

CHANGES IN THE WATER SURFACE LEVEL OF THE BALTIC SEA FROM SATELLITE ALTIMETRY AND GRAVITY MISSIONS

Jakub BIAŁAS, Krzysztof SOŚNICA

Wrocław University of Environmental and Life Sciences, Institute of Geodesy and Geoinformatics, Grunwaldzka 53, 50-357 Wrocław, Poland

e-mails: jakub.bialas@upwr.edu.pl, krzysztof.sosnica@upwr.edu.pl

ABSTRACT. Satellite altimetry provides high-accuracy geometrical measurements of sea level changes. We analyze altimetry time series representing sea surface height anomalies over the mean sea surface provided by the TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 satellite missions to estimate the annual rate of sea level rise. Then, we compare the results with satellite gravimetric data from GRACE and GRACE Follow-On missions and surface water temperature data, employing statistical analyses to examine the interrelationships and correlations between them. We carry out the main analyses for the period 2001–2021 with a division into 5-year periods for six different areas of the Baltic Sea. The altimetric results show that between 2001 and 2021, the water level of the Baltic Sea rose by 5.8 mm/year on average. About 72% of the changes detected by altimetry missions can be explained by satellite gravimetry from GRACE and GRACE Follow-On, which means that the mass component is responsible for most of the observed sea level change, whereas the remaining 28% can be greatly explained by thermal expansion due to the water temperature rise.

Keywords: satellite altimetry, sea level changes, Jason-1/2/3, GRACE, Baltic Sea

1. INTRODUCTION

The Baltic Sea is one of the most important water bodies in Europe, with a coastal zone highly sensitive to environmental and climatic changes. Rising sea levels in this region pose increasing risks, intensifying the destructive effects of storms, floods, and erosion on densely populated and economically vital coastal areas. With about 44% of the European Union (EU) and UK population living within 50 km of the coastline, addressing sea level rise is essential for socioeconomic stability (Milne et al., 2009; Cortés Arbués et al., 2024). Hence, understanding and predicting sea level changes in the Baltic Sea are crucial for identifying coastal areas at risk of future flooding.

Before the era of satellite altimetry, historical measurements of Baltic Sea level were conducted mainly by tide gauges along the Polish coast. For the period 1811–2015, Władysławowo (2.0–2.7 mm/yr) and Gdańsk (1.8–3.4 mm/yr) showed the most significant increases of sea level, with similar trends in other gauges, though variations occurred in specific time intervals (Kowalczyk, 2019). Development of research on sea topography occurred with satellite altimetry, thanks to the coverage of large areas of the globe in a relatively short time by satellites. Satellite altimetry is based on the measurement of the time it takes microwave impulse to make a round trip from the satellite transmitter to the sea surface and back. Because



microwave impulse travels with the speed of light, it is possible to compute the round trip distance satellite and the sea surface (Chambers, 2015).

Sea surface level anomalies are estimated in reference to mean sea surface (MSS), which is locally computed from the altimetric data. As a result of aggregating altimetric measurements from around the globe and creating an average value from them, the global mean sea level (GMSL) is obtained. Altimetry data from TOPEX/Poseidon, Jason-1, and Jason-2 missions (2005–2011) indicated an annual GMSL rise of about 2.4 ± 0.5 . Similar results were obtained from the same missions (1993–2014), estimating GMSL growth to be between 2.6 and 2.9 ± 0.4 mm/yr (Watson et al., 2015).

The GMSL results, for example, can be affected by the choice of minimum sea depth criterion, as shallower basins exhibit strong seasonal and interannual signals affecting altimetric measurements (Masters et al., 2012). Further crucial factors that can change GMSL are alterations in oceanic water mass, density changes, and fluctuations in ocean basin volume. These changes are driven by environmental and climate factors like ice caps and glacier melting (mass contribution), sea surface temperature (thermohaline contribution), and seawater salinity (halohaline contribution).

