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ORIGINAL PAPER

CHANGES IN MEAN SEA LEVEL ON THE POLISH COAST OF THE BALTIC SEA BASED ON TIDE GAUGE DATA FROM THE YEARS 1811–2015

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ABSTRACT

Changes in the mean sea level are the result of climate change, environmental change and human activity. The Baltic Sea is located in an area of glacial isostatic adjustment (GIA) which scientists are particularly interested in. However, published reports from this region do not include tide gauges located on the Polish coast of the Baltic Sea. Previous scientific studies include only selected tide gauges at various time intervals. The authors used different types of data (Revised Local Reference (RLR) data and metric data). They did not analyze the occurrence of vertical shifts (jumps) in time series.
The main aim of this article is to determine changes in the mean level of the Baltic Sea at selected tide gauges on the southern Baltic Sea coast.
The tide gauge data to determine changes in the mean sea level of the Baltic Sea on the Polish coast for the years 1811-2015, were acquired from the Institute of Meteorology and Water Management – National Research Institute (IMGW–PIB) in Poland and from the PSMSL (Permanent Service for Mean Sea Level) database. In the calculations, metric data, i.e. average monthly values, were used for tide gauges in Świnoujście, Kołobrzeg, Ustka, Stolpmunde, Władysławowo, and Gdańsk. For the reduction of vertical shifts in time series due to a change in the reference level, the author's proprietary VSED algorithm was applied. Time series were analyzed in terms of seasonality effect. Statistical methods were used to determine the trend: linear regression analysis, spectral analysis, index method. A moving average with a "window" of 19 years was used to smooth the data.
Changes in the mean level of the Baltic Sea at the analyzed tide gauges indicate small, short-time positive changes as well as a gradual, slight I ncrease in the mean sea level ranging from +0.8 mm/y to +2.4 mm/y. The best-fitting trend line was obtained when adopting the application of the Fourier function and the moving average with a 19-year window. The analysis of vertical shifts (jumps) showed that there are vertical shifts not revealed at the stage of metric data reduction to the reference level. It has been shown that series from two tide gauges located close to each other can be combined and the series can thus be extended, which results in a reduction in the theoretical error of the determination of the trend.

1. INTRODUCTION

There are a few regions in the world where the impact of the GIA (glacial isostatic adjustment) can be clearly seen (http://grace.jpl.nasa.gov,) (Peltier et al., 2015). One of these regions is Scandinavia, where significant vertical movements of the Earth's crust have been recorded, caused by the melting of the glacier and by the uplift of the freed area (Milne et al., 2001). In addition to the typical environmental changes (altered water salinity and pressure), the process also causes changes in the mean level of the nearby seas (the Norwegian Sea, the Baltic Sea). One of the ways to monitor changes in the mean level of seas and oceans is ground-based observations at tide gauge stations. Based on the tide gauge data, not only mean water levels but also short- and long-term trends are determined (Jevrejeva et al., 2006; Church and White, 2011; Jevrejeva et al., 2014). The observations have been made for a long time (even a few hundred years) using equipment of various designs and accuracy as well as satellite observations.

In tide gauge databases, the data (annual and monthly) are stored as direct readouts (metric data) and as data corrected to include the water-level gauge differences in relation to the Revised Local Reference (RLR).

In time series, a trend can be distinguished. A trend provides an overall linear (or non-linear) component which changes over time and never repeats (or does not repeat in the time span of the analyzed series). Periodical changes repeat at regular time intervals (Łyszkowicz, 2003). The most popular method of determining the trend is linear regression analysis (Dziadziuszko and Jednorał, 1987; Wöppelmann et al., 2000; Łyszkowicz, 2003), spectral analysis or the index method (Kryński and Zanimonskiy, 2004; Wisniewski et al., 2011; Pająk and Kowalczyk, 2019) (Table 1).

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Table 1 Selected solutions in the development of tide gauge data of the southern Baltic.

autors	Dziadziuszko and Jednorał (1987)	Łyszkowicz (2003)	Kowalczyk (2005)	Kowalczyk (2019)	Wiśniewski et al. (2011)		Wöppelmann et al. (2000)	Kryński and Zanimonskiy (2004)
analysis	linear regression	linear regression	linear regression	linear regression, Fourier spectral analysis,the index method	linear regression, Fourier spectral analysis	linear regression, Fourier spectral analysis	linear regression	regression and corerelation, spectral analysis
monthly and annual mean see level time series	annual	monthly	monthly	monthly	annual	annual	annual	monthly
data collection	RLR	RLR	RLR	metric	metric	metric	RLR (for polish tide gauge)	no information
smoothing filter	moving average (Windows – 11 years)	moving average (window - 20 years)	moving average (window - 20 years)	moving average (window - 19 years)	moving average (window - 11 years)	moving average (window - 11 years)	no	no
maximum number of data	186	576	576	2376	708	349	168	2184

When determining a trend from tide gauge records, it should be considered that they are affected by errors (Bos et al., 2013). In order to minimize the impact of these errors on the final result, they must be pre-processed. The most common methods for smoothing data include the moving average and median methods. The moving average method is more sensitive to gross errors. In this method, each element of the series is replaced by a weighted average of the neighboring elements, the number of which is determined by the “window”. The "window" of 11 years old is often used (Dziadziuszko, 1993; Wisniewski et al., 2011). An alternative is to adopt a period from the Fourier analysis or another “window” value, e.g. equal to the longest period occurring in observation data, to approx. 19 years (18.6 years is the duration of the period of lunar node precession (Haigh et al., 2011)).

In this article, the Fourier function and the index method were applied to eliminate the annual and semi-annual seasonality. The moving average was used to eliminate the longest forecasted period (a 19-year window). The use of the 11-year "window" was omitted (tests have shown decrease in the coefficient R ^ 2 - an average of 0.07 with respect to 19-year window). The trend was determined using linear regression analysis using various combinations:

- no data smoothing (Table 4),
- data smoothing - 19-year moving average (Table 5),
- removed seasonality using the index method, no data smoothing (Table 6),
- removed seasonality using the index method, data smoothing - 19-year moving average (Table 7),
- removed seasonality using the Fourier function, no data smoothing (Table 8),
- removed seasonality using the Fourier function, data smoothing - 19-year moving average (Table 9).

Monthly data from tide gauges located on the southern coast of the Baltic Sea (Fig. 1) from the years 1811-2015, acquired 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, were used.

The main goal of the article is to analyze changes in the mean level of the Baltic Sea using tide gauge data at selected tide gauges on the southern Baltic Sea coast, through:

- determination of the trend in different measurement periods,

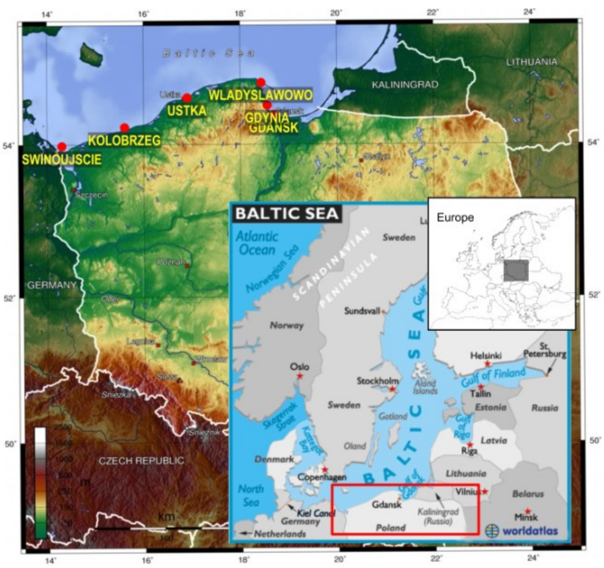

Fig. 1 Localization selected tide gauge in Poland (http://www.worldatlas.com/aatlas/infopage/balticsea.htm).

