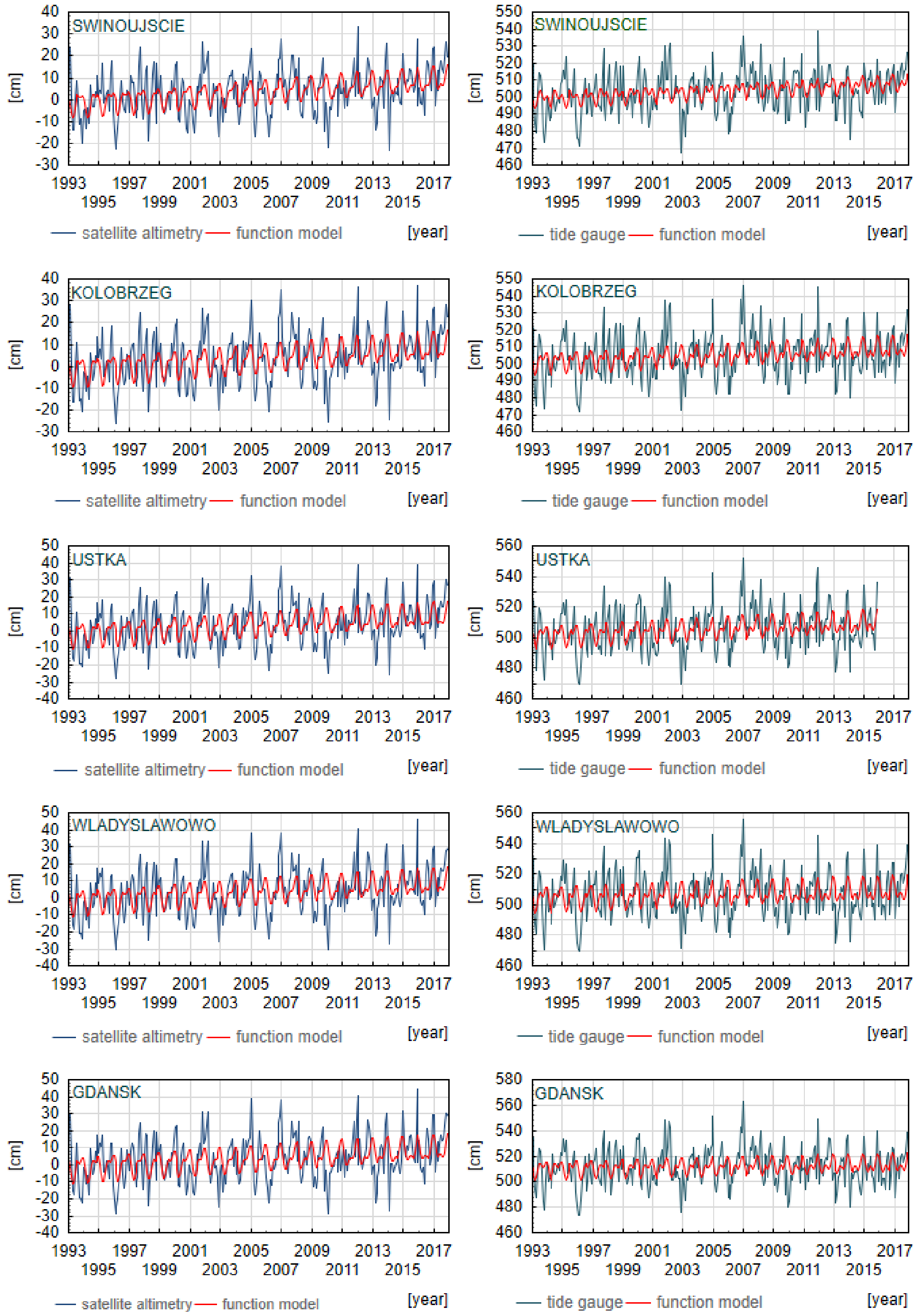

Fig. 2 Sea level change time series at all analysed stations using satellite altimetry and tide gauges with the best fitting seasonal variation curves (seasonal curves – the function model).

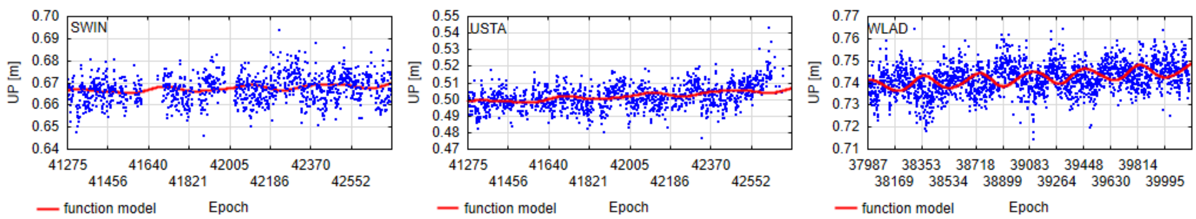

Fig. 3 Up coordinate time series of selected GNSS stations.

Table 3 Relative vertical movements between GNSS stations of the southern Baltic coast determined using the satellite data and precise levelling (WLAD - reference GNSS station).