Higher water temperatures cause thermal expansion, raising the sea levels, while increased salinity makes water denser and typically lowers sea levels. However, this phenomenon is more complex, as many of the mechanisms that affect salinity also affect water temperature (e.g., water evaporation) (Durack, Wijffels and Gleckler, 2014). Observations from Argo floats and GRACE missions indicate that glacier melting contributes three times more (1.8 mm/yr) to GMSL rise than temperature and salinity combined (0.6 mm/yr) (Chen, Wilson and Tapley, 2013).

It is worth mentioning that the quality of altimetry data can be inferior for lakes and coastal zones due to vegetated shorelines, proximity to land, and less accurate corrections. Liibusk et al. (2020) validated Sentinel 3A/B and Copernicus Marine Environment Monitoring Service (CMEMS) products, focusing on the Baltic Sea coast and Estonian lakes. The study revealed that the achieved results in the research area had measurement uncertainties below a decimeter (Donlon et al., 2012; Strugarek et al., 2019; Liibusk et al., 2020).

To evaluate the changes in sea level off the southern coast of the Baltic Sea, Łyszkowicz and Bernatowicz (2019) combined tide gauge measurements (1951–2017) with Global Navigation Satellite System (GNSS) observations (2002–2017). As a result of this study, absolute long-term trends in sea level rise were obtained, which ranged between 2.6 and 3.5 mm/yr. It was also deduced that the estimates of the studied trends are sensitive to the length of the data record (Łyszkowicz and Bernatowicz, 2019). Moreover, the study conducted by Stramska et al. (2013) exposed an asymmetric-shaped seasonal cycle in the variability of the Baltic Sea surface with an amplitude of about 18 cm. The asymmetry of the cycle was manifested by higher average daily amplitudes during autumn and winter in comparison to spring and summer. These fluctuations are mainly due to meteorological factors such as the magnitude of local atmospheric pressure and strong winds (Stramska, Kowalewska-Kalkowska and Świrgoń, 2013; Pajak and Kowalczyk, 2019).

Relative and absolute sea level rise results in the Baltic Sea were also presented by Kapsi et al., (2023) who used data from tide gauges, satellite altimetry, and land uplift models. The absolute sea level rise from 1995 to 2019 was from 2.4–6.5 mm/yr and was computed using European Space Agency's (ESA's) BalticSEAL data. Furthermore, the NKG2016LU and EST2020VEL post-glacial land uplift models were analyzed, with the northern part of the Gulf of Bothnia exhibiting the highest values of approximately 10 mm/yr due to the greater mass of ice sheet in northern Europe in the past. The relative sea level rise model indicates that the

southern coast of the Baltic Sea is most threatened by sea level rise, reaching about 4 mm/yr in this area (Kapsi, Kall and Liibus, 2023).

The main objective of this study is to determine changes in the mean sea level of the Baltic Sea using satellite altimetry missions such as TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3. We compare these data with gravimetric measurements from the GRACE and GRACE Follow-On missions and the sea surface temperature to identify significant correlations (Tapley et al., 2004, 2019). Altimetry missions provide information about geometrical changes in the sea level surface, that is, the volume expansion, whereas gravimetry missions provide information about mass changes. Therefore, both satellite techniques are complementary and can deliver additional information about density changes, as well as explain the contribution of different components to the observed sea level rise.

2. MATERIALS AND METHODS

We chose the Baltic Sea as the study area because of its landlocked nature and poor connection to the Atlantic Ocean and the North Sea. These, as well as the Baltic's shallow depth, mean that tidal and wave phenomena are relatively limited there. The Baltic Sea allows us to obtain altimetric data that are not subject to the large errors of background geophysical models (Granskog et al., 2006; Medvedev, Rabinovich and Kulikov, 2013). We made and compared statistical analyses for both the entire Baltic area and for the Gulf of Gdańsk, the Gulf of Bothnia, the Gulf of Finland, the Gulf of Riga, and a small zone of open sea in the central Baltic near Gotland.

For the study, we used a time series with monthly intervals downloaded from the National Aeronautics and Space Administration (NASA) Data Analysis Tool (https://sealevel.nasa.gov/data_tools/1). We retrieved data both before and after the removal of the seasonal signals, which allowed us to obtain results free of seasonal variability. The main data of our study are gridded sea surface height anomalies (SSHA), which represent SSHA over MSS. The time series were provided by altimetric measurements from the TOPEX/Poseidon, Jason-1, Jason-2, and Jason-3 satellite missions. These satellites used dual-frequency radar altimeters, which are able to measure the distance between the satellite and the Earth's surface, wave height, and wind speed. Combining the measurements from the different instruments produced fully corrected heights, which are the data product at level 4.