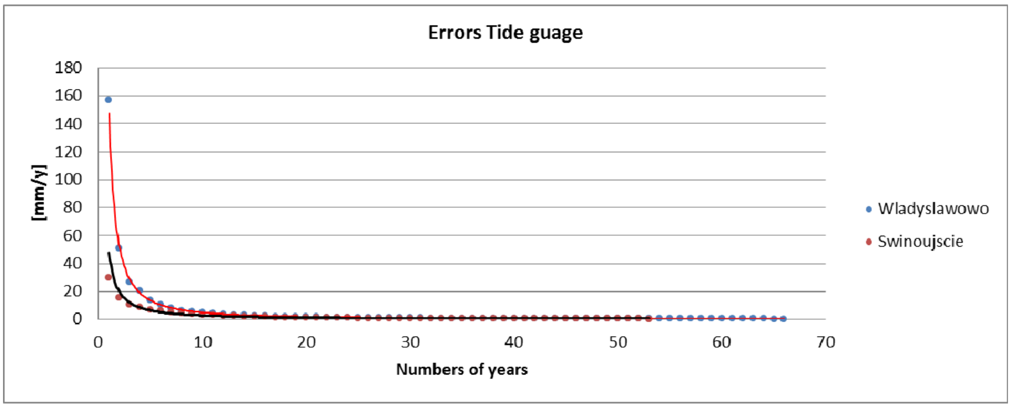

Fig. 2 Change in the standard deviation depending on the duration of tide gauges operation (Władysławowo and Świnoujście).

- using different methods to determine the trend,
- determination of trend errors,
- choosing the optimal method for developing tide gauge data,
- evaluation of the trend for individual tide gauge,
- checking the possibility of connecting data from two close tide gauge,
- checking the stability of the tide gauge by analyzing vertical shifts (jumps) in the time series.

2. BACKGROUND INFORMATION ON SELECTED TIDE GAUGES AND TIDE GAUGE DATA ON THE POLISH BALTIC SEA COAST

Numerous tide gauges are in operation along the Baltic Sea coast. The most reliable tide gauges for all analyses are those included in the Baltic Sea Level Project (BSLP) (Poutanen and Kakkuri, 2000; Kryński and Zanimonskiy, 2004). Ultimately, data from the following tide gauge stations: Świnoujście, Kołobrzeg, Ustka, Stolpmunde, Władysławowo and Gdańsk, were used in the article. For the analysis of vertical shifts in time series due to a change in the reference level, data from the following tide gauges: Świnoujście, Stolpmunde, Ustka, Gdańsk and Gdynia were used. Brief descriptions of selected tide gauge stations are presented below.

Świnoujście. The longest operating tide gauge station on Polish Baltic Sea coast (it has been recording changes since 1810), located in the area of the alluvial region of the Bay of Pomerania.

Kołobrzeg. The tide gauge station has been operating since the early 18th century. During the Second World War, no readouts were taken from the staff gauge. Since 1949, the station has been equipped with a continuously recording tide gauge.

Ustka (Stolpmunde). A tide gauge station located on a stable hydrological structure (area of the plate crystalline), established in 1858. Observations were resumed after the Second World War (since July, 1946) using an old staff gauge. In 1952, a tide gauge was installed in a new location.

Władysławowo. The tide gauge station was established in 1938. It is situated near the central shore, in a deep-water location, on the crystalline plate area. During the Second World War, the measurements were suspended and they resumed in 1947. This is the only tide gauge station in Poland with a GNSS receiver installed. In the years 1986-1996, a new northern breakwater was constructed, the Unloading Quay was reconstructed, holding platforms were upgraded and the eastern breakwater was reconstructed.

Gdańsk. The tide gauge is located in the northern port (outskirts) of the Vistula delta. Systematic observations began in 1815. Since 1990, a series of projects to upgrade the northern port have been carried out.

Prior to the preparation of data, a standard deviation change analysis was conducted depending on the duration of tide gauges operation.

This demonstrates that longer observations yield theoretically more reliable results. For unrefined observations, in order to obtain the accuracy of the determination of a linear trend at a level of 0.5 mm/y and 0.1 mm/y, respectively, the duration of the operation of the following tide gauge stations should be as follows:

- tide gauge Władysławowo: 46 years and 140 years
- tide gauge Świnoujście: 38 years and 140 years

Tide gauge data (monthly average) were acquired from the PSMSL tide gauge database at www.psmsl.org as RLR reduced data and metric data (Table 2). In this database, the Polish tide gauges data were collected till 1999. The data from 1999 to 2015 were acquired as metric data (Table 2) from the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB), Poland.

3. REDUCTION IN VERTICAL SHIFTS IN TIDE GAUGE DATA TIME SERIES

The location of tide gauges changes due to the silted-up vicinity of a tide gauge, quay upgrading, or a period of war. These changes cause discontinuities in observations as well as changes in reference levels

Table 2 Differences between the RLR data and the metric data.

database	Świnoujście (Epoch start-end/ RLR-MET [mm])	Kolobrzeg (Epoch start-end/ RLR-MET [mm])	Ustka (Epoch start-end/ RLR-MET [mm])	Władysławowo (Epoch start-end/ RLR-MET [mm])	Gdańsk (Epoch start-end/ RLR-MET [mm])	Gdynia (Epoch start-end/ RLR-MET [mm])
PSMSL	1811.04 - 1822.71					
	5818					
	1822.79-1823.29					
	n. d.					
	1823.38-1881.96					1931.04-1938.96
	5818					*4976*
	1882.04-1944.96					1939.04-1964.96
	6891					*n. d.*
	1945.04-1950.96					1965.04-1967.88
	n. d.					*1976*
	1951.04-1999.96	1951.04-1999.96	1951.04-1999.96	1951.04-1999.96	1951.04-1999.96	
	1953	*2001*	*1978*	*1941*	*1871*	
IMGW-PIB	2000.04-2015.96	2000.04-2015.96	2000.04-2015.96	2000.04-2015.96	2000.04-2015.96	
	1953	*2001*	*1978*	*1941*	*1871*	

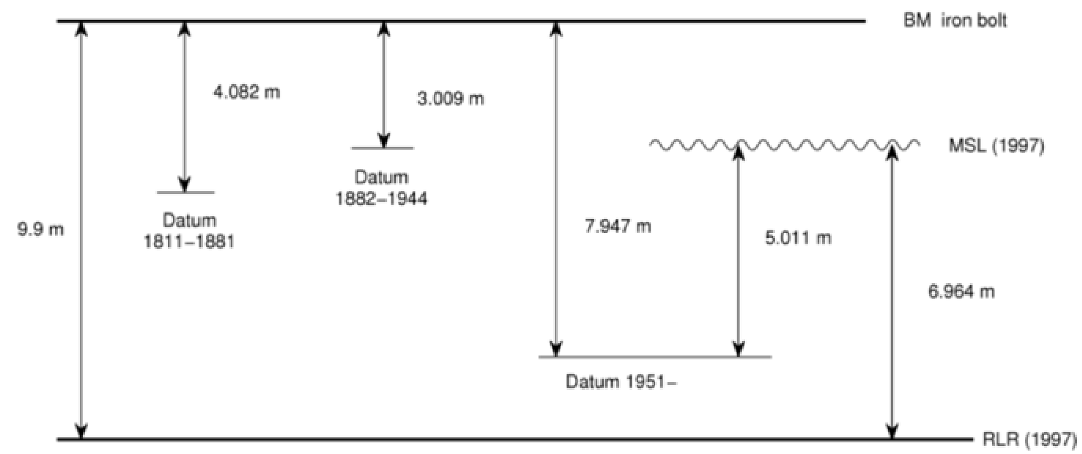

Fig. 3 Revised Local Reference (RLR) Diagram for ŚWINOUJSCIE (http://www.psmsl.org/data/obtaining/rlr.diagrams/2.php).

for the newly installed measuring instruments (Fig. 3). The methods of eliminating vertical shifts in a data series include follow-up measurements and bringing the recorded observations to a common reference level, e.g. Revised Local Reference (RLR) www.psmsl.org.