Name of station	Name of GNSS station	Time span	Differences velocity (mm/yr) GNSS	Precise leveling	WLAD (mm/yr) 0.79	0.99
SWIN	Swinoujscie	2013-2016	-0.21	0.21	**-0.42**	-0.62
KOLO	Kolobrzeg	2013-2014	0.51	0.29	**0.22**	0.02
KOL1	Kolobrzeg	2015-2018	0.19	0.29	**-0.10**	-0.30
KOSZ	Koszalin	2008-2014	-0.61	0.44	-1.05	-1.25
KLIN	Koszalin	2013-2018	0.10	0.44	**-0.34**	-0.54
REDZ	Slupsk	2009-2017	0.28	-0.12	**0.40**	0.20
USTA	Ustka	2013-2016	-0.59	-0.58	**-0.01**	-0.21
LEBI	Leba	2013-2016	-0.78	-0.03	-0.75	-0.95
REDA	Reda	2013-2016	-0.18	-0.2	**0.02**	-0.18
GDAN	Gdansk	2008-2014	-0.79	-0.18	-0.61	-0.81
GDPG	Gdansk	2013-2016	1.28	-0.18	1.46	1.26

Table 4 Distance from the tide-gauge stations to the GNSS station.

Tide gauge station	ID	Location of tide gauge Latitude	Longitude	Distance to GNSS station [km]
Swinoujscie	2	53.917ºN	14.233ºE	~1.5
Kolobrzeg	643	54.183 ºN	15.550 ºE	~2
Ustka	644	54.583 ºN	16.867 ºE	~1
Wladyslawowo	645	54.800 ºN	18.417 ºE	Tens of meters
Gdansk	64	54.400 ºN	18.683 ºE	~7

Table 5 Absolute vertical crustal movements v_h of the southern Baltic coast determined on the data from tide gauge stations and satellite altimetry.

Name of station 1	Velocity (mm/yr) 2 GNSS station	Velocity (mm/yr) 3 V_{SA}-$V_{TG(1993\text{-}2017)}$	Velocity (mm/yr) 4 Differences (3-2)	Velocity (mm/yr) 5 V_{SA}-$V_{TG(1951\text{-}2017)}$	Velocity (mm/yr) 6 Differences (6-2)
SWIN	0.58 ± 0.18	0.59 ± 0.38	0.01	**2.68 ± 0.31**	**2.10**
KOLO	1.30 ± 0.52	0.96 ± 0.47	-0.34	**2.64 ± 0.36**	**1.34**
KOL1	0.98 ± 0.18	0.96 ± 0.47	-0.02	**2.64 ± 0.36**	**1.66**
USTA	0.20 ± 0.19	0.62 ± 0.57	0.42	**2.60 ± 0.40**	**2.40**
WLAD	0.79 ± 0.06	2.42 ± 0.57	1.65	**2.41 ± 0.42**	**1.62**
GDAN	0.00 ± 0.12	3.01 ± 0.54	3.01	**2.20 ± 0.42**	**2.20**

CONCLUSION

The aim of this paper was to calculate absolute vertical crustal movements in the north of Poland based on tide gauge data and satellite altimetry and to verify the data against data from GNSS stations situated in the vicinity.

We reached several conclusions in this paper. The mean trends of change in the Baltic Sea levels (1993-2017) at selected locations from tide gauge measurements ranged from +1.52 ± 0.36 mm/yr (tide gauge Gdansk) to +3.80 ± 0.42 mm/yr (tide gauge Ustka), and for the period of 1951-2017: +1.73 ± 0.10 mm/yr (tide gauge Ustka) to +2.33 ± 0.12 mm/yr (tide gauge Gdansk). According to altimetric data, the trend ranged from +4.37 ± 0.35 mm/yr (tide gauge Kolobrzeg) to +4.53 ± 0.29 mm/yr (tide gauge Swinoujscie). This obtained results are reliable in the assumption that the absolute trend of sea level change determined by satellite altimetry for the period 1993-2017 is equal to the absolute trend of sea level change for the period 1951-2017.

Absolute vertical movements based on GNSS data v_{hGNSS} ranged from 0.00 mm/yr to +1.30 mm/yr. The errors ranged from ± 0.06 mm/yr to ± 0.52 mm/yr.

The absolute vertical movements v_h (tide gauge data from 1951-2017) were similar. They ranged from +2.20 mm/yr ± 0.42 mm/yr to +2.68 mm/yr ± 0.31 mm/yr. A comparison v_h and v_{hGNSS} revealed large discrepancies between the results.

The quality of absolute vertical crustal movements was considerably affected by the length of the time series under analysis: from tide gauge data, from satellite altimetry and from GNSS stations. The trends in the Baltic Sea level changes differed between individual time intervals (tide gauges: Swinoujscie, Kolobrzeg and Ustka). The velocities for the tide gauge in Wladyslawowo were very similar, whereas for the Gdansk tide gauge they increased compared to the period of 1993-2017.

The comparison showed that the absolute movements v_h and v_{hGNSS} were different. This may result from several factors: short and incomplete time series, other unidentified movements of the GNSS station, the tide gauge own movements, human activity, geological and hydrological factors, the method of working out of time series, data used to work out vertical crustal movements and construction of the vertical movement network. This can be controlled by monitoring altitude changes relative to the neighbouring stations or additional calculations using other measurement techniques.

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