We compared altimetric data with gravimetric measurements from the GRACE and GRACE Follow-On missions for the period 2001–2021 with a division into 5-year intervals. GRACE data represent in equivalent water thickness (EWT) unit monthly changes in the mass of water stored in the oceans relative to the average obtained over a given period. Gravimetric data are obtained by measuring the varying distance between a pair of GRACE satellites using the K-band ranging system (KBR) instrument. When a pair of satellites approach an area of stronger gravity (higher mass concentration), the force of the Earth's gravity acts first on the leading satellite, pulling it away from the following satellite. Precise orbit determination (POD) provides additionally accurate positioning of satellites and improves relative orbit accuracy, which is essential for high-quality measurements of gravity (Kang et al., 2020).

The GRACE gravity field model is corrected for the effects of the pole tide, the solid earth tide, and the ocean tide (Pajak and Kowalczyk, 2018). It also takes into account a glacial isostatic adjustment (GIA) correction, which is based on the ICE6G-D model. The GIA correction is relatively minor, amounting to approximately 0.3 mm/yr. Nevertheless, it can be characterized with around 40% uncertainty. For high-latitude regions (above 60°), these uncertainties can be even higher, which can make GIA a critical factor in these areas (Caron et al., 2018). However,

the GIA correction is necessary to conduct consistent comparisons between satellite altimetry and gravity observations.

In the study, we used data from both the Center of Space Research in Texas (CSR) and the Jet Propulsion Laboratory in California (JPL) processing centers, which differ in the applied algorithms and resolution of the mascon grid (Chambers, 2006; Save, Bettadpur and Tapley, 2016). Data from CSR has a $0.5^\circ \times 0.5^\circ$ grid resolution, while data from JPL has a $3^\circ \times 3^\circ$ grid resolution. We compared both centers and assessed which one shows greater agreement with the altimetric data. Next, we compared SSHa with high-resolution sea surface temperature (HRSST) data delivered by the National Centers for Environmental Information (NCEI). Due to the different availability of the data, we made a comparison for the 1993–2018 period with a division into 5-year periods. The 5-year periods were selected to remove the effects related to the El Niño Southern Oscillation (ENSO) cycle, which are typically detectable in 1-year analyses.

Table 1. Configurations of the compared satellite data

Period	Data set No. 1	Data set No. 2
01.01.2001–01.01.2021	Seasonalized SSHa	Seasonalized EWT (JPL)
01.01.2001–01.01.2021	Deseasonalized SSHa	Deseasonalized EWT (JPL)
01.01.2001–01.01.2021	Seasonalized SSHa	Seasonalized EWT (CSR)
01.01.2001–01.01.2021	Deseasonalized SSHa	Deseasonalized EWT (CSR)
01.01.1993–01.01.2018	Seasonalized SSHa	Seasonalized HRSST
01.01.1993–01.01.2018	Deseasonalized SSHa	Deseasonalized HRSST

For each data set provided in Table 1, we computed trend line equations as:

$$y = Bx + A \quad (1)$$

$$A = \frac{(\Sigma y)(\Sigma x^2) - (\Sigma x)(\Sigma xy)}{n(\Sigma x^2) - (\Sigma x)^2} \quad (2)$$

$$B = \frac{n(\Sigma xy) - (\Sigma x)(\Sigma y)}{n(\Sigma x^2) - (\Sigma x)^2} \quad (3)$$

where y represents the dependent variable expressing the theoretical value of the time series, x represents the independent variable expressing time in days, B represents the slope of the line (multiplied by 365 days to gain the value of the annual trend of the time series), and A represents the y-axis intercept.