In order to create a multi-annual observation series suitable for analyses for a particular tide gauge station, monthly averages must be reduced to a common reference level. This reduction is carried out by the PSMSL based on historical materials provided by a relevant national agency (Fig. 4). However, research into the vertical movements of the Earth's crust and long control intervals indicate that it can be expected that since the reduction values changed, metric data were used for analyses. The reduction was carried out using the author's own algorithm Vertical Switching Edge Detection - VSED (Rapiński and Kowalczyk, 2016; Kowalczyk and Rapiński, 2017; Kowalczyk and Rapiński, 2018).

The main purpose of the algorithm is to determine a linear trend based on the least-squares method while determining the vertical discontinuity in the data. Table 3 shows the results of the algorithm, including the indication of the jump locations and values. Data from tide gauges Ustka - Stolpmunde were included in the calculations as well. By the year 1943, a tide gauge operated there under the name of Stolpmunde; in 1951, its location was changed slightly, and it has been operating under the name Ustka since then. Since the change in location was relatively minor, it was adopted for the purposes of the study that it was the same tide gauge. For the Stolpmunde location, the shift in relation to the reference point is not known to the author. A similar situation occurs at the tide gauge in Gdańsk where the RLR reduced data are partially lacking in the PSMSL database. The obtained results were compared with the information provided on the PSMSL website.

Table 3 shows that the value of the tide gauge shift in relation to the reference level is not constant over time. Data reduction without cyclical check measurements causes disturbances in the reduced data. The absolute differences in values range from 20 mm to 67 mm. The applied approach enables the calculation of the unknown values of the tide gauge shift in relation to the Revised Local Reference.

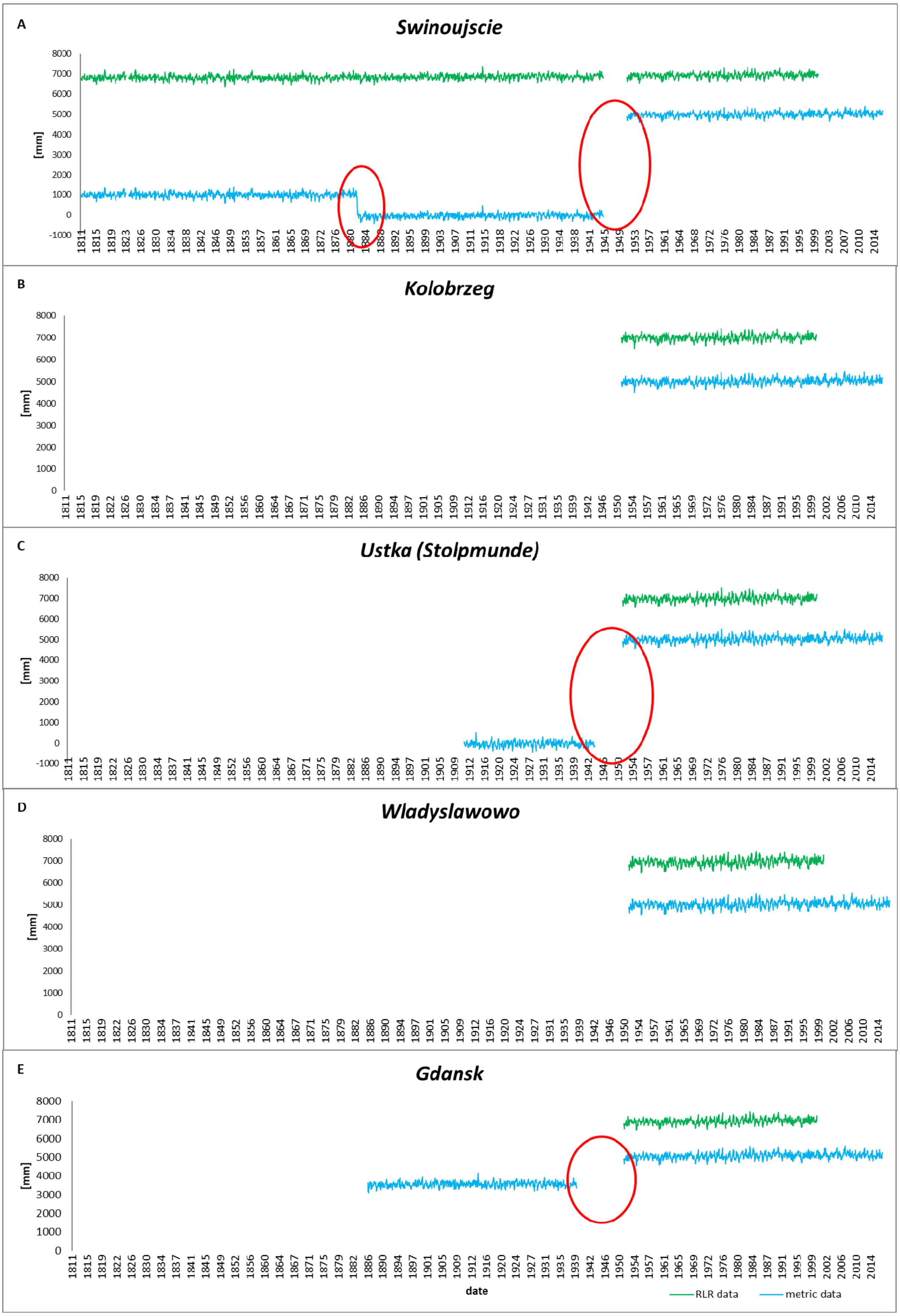

Fig. 4 Metric and RLR time series at the selected Polish tide gauges.

Table 3 Values of the discontinuity of tide gauge data (jumps) calculated from the RLR data (the PSMSL database) and VSED algorithm.

Tide gauge	Jump	PSMSL data		VSED		Difference
		[mm]	epoch	[mm]	epoch	[mm]
	1	-1073	1882.042	-1093	1882.042	20
Świnoujście	2	4938	1951.042	4970	1951.042	-22
Ustka	1	No data	1951.042	4967	1951.042	
Gdynia	1		1951.042	3067	1951.042	-67

4. DETERMINATION OF TRENDS IN CHANGES IN THE MEAN LEVEL OF THE BALTIC SEA

Linear regression assumes that the line

$$\hat{y}_i = a + bx_i \tag{1}$$

is adjusted to the data. Coefficients of regression *a* (the initial constant) and *b* (the line inclination) are selected to minimize the squares of deviations between the estimated trend and the source data. The value of the coefficient of determination R^2 falls within a range from 0 to 1, and indicates how close the estimated values are to the actual values. An estimated value is most reliable when it is equal or close to 1. This value is also referred to as the R- squared. The method is suitable for the determination of the sea level value from smoothed, free from gross data errors.

Figures 5, 6, 7, 8, 9 show the mean monthly levels of the Baltic Sea at the analyzed tide gauge stations along with the course of the moving average.

The data was brought to one level based on the jump values calculated using the VSED algorithm. The span of the measurement window was adopted as 19 years, which implies that the starting point being smoothed is situated in the center of the window. The weight of the moving variable was adopted as equal to one, as tide gauge operations are equally accurate.

The overall direction of changes in the mean level of the Baltic Sea for Polish tide gauge stations is positive. The data are not referred to the same reference level, which causes differences between particular values in the same epoch.

The absolute differences in the mean sea level between extreme values for the same time interval (1951-2015) range from 77 mm (Świnoujście) through 84 mm (Kołobrzeg) and 83 mm (Ustka) to 102 mm (Władysławowo) and 114 mm (Gdańsk). Vertical lines (Fig. 10) indicate years in which the values of the mean sea level change the direction, i.e. rise or drop.

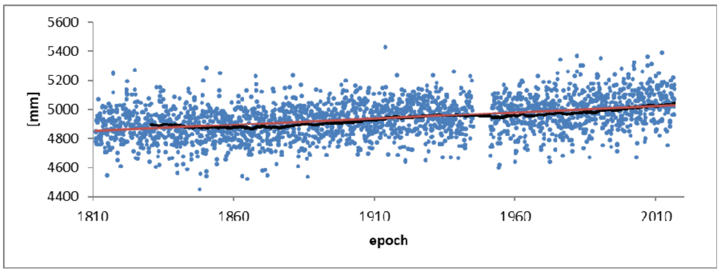

Fig. 5 Changes in the mean sea level in Świnoujście in 1811-2016 (the straight line represents the linear trend; the curve represents the 19-year moving average).

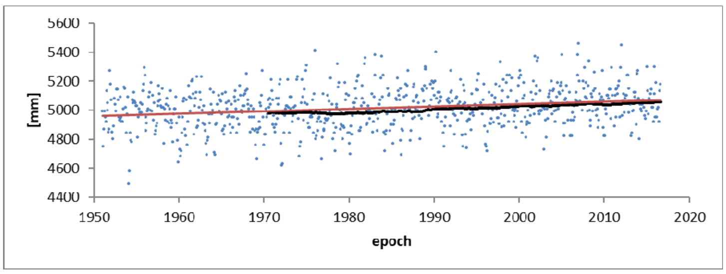

Fig. 6 Changes in the mean sea level in Kołobrzeg in 1951-2016 (the straight line represents the linear trend; the curve represents the 19-year moving average).

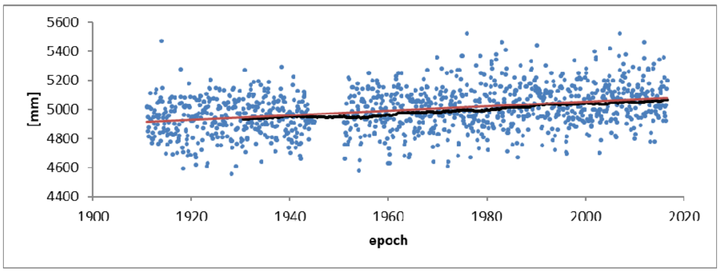

Fig. 7 Changes in the mean sea level in Ustka in 1911-2016 (the straight line represents the linear trend; the curve represents the 19-year moving average).

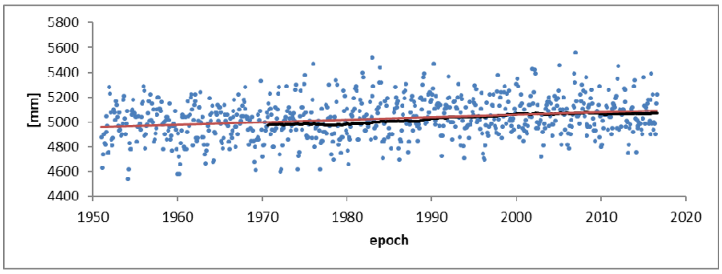

Fig. 8 Changes of the mean sea level in Władysławowo in 1951-2016 (the straight line represents the linear trend; the curve represents the 19-year moving average).

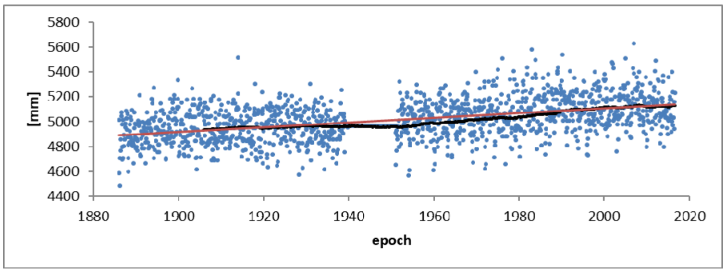

Fig. 9 Changes in the mean sea level in Gdańsk in 1886-2016 (the straight line represents the linear trend; the curve represents the 19-year moving average).

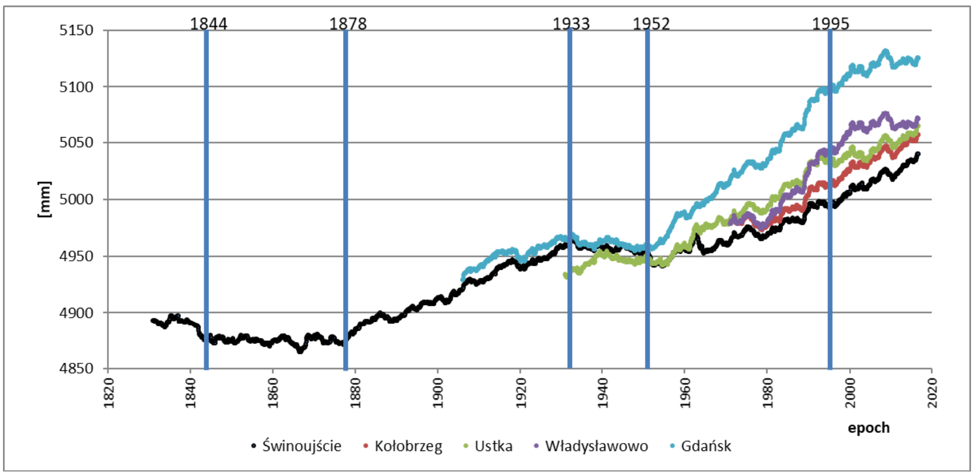

Fig. 10 Moving averages for analyzed tide gauge stations.

Table 4 Trend magnitudes in the observed time series (metric data) at the tide gauge stations on the Polish coast (the jumps in the time series were reduced, no data smoothing).

the time interval [y]		1811-2015	1886-2015	1911-2015	1951-2015	1811-1995	1886-1995	1911-1995	1951-1995	1996-2015
number of years		*204*	*129*	*104*	*64*	*204*	*129*	*104*	*44*	*20*
Świnoujście	**velocity** [mm/y]	0.84			1.71	0.76			1.63	2.96
	St. Dev. [mm/y]	0.04			0.23	0.05			0.40	1.34
	R^2	*0.14*			*0.06*	*0.09*			*0.03*	*0.02*
Kołobrzeg	**velocity** [mm/y]				1.65				1.46	2.99
	St. Dev. [mm/y]				0.26				0.46	1.48
	R^2				*0.05*				*0.02*	*0.01*
Ustka	**velocity** [mm/y]			1.60	1.82			1.58	2.15	4.04
	St. Dev. [mm/y]			0.13	0.28			0.18	0.49	1.58
	R^2			*0.10*	*0.05*			*0.07*	*0.03*	*0.02*
Władysławowo	**velocity** [mm/y]				2.03				2.74	1.00
	St. Dev. [mm/y]				0.30				0.52	1.68
	R^2				*0.06*				*0.05*	*0.001*
Gdańsk	**velocity** [mm/y]		1.88		2.39		2.18		3.40	1.57
	St. Dev. [mm/y]		0.10		0.29		0.13		0.51	1.67
	R^2		*0.13*		*0.08*		*0.09*		*0.07*	*0.00*

4.1. DETERMINATION OF CHANGES IN THE MEAN SEA LEVEL USING THE LINEAR REGRESSION METHOD FOR UNREFINED AND SMOOTHED DATA

As in the previous chapter, monthly mean sea levels at the five Polish tide gauge stations, reduced by the jump values, were used to calculate the linear regression. The linear trend was calculated for the unrefined data and the smoothed data. For the seasonal decomposition of time series, the index method, Fourier analysis method and the moving variable were applied. The time intervals from which the linear trend was determined were selected as: a complete available time series for the years 1951-2015 (a uniform length of the series for all stations – the change indicated in Figure 10), a short data series for the years 1996-2015 (the change indicated in Figure 4). In 1995, upgrading works were commenced in a few ports along the Polish coast. Since these works mainly focused on the construction of breakwaters, the study adopted that date as the next cut-off date.