In addition, we computed linear regression equations for paired data sets, showing their linear relationships. We calculated the coefficient of determination R^2 , which indicates what percentage of the dependent variable is explained by the independent variable (takes the value from 0 to 1). The square root of R^2 is the Pearson correlation coefficient, which demonstrates the strength of the linear relationship between two variables (takes the value from -1 to 1). For the results obtained from the analyses, we prepared corresponding figures presenting data variability depending on the considered time, the Baltic area, the chosen gravimetric data analysis center, and the removal or retaining seasonal signals.

3. RESULTS

3.1. Time series of altimetric, gravimetric, and sea surface temperature data

Figure 1 and 2 compare the altimetric (SSHA) and gravimetric (EWT JPL) anomalies of the Baltic Sea level between 2001 and 2021, both before and after the removal of seasonal signals. The altimetric anomalies are consistently about 10 cm higher than the gravimetric anomalies, regardless of the presence of seasonal signals, which is because satellite altimetry considers factors such as temperature, salinity, tides, and ocean currents, while gravimetry includes mainly the changes in Earth's mass distribution. Furthermore, it should be noted that the GRACE mission may underestimate the impact of glacier melting on sea level rise by about 30% due to the limited spatial resolution of the data. Conversely, the growth of the EWT indicator may be caused by the uplift of land masses due to post-glacial rebound, which is discernible in Scandinavia (Wahr and Velicogna, 2003; Chambers et al., 2007; Milne et al., 2009; Steffen, Müller and Denker, 2009). However, it is important to note that the impact of post-glacial rebound is majorly considered from GRACE solutions due to GIA correction. Consequently, this factor has a rather limited influence on our results.

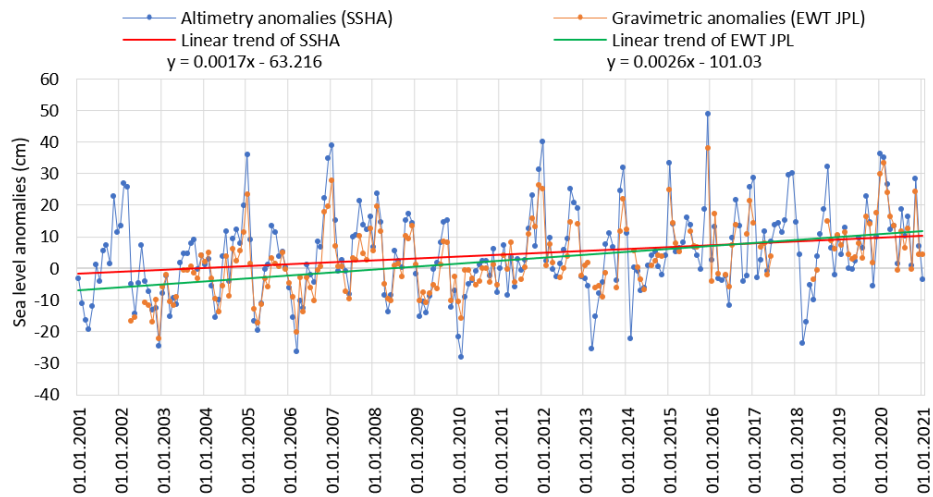


Figure 1. Sea level anomalies from altimetric (SSHA) and gravimetric (EWT JPL) data from 2001–2021 before the removal of seasonal signals for the Baltic Sea.
The trend values are given in cm/day