The linear trend (Table 4) is characterized by a standard deviation ranging from 0.04 mm/y to 1.67 mm/y. The lowest standard deviation was noted for the station with a long observation period. For the time interval of 1951-2015, the standard deviation ranges from 0.23 mm/y (Świnoujście) to 0.30 mm/y (Władysławowo). The highest standard deviation was noted for short data series. It is close to the determined value of the trend. For the time intervals by the year 1996, the obtained standard deviation is higher than those corresponding to it in the interval by the year 2015 by approx. 50 %. The coefficient of trend determination R^2 is at a very low level for all analyzed time intervals.

In the subsequent stage, a linear trend was determined using the moving average with the 19-year window (Table 5).

The obtained trend values (Table 5) differ from those – shown in Table 4, particularly for the data from 1951-2015 and 1951-1999. The greatest differences were noted for the Władysławowo, Gdańsk, and Kołobrzeg stations. For all stations, the standard deviation decreased considerably. The obtained determination coefficients R^2 indicate that the trend line fits well to the data.

4.2. DETERMINATION OF CHANGES IN THE MEAN SEA LEVEL USING THE LINEAR REGRESSION AND THE INDEX DECOMPOSITION METHOD

The time series of changes in the mean level of the Baltic Sea were decomposed and possible seasonal periods were analyzed. The analysis demonstrates that at most stations, there are two dominant periods, i.e. 12-month and 6-month periods. Following the decomposition, rates in the change in the mean sea level were re-calculated based on the obtained series. The index method was used for the decomposition. The annual and semi-annual seasonality were removed. Table 6 shows the results after the removal of the annual seasonality.

Table 5 Trend magnitudes in the observed time series (metric data) at the tide gauge stations on the Polish coast (the jumps in the time series were reduced, data smoothing - 19 year moving average).

the time interval [y]		1811-2015	1886-2015	1911-2015	1951-2015	1811-1995	1886-1995	1911-1995	1951-1995
number of years		*204*	*129*	*104*	*64*	*204*	*129*	*104*	*44*
Świnoujście	**velocity** [mm/y]	0.84			1.61	0.79			1.35
	St. Dev. [mm/y]	0.01			0.01	0.01			0.03
	R^2	*0.91*			*0.96*	*0.89*			*0.85*
Kołobrzeg	**velocity** [mm/y]				1.93				1.68
	St. Dev. [mm/y]				0.02				0.05
	R^2				*0.96*				*0.79*
Ustka	**velocity** [mm/y]			1.67	1.73			1.60	2.38
	St. Dev. [mm/y]			0.02	0.02			0.02	0.04
	R^2			*0.92*	*0.93*			*0.84*	*0.93*
Władysławowo	**velocity** [mm/y]				2.59				3.08
	St. Dev. [mm/y]				0.03				0.07
	R^2				*0.91*				*0.88*
Gdańsk	**velocity** [mm/y]		1.9		2.75		2.26		3.63
	St. Dev. [mm/y]		0.02		0.03		0.02		0.05
	R^2		*0.85*		*0.93*		*0.77*		*0.95*

Table 6 Trend magnitudes in the observed time series (metric data) at the tide gauge stations on the Polish coast (the jumps in the time series were reduced, the seasonality removed using the index method, no data smoothing).

the time interval [y]		1811-2015	1886-2015	1911-2015	1951-2015	1811-1995	1886-1995	1911-1995	1951-1995	1996-2015
number of years		*204*	*129*	*104*	*64*	*204*	*129*	*104*	*44*	*20*
Świnoujście	**velocity** [mm/y]	0.79			1.69	0.79			1.57	2.77
	St. Dev. [mm/y]	0.02			0.14	0.03			0.24	0.81
	R^2	*0.30*			*0.16*	*0.21*			*0.07*	*0.04*
Kołobrzeg	**velocity** [mm/y]				1.63				1.39	2.66
	St. Dev. [mm/y]				0.15				0.27	0.88
	R^2				*0.13*				*0.05*	*0.03*
Ustka	**velocity** [mm/y]			1.58	1.77			1.55	2.07	3.66
	St. Dev. [mm/y]			0.08	0.16			0.10	0.29	0.97
	R^2			*0.25*	*0.13*			*0.18*	*0.09*	*0.05*
Władysławowo	**velocity** [mm/y]				2.01				2.66	0.50
	St. Dev. [mm/y]				0.18				0.31	1.03
	R^2				*0.14*				*0.12*	*0.003*
Gdańsk	**velocity** [mm/y]		1.87		2.35		2.16		3.32	1.05
	St. Dev. [mm/y]		0.06		0.18		0.07		0.30	1.07
	R^2		*0.31*		*0.18*		*0.22*		*0.18*	*0.0001*

Table 7 Trend magnitudes in the observed time series (metric data) at the tide gauge stations on the Polish coast (the jumps in the time series were reduced, the seasonality removed using the index method, data smoothing – 19-yr moving average).

the time interval [y]		1811-2015	1886-2015	1911-2015	1951-2015	1811-1995	1886-1995	1911-1995	1951-1995
number of years		*204*	*129*	*104*	*64*	*204*	*129*	*104*	*44*
Świnoujście	**velocity** [mm/y]	0.79			1.61	0.76			1.35
	St. Dev. [mm/y]	0.01			0.01	0.01			0.03
	R^2	*0.90*			*0.97*	*0.88*			*0.85*
Kołobrzeg	**velocity** [mm/y]				1.94				1.69
	St. Dev. [mm/y]				0.02				0.05
	R^2				*0.96*				*0.80*
Ustka	**velocity** [mm/y]			1.64	1.73			1.58	2.38
	St. Dev. [mm/y]			0.01	0.02			0.02	0.04
	R^2			*0.94*	*0.94*			*0.88*	*0.93*
Władysławowo	**velocity** [mm/y]				2.59				3.09
	St. Dev. [mm/y]				0.03				0.07
	R^2				*0.91*				*0.88*
Gdańsk	**velocity** [mm/y]		1.90		2.75		2.25		3.64
	St. Dev. [mm/y]		0.02		0.03		0.02		0.05
	R^2		*0.82*		*0.93*		*0.69*		*0.95*

Table 8 Trend magnitudes in the observed time series (metric data) at the tide gauge stations on the Polish coast (the jumps in the time series were reduced, the seasonality removed using the Fourier function, no data.

the time interval [y]		1811-2015	1886-2015	1911-2015	1951-2015	1811-1995	1886-1995	1911-1995	1951-1995	1996-2015
number of years		*204*	*129*	*104*	*64*	*204*	*129*	*104*	*44*	*20*
Świnoujście	**velocity** [mm/y]	0.83			1.73	0.75			1.67	3.22
	St. Dev. [mm/y]	0.01			0.06	0.03			0.16	0.34
	R^2	*0.57*			*0.49*	*0.27*			*0.17*	*0.27*
Kołobrzeg	**velocity** [mm/y]				1.68				1.51	3.33
	St. Dev. [mm/y]				0.08				0.21	0.44
	R^2				*0.34*				*0.09*	*0.19*
Ustka	**velocity** [mm/y]			1.61	1.85			1.59	2.21	4.41
	St. Dev. [mm/y]			0.06	0.10			0.08	0.24	0.53
	R^2			*0.38*	*0.32*			*0.26*	*0.13*	*0.22*
Władysławowo	**velocity** [mm/y]				2.07				2.80	1.34
	St. Dev. [mm/y]				0.10				0.25	0.58
	R^2				*0.35*				*0.18*	*0.02*
Gdańsk	**velocity** [mm/y]		1.89		2.43		1.85		3.46	1.78
	St. Dev. [mm/y]		0.04		0.10		0.05		0.24	0.51
	R^2		*0.45*		*0.44*		*0.48*		*0.27*	*0.04*

Table 9 Trend magnitudes in the observed time series (metric data) at the tide gauge stations on the Polish coast (the jumps in the time series were reduced, the seasonality removed using the Fourier function, data smoothing - 19-yr moving average).

the time interval [y]		1811-2015	1886-2015	1911-2015	1951-2015	1811-1995	1886-1995	1911-1995	1951-1995
number of years		*204*	*129*	*104*	*64*	*204*	*129*	*104*	*44*
Świnoujście	**velocity** [mm/y]	0.83			1.72	0.76			1.63
	St. Dev. [mm/y]	0.01			0.01	0.01			0.01
	R^2	*1*			*1.00*	*1.00*			*1.00*
Kołobrzeg	**velocity** [mm/y]				1.66				1.46
	St. Dev. [mm/y]				0.01				0.01
	R^2				*1.00*				*1.00*
Ustka	**velocity** [mm/y]			1.60	1.83			1.57	2.15
	St. Dev. [mm/y]			0.01	0.01			0.01	0.01
	R^2				*1.00*			*1.00*	*1.00*
Władysławowo	**velocity** [mm/y]				2.04				2.74
	St. Dev. [mm/y]				0.01				0.01
	R^2				*1.00*				*1.00*
Gdańsk	**velocity** [mm/y]		1.88		2.40		1.84		3.4
	St. Dev. [mm/y]		0.01		0.01		0.01		0.01
	R^2		*1.00*		*1.00*		*1.00*		*1.00*

Compared to the data from Table 4, after the removal of the seasonality effect, the coefficient of determination R^2 was improved for all stations; moreover, the standard deviation decreased. However, none of the coefficients are at a satisfactory level yet. Therefore, the refined series' were smoothed using the moving average with a 19-year window. The obtained results are shown in Table 7.

The obtained standard deviation decreased significantly compared to the results presented in Table 6. The coefficient of determination R^2 was improved significantly, which indicates that the trend line is better fitted into the data. The differences in the trend are at the level of standard deviation presented in Table 6, with the exception of the Gdańsk station (1951-2015), where the difference is at the level of double standard deviation.

4.3. DETERMINATION OF CHANGES IN THE MEAN SEA LEVEL USING THE LINEAR REGRESSION AND THE FOURIER FUNCTION

The data were refined by removing the impact of seasonal factors using another method, i.e. the Fourier function. In a similar manner, the refined series were smoothed using the moving average. Table 8 shows the obtained results after the series refinement.

Compared to Table 6, the coefficient of determination R^2 is greater, while the standard deviation decreased. Differences in the trend occur. The greatest differences are in the data from the years 1996-2015. The refined series were smoothed using the moving average with a 19-year window. The obtained results are shown in Table 9.

After smoothing using the moving average (Table 9), the standard deviation is below 0.01 mm/y. The R^2 coefficient indicates a very good (1.0) fit to the data. Based on these coefficients, it can be demonstrated that the above solution is the most appropriate. Trend values calculated using this solution are the most probable.

5. DISCUSSION AND RESULTS

The obtained results were analyzed to select the most reliable solution. Figure 11 shows a comparison of trends obtained from particular solutions (Tables 6, 7, 8 and 9).

The greatest changes in the trend in relation to other determinations shown in Figure 11 were noted for the data in which the seasonality effect was removed, and which were smoothed using the moving average. Short time series also exhibit significant changes due to the applied approach. The data after 1995 have significantly affected the value of the trend, particularly for the Ustka, Władysławowo and Gdańsk stations.

In order to better illustrate the changes in the trend, an analysis of the continuous change in the trend at tide gauge stations was carried out (Fig. 12). The trend was determined for the subsequent measurement epochs in relation to the initial epoch 1970.042.

The nature of the trend for particular stations is similar. The initial high values result from a smaller amount of data, but it does not affect the overall assessment of the trend behavior. It can be seen that the trend at the Świnoujście station differs from the

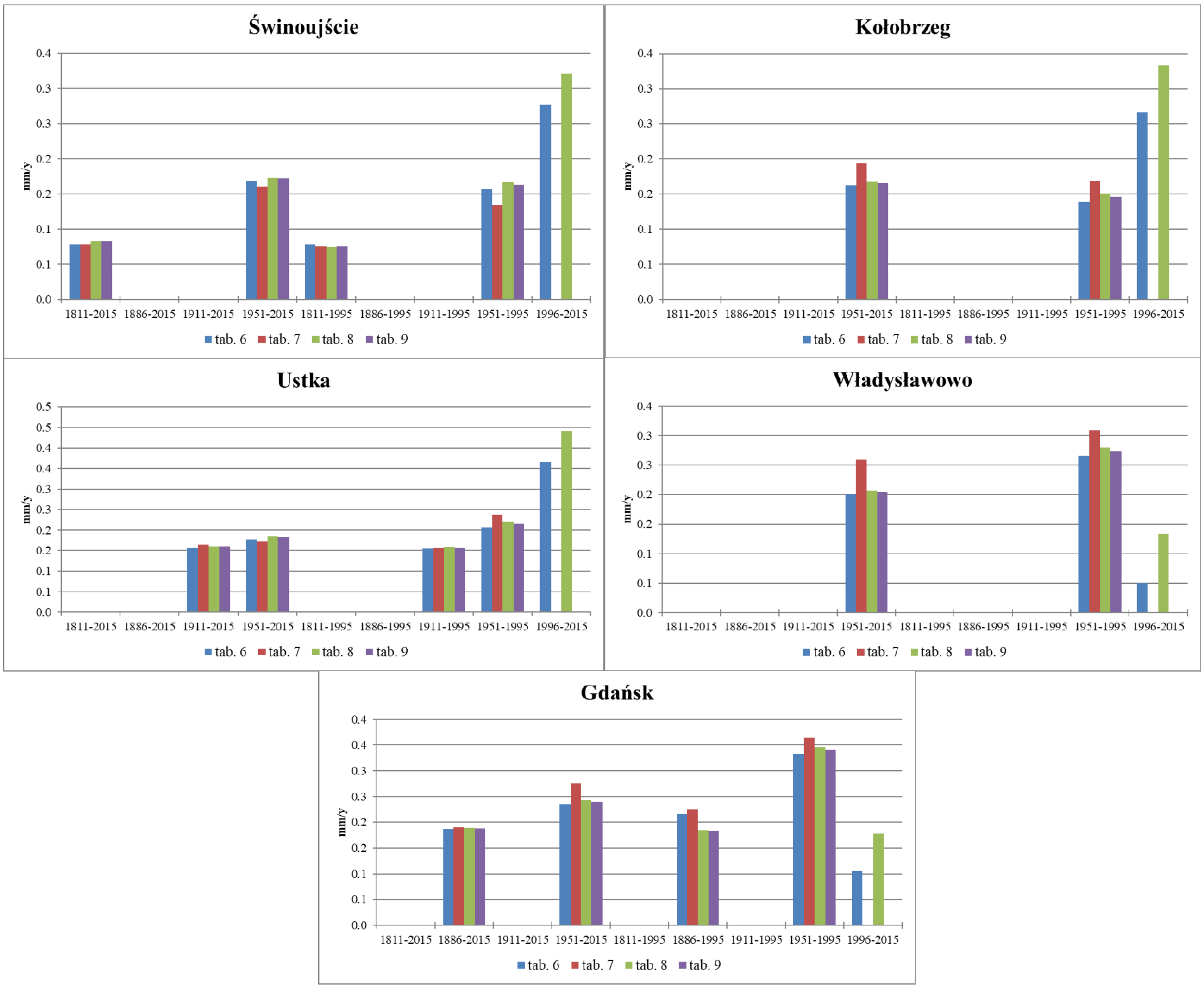

Fig. 11 Trend magnitudes in the Baltic Sea level at selected tide gauge stations based on the data from Tables 6, 7, 8 and 9.