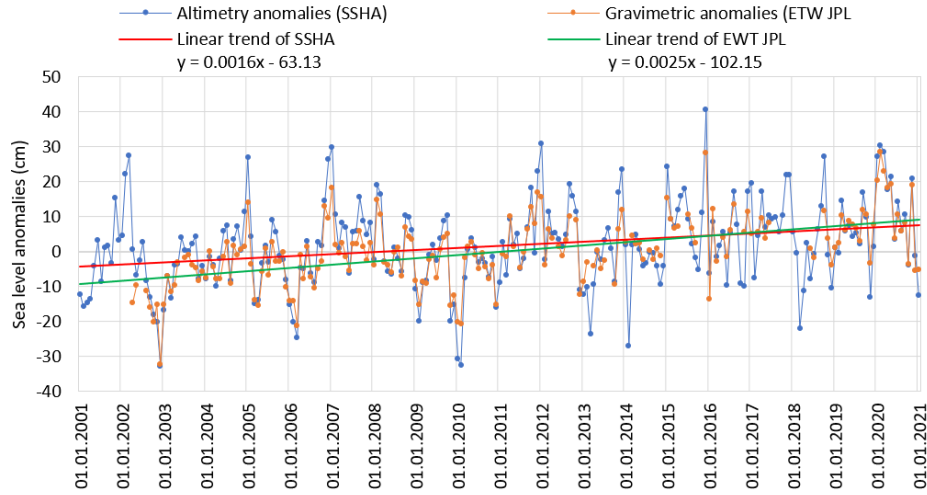


Figure 2. Sea level anomalies from altimetric (SSHA) and gravimetric (EWT JPL) data from 2001–2021 after the removal of seasonal signals for the Baltic Sea.
The trend values are given in cm/day

Discontinuity of data is evident in the gravimetric time series. The first gap is a result of the start of the Gravity Recovery and Climate Experiment (GRACE) mission on 03.17.2002, while the second gap occurred between the end of the GRACE mission and the start of the GRACE-Follow On (GRACE-FO) mission. The lack of gravimetric data at the beginning of the period may increase the trend line slope coefficient, which should be taken into account during the interpretation of results.

We can observe that the impact of seasonal signals on altimetric and gravimetric anomalies is minor. Removing the seasonal signal slightly decreases the annual sea level rise trend for both SSHA from 0.62 to 0.58 cm/yr and for EWT JPL from 0.95 to 0.91 cm/yr. The difference between these results oscillates close to the measurement uncertainty value of ± 0.04 cm/yr (Chen, Wilson and Tapley, 2013; Watson et al., 2015).

Figure 3 and 4 reveal a strong positive linear relationship between altimetric anomaly values and the EWT index from the JPL center. The linear regression coefficients are 0.72 before the removal of the seasonal signals and 0.71 after the removal of seasonal signals, indicating moderate-to-strong positive linear relationships. Consequently, we can interpret that a 1.00 cm increase in the altimetric anomaly value corresponds to a 0.71–0.72 cm increase in the EWT index. Lower values for gravimetric anomalies may result from not taking into account factors such as sea surface temperature or salinity, which impact the water density, and underestimating the impact of glacier melting by the GRACE mission.

The coefficient of determination R^2 is 0.84 and the coefficient of Pearson linear correlation R is 0.92 in Figure 3 and 4, indicating a strong positive linear relationship between these variables. However, the time series from CSR shows a poorer agreement with the satellite altimetry results than JPL, which will be examined in more detail when discussing Table 2.

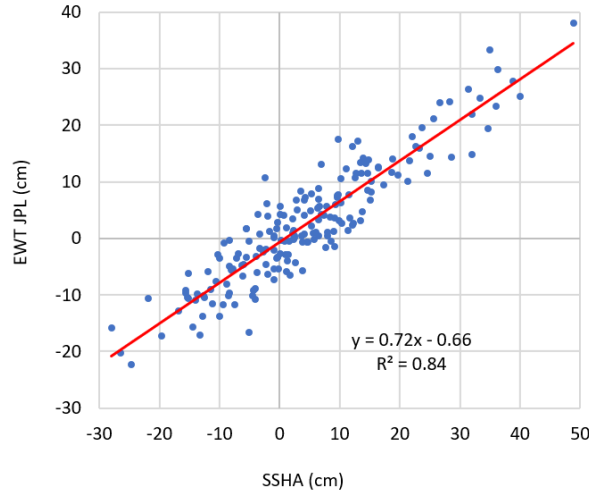


Figure 3. Correlation between altimetric (SSHA) and gravimetric (EWT JPL) anomalies for 2001–2021 before removal of seasonal signals for the Baltic Sea

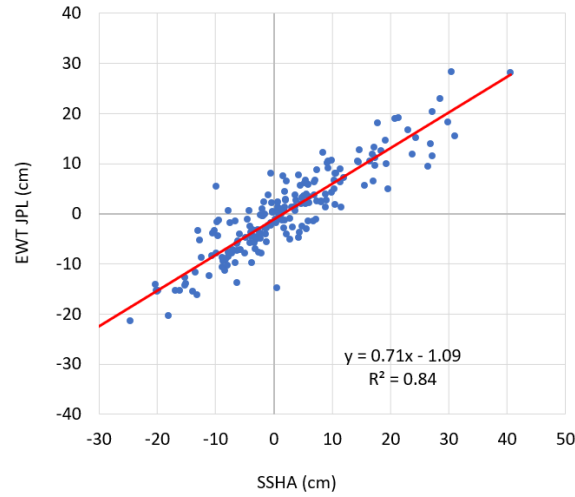


Figure 4. Correlation between altimetric (SSHA) and gravimetric (EWT JPL) anomalies for 2001–2021 after removal of seasonal signals for the Baltic Sea

Figure 5 and 6 depict a comparison between altimetric anomalies (SSHA) and sea surface temperature (HRSST) from 1993 to 2018, both before and after eliminating seasonal signals. We can see significant changes in the HRSST range after removing seasonal signals (from 0–19°C to –2–2°C). The remaining temperature anomalies after removing the seasonal effects are caused by the variability of the seasons including El Niño events. Local maxima and minima in the deseasoned time series of sea surface temperature may be caused by short-term weather fluctuations, climate variation, different hydrologic conditions, and changes in the marine ecosystem of the Baltic Sea.

In contrast, the trend line slope coefficient of sea surface temperature is the same both before and after removal of the seasonal signals and amounts to 0.04°C/yr. We can conclude that, although the seasonal signal affects the range and character of the oscillations, the increase in value over time itself follows a very similar pattern.

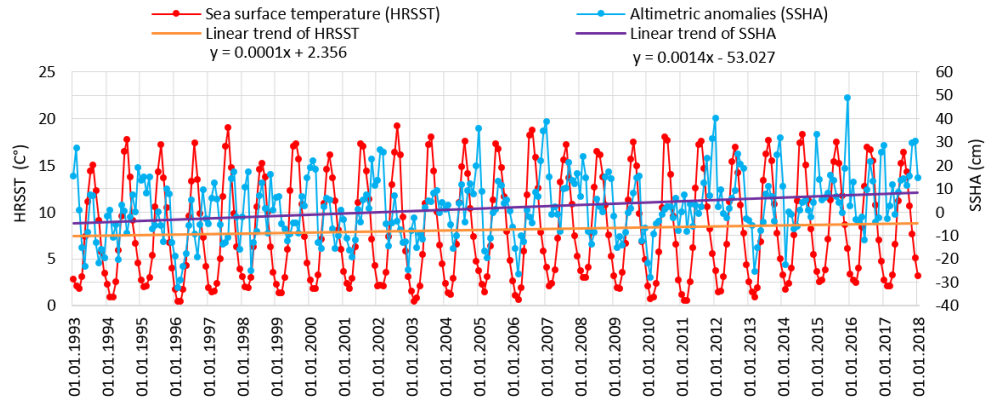


Figure 5. Altimetric anomalies (SSHA) and sea surface temperature (HRSST) from 1993 to 2018 before the removal of seasonal signals for the Baltic Sea. The trend values are given in cm/day

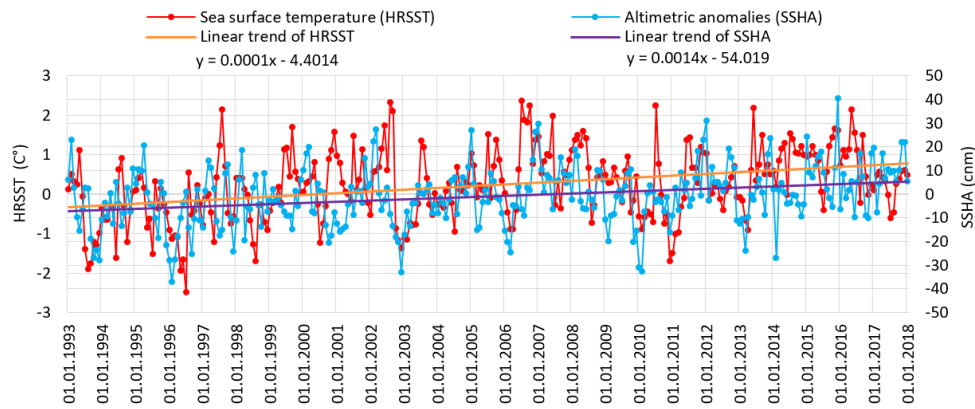


Figure 6. Altimetric anomalies (SSHA) and sea surface temperature (HRSST) from 1993 to 2018 after the removal of seasonal signals for the Baltic Sea. The trend values are given in cm/day