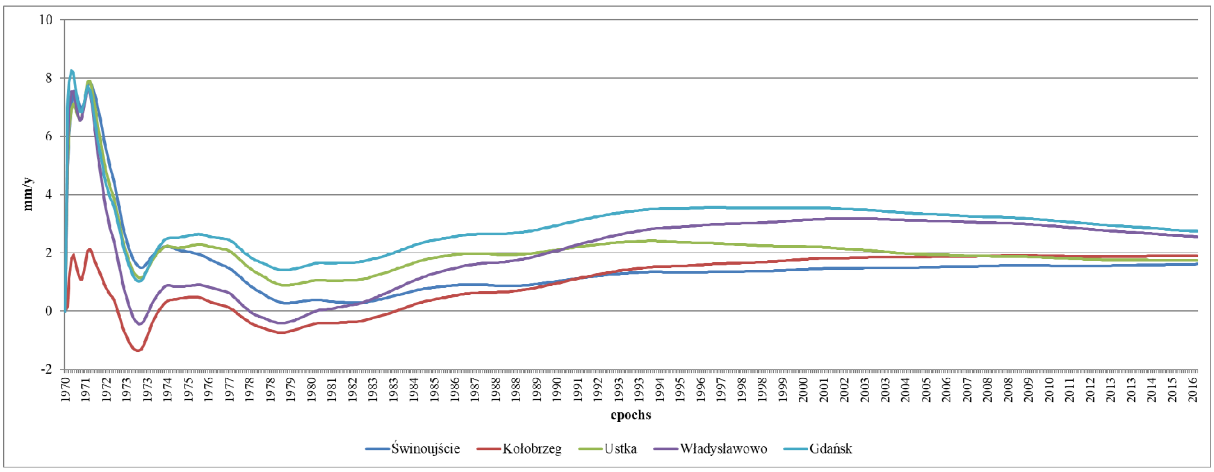

Fig. 12 The change in the trend at tide gauge stations, determined based on the 19-year moving average.

others (1973-1977). For the Ustka and Gdańsk stations, the changes in the trend become visible in 1990, and for the Władysławowo station, around the year 1986. Since 2005, a change in the trend direction has been noted for the Władysławowo and Gdańsk stations.

The lowest standard deviation (Fig. 13) was noted at the stations with long observation periods, while the highest deviation was noted for the station with a short observation period (which is consistent with the assumptions presented in Figure 2). Figure 14 shows the coefficient of determination R^2 calculated for the trend in the change of the mean level of the Baltic Sea at selected tide gauge stations based on the data from Tables 6, 7, 8 and 9. The best coefficient of the determination R^2 (Fig. 14) was obtained using

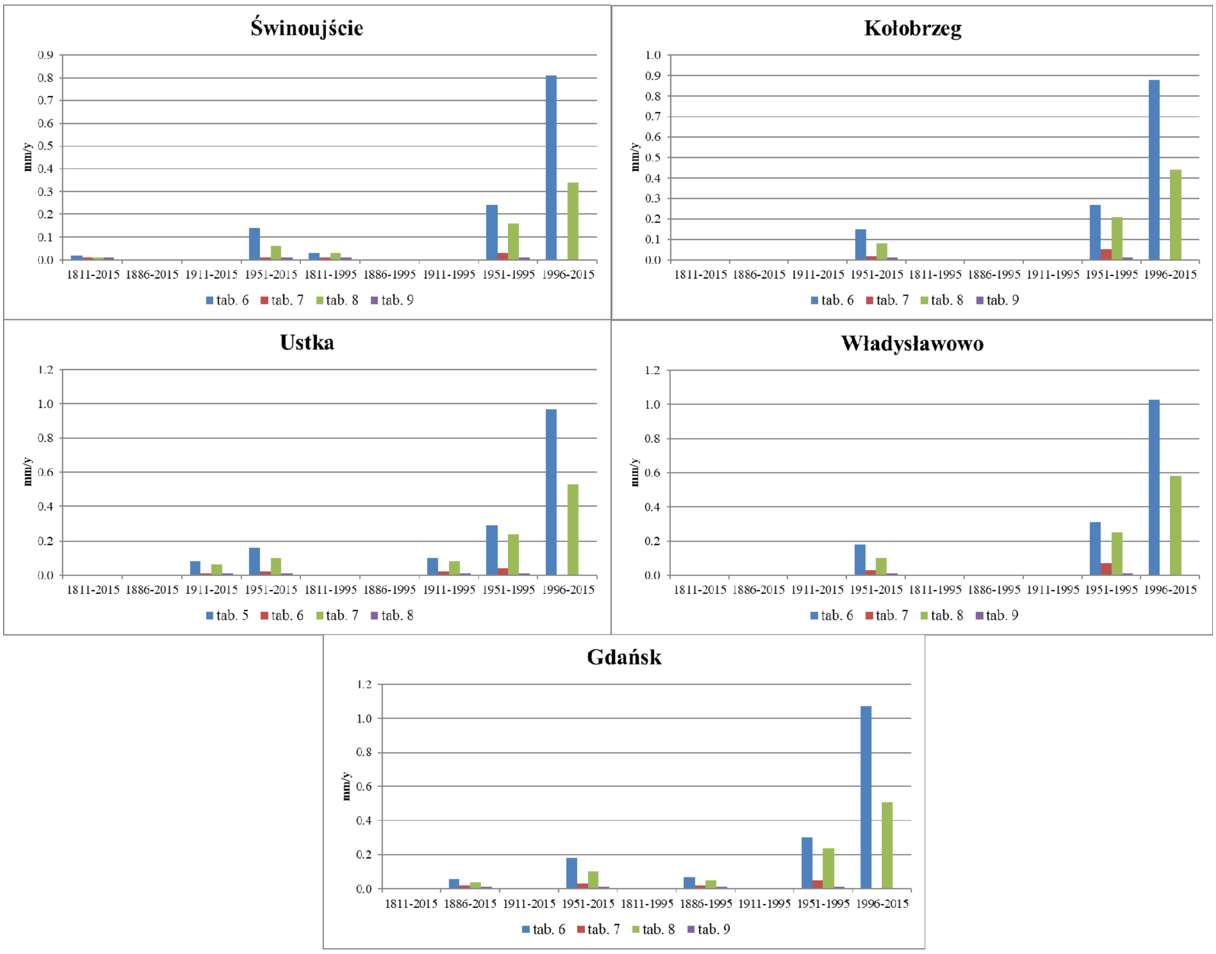

Fig. 13 Standard deviation of the trend in changes in the mean level of the Baltic Sea at selected tide gauge stations based on the data from Tables 6, 7, 8 and 9.

the Fourier function and the moving average with the 19-year window.

Table 10 shows the values of long-term changes calculated by author and provided in the literature.

The results presented in this article are in line with the results obtained by other reserchers (Wöppelmann et al., 2000; Łyszkowicz, 2003; Kryński and Zanimonskiy, 2004; Kowalczyk, 2005; Wiśniewski et al., 2011), as marked in color in Table 10. They do not coincide with the results presented in the paper (Dziadziuszko and Jednorał, 1987). It results from the application of a different method for determining changes, the type of data (metric or RLR), and the length of the applied time series.

The absolute differences in the mean sea level between extreme values for the same time interval (1951-2015) range from 77 mm (Świnoujście) through 84 mm (Kołobrzeg) and 83 mm (Ustka) to 102 mm (Władysławowo) and 114 mm (Gdańsk).

An analysis of vertical shifts (jumps) in the metric data time series demonstrated differences between the values for the RLR data adopted for the reduction, from 20 mm (Świnoujście) to 67 mm (Gdynia).

The linear trend determined from unrefined metric data corrected to include the jump (Table 4) is characterized by standard deviation ranging from 0.04 mm/y to 1.67 mm/y. The coefficient of trend determination R^2 is at a very low level for all analyzed time intervals.

The seasonal analysis demonstrated that at most tide gauges, there are two dominant periods, i.e. 12-month and 6-month periods. Following the removal of the seasonality effect, the coefficient of determination R^2 improved for all tide gauges; moreover, the standard deviation decreased. After smoothing the moving average (19-year), the obtained standard deviation decreased significantly. The trend line obtained fits very well to the data.