While analyzing the altimetric anomalies for 1993–2018, we can notice very comparable results and dependencies as for 2001–2021. However, the secular trend is lower by about 0.07 cm/yr than the same trend from 2001–2021, which can be the result of the presence of observations from the 1990s, when the rate of mean sea level rise was lower.

Figure 7 and 8 show the major impact of removing the seasonal signal on the linear regression parameters between altimetric anomalies and sea surface temperature. After the removal, the linear regression coefficient increases from 0.26 to 3.55 cm/°C, indicating that a change of sea surface temperature by 1°C corresponds to a change of sea level height by 3.55 cm. We can observe a similar growth for the coefficient of determination R^2 and the Pearson correlation coefficient R , which increased from 0.01 to 0.07 and from 0.11 to 0.26 before and after the removal of the seasonal signals for R^2 and R , respectively. Nevertheless, this is still a rather weak positive correlation between these variables.

We can obtain the projected sea level rise due to the change in sea surface temperature by multiplying the annual sea surface temperature rise trend by the linear regression coefficient. For the deseasoned data, the temperature component is equal to 0.13 cm/yr. Considering that the sea level rise trend from altimetric measurements for the same period was 0.51 cm/yr, we can conclude that sea surface temperature rise was responsible for about 25% of the sea level rise in the Baltic Sea. Chen et al. (2013) presented similar results for the global sea level rise trend, where the steric part was 0.06 cm/yr, which was 25% of the total value (0.24 cm/yr). An even closer outcome can be found on the website of NASA (<https://sealevel.nasa.gov>), where

the increase in the steric height of the sea is 0.13 cm/yr at the time of access on February 16, 2024. Nonetheless, we should note that the cited results also considered the salinity factor, while we study only sea surface temperature impact in our research.

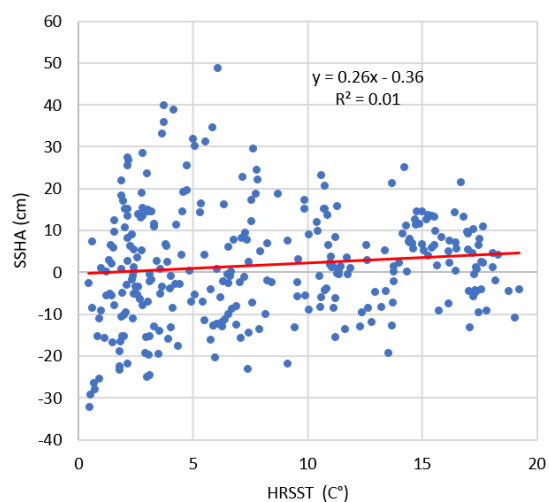


Figure 7. Correlation between altimetric anomalies (SSHA) and sea surface temperature for 1993–2018 before removal of seasonal signals for the Baltic Sea

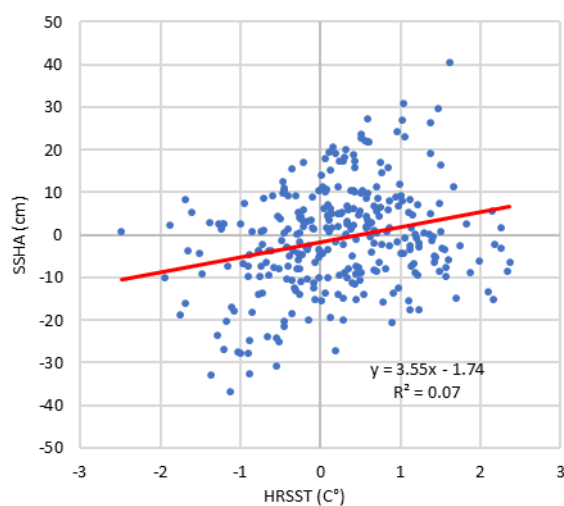


Figure 8. Correlation between altimetric anomalies (SSHA) and sea surface temperature for 1993–2018 after removal of seasonal signals for the Baltic Sea