The greatest changes were noted at the Władysławowo and Gdańsk tide gauge stations. The lowest trend was observed for the Świnoujście tide gauge and increases in the eastern direction. The overall nature of the time series and the changes in the trend is similar. It differs in certain time intervals. For particular tide gauges, the trend ranges as follows: Świnoujście 0.76 mm/y - 1.72 mm/y; Kołobrzeg 1.46 mm/y - 1.66 mm/y; Ustka 1.57 mm/y - 2.15 mm/y; Władysławowo 2.04 mm/y - 2.74 mm/y; Gdańsk 1.84 mm/y - 3.40 mm/y.

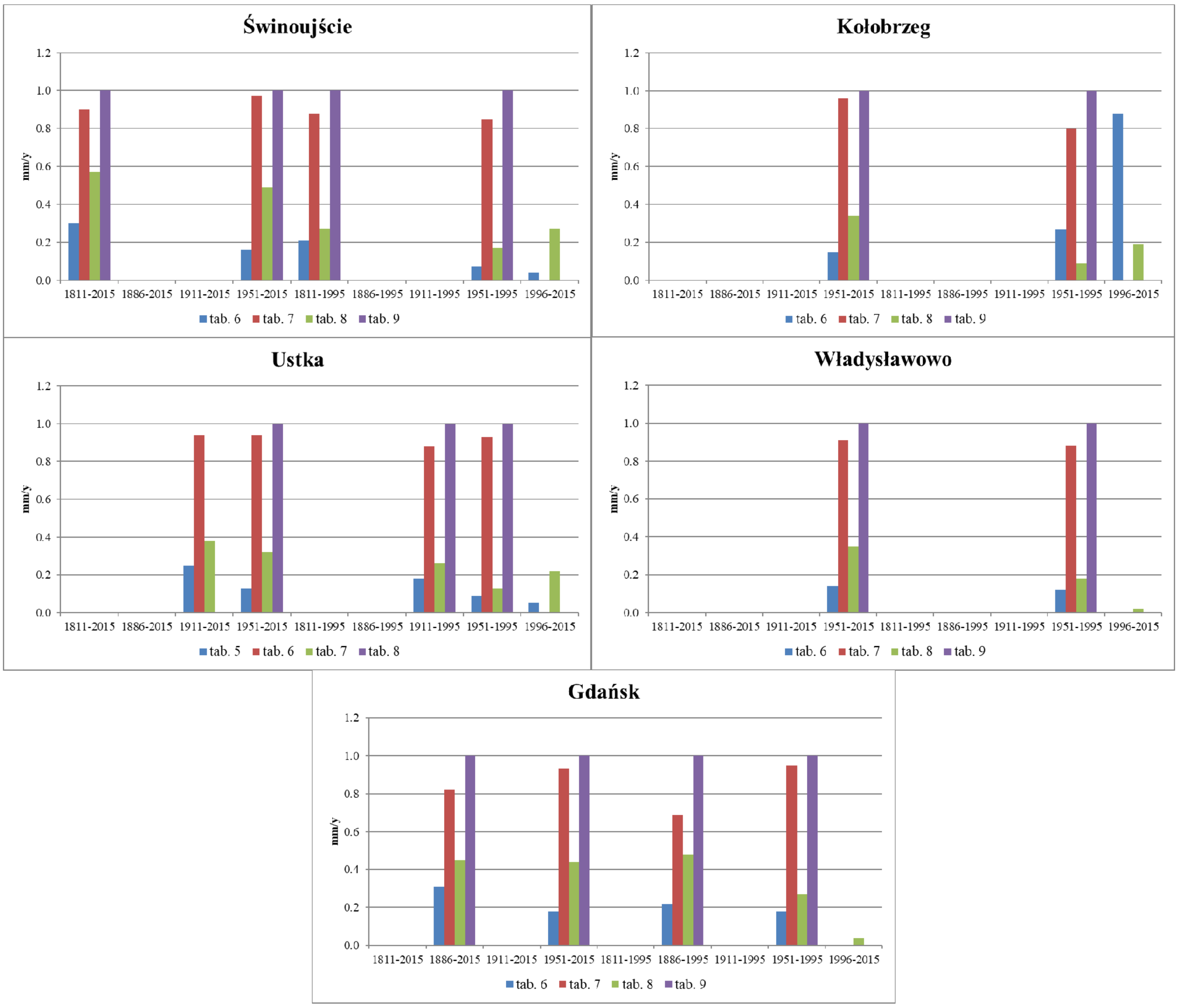

Fig. 14 The coefficient of determination R^2 for the trend in the change in the mean level of the Baltic Sea at selected tide gauge stations based on the data from Tables 6, 7, 8 and 9.

Table 10 List of values of long-term changes calculated by author and provided in the literature.

Name station	Dziadziuszko and Jednoral (1987)		Łyszkowicz (2003)		Kowalczyk (2005)		Kowalczyk (2019)	
	velocity [mm/y]	the time interval [y]	velocity [mm/y]	the time interval [y]	velocity [mm/y]	the time interval [y]	velocity [mm/y]	the time interval [y]
Świnoujście	0.7	1811-1985	0.82	1811-1999	1.35 0.85	1951-1999 1811-1999	1.72 0.83	1951-2015 1811-2015
Kołobrzeg	1.1	1868-1985	1.25	1951-1999	1.66	1951-1999	1.66	1951-2015
Ustka	0.2	1901-1985	1.69	1951-1999	2.12	1951-1999	1.60 1.83	1911-2015 1951-2015
Władysławowo	0.1	1950-1985	2.40	1951-1999	2.98	1951-1999	2.04	1951-2015
Gdańsk	1.2	1886-1985	2.88	1951-1999	-	-	2.43 1.88	1951-2015 1886-2015

Name station	Wiśniewski et al. (2011)				Wöppelmann et al. (2000)		Kryński and Zanimonskiy (2004)	
	velocity [mm/y]	the time interval [y]	velocity [mm/y]	the time interval [y]	velocity [mm/y]	the time interval [y]	velocity [mm/y]	the time interval [y]
Świnoujście	1.0	1947-2006	1.8	1977-2006	0.82	1811-1997	1.07	1811-1999
Kołobrzeg	1.0	1947-2006	1.8	1977-2006	-	-	-	-
Ustka	1.4	1947-2006	0.9	1977-2006	1.63	1951-1997	1.25	1951-1999
Władysławowo	1.9	1947-2006	1.7	1977-2006	2.28	1951-1997	1.95	1951-1999
Gdańsk	2.5	1947-2006	1.8	1977-2006	-	-	-	-

6. CONCLUSIONS

There are no previous studies on changes in the mean level of the Baltic Sea using such a long time series. Data from Polish tide gauges are omitted in reports created for the entire Baltic Sea basin. The main aim of the article is to determine changes in the mean level of the Baltic Sea using tide gauge data on the southern Baltic Sea coast. In the research, several statistical methods were used, including the moving average smoothing with a 19-year window corresponding to the 18.6 years cycle, which is the duration of lunar node precession. Vertical jumps in the time series were verified. The results showed that the RLR data (from the PSMSL database) are not always well-reduced.

Despite the change of the tide gauge location (Stolpmunde - Ustka), both time series can be connected using the VSED algorithm. Better coefficients R^2 fitting was obtained using the Fourier function than the index method.

The final linear trend was obtained from the metric data after the application of the Fourier function and the moving average with a 19-year window. The standard deviation is below 0.01 mm/y. The R^2 coefficient indicates a very good (1.0) fit to the data. This solution is the best from all the analyzed.

It was shown that the value of the tide gauges shift in relation to the reference level is not constant over time. The overall direction of changes in the mean level of the Baltic Sea for Polish tide gauge stations is positive. The greatest changes were noted at the Władysławowo and Gdańsk tide gauge stations.

The obtained results may be included in other studies on changes in the mean sea level of the Baltic Sea, e.g. using satellite altimetry data, or in studies of the vertical crustal movements.

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