Table 2. Results of statistical analyses of sea level changes from altimetric (SSHA) and gravimetric (EWT) data before removal of seasonal signals

Region	Period	Sea level rise trend (cm/yr)			Linear regression coefficient		Pearson correlation coefficient	
		SSHA	EWT JPL	EWT CSR	SSHA – EWT JPL	SSHA – EWT CSR	SSHA – EWT JPL	SSHA – EWT CSR
Baltic Sea	2001–2006	1.20	3.76	3.36	0.70	0.59	0.92	0.87
	2006–2011	–1.50	–0.69	–0.47	0.65	0.56	0.94	0.90
	2011–2016	0.99	1.13	–0.66	0.67	0.56	0.92	0.86
	2016–2021	1.68	1.90	1.06	0.67	0.56	0.88	0.79
	2001–2021	0.62	0.95	0.33	0.72	0.55	0.92	0.86
The central part of the Baltic Sea	2001–2006	1.20	4.49	3.39	0.76	0.62	0.89	0.83
	2006–2011	–1.93	–1.13	–0.58	0.64	0.58	0.89	0.86
	2011–2016	1.64	0.62	–0.58	0.73	0.58	0.89	0.82
	2016–2021	1.50	1.57	0.95	0.67	0.56	0.83	0.73
	2001–2021	0.58	0.84	0.29	0.72	0.56	0.88	0.81
Gulf of Gdańsk	2001–2006	1.02	2.48	1.57	0.54	0.35	0.85	0.73
	2006–2011	–1.53	–1.10	–0.95	0.59	0.38	0.91	0.83
	2011–2016	1.10	0.33	–1.10	0.55	0.38	0.87	0.73
	2016–2021	1.13	0.77	0.37	0.55	0.42	0.85	0.74
	2001–2021	0.62	0.51	–0.18	0.57	0.32	0.89	0.67
Gulf of Bothnia	2001–2006	1.50	3.94	4.49	0.67	0.63	0.92	0.89
	2006–2011	–1.53	–2.92	–0.37	0.65	0.60	0.94	0.89
	2011–2016	0.99	1.06	–0.11	0.67	0.58	0.93	0.88
	2016–2021	1.75	2.01	1.68	0.67	0.60	0.88	0.80
	2001–2021	0.62	1.13	0.58	0.73	0.61	0.90	0.88
Gulf of Finland	2001–2006	1.17	5.66	7.01	0.94	1.01	0.91	0.85
	2006–2011	–1.57	–0.58	1.06	0.76	0.68	0.92	0.81
	2011–2016	1.39	0.51	–0.99	0.76	0.56	0.89	0.75
	2016–2021	2.15	1.93	2.12	0.63	0.56	0.83	0.74
	2001–2021	0.62	1.02	0.91	0.81	0.72	0.90	0.81
Gulf of Riga	2001–2006	1.24	4.05	2.30	0.74	0.46	0.90	0.80
	2006–2011	–1.50	–0.29	–0.62	0.65	0.46	0.91	0.87
	2011–2016	1.35	0.77	–0.55	0.53	0.32	0.87	0.81
	2016–2021	1.93	1.57	0.88	0.52	0.35	0.82	0.68
	2001–2021	0.62	0.95	–0.03	0.64	0.35	0.87	0.74

3.2. Summary of the results of the statistical analyses

Table 2 and Tables A1–A3 from the Appendix A show the results of the comparison for different gulfs and parts of the Baltic Sea including altimetric (SSHA), gravimetric (EWT), and sea surface temperature (HRSST) data. We visualize them in the following bar charts and choropleth maps to show relevant trends, dependencies, and patterns in Baltic sea level changes. They depict the variability of individual values across the Baltic regions during specific periods. The analysis considers the area of the Baltic Sea (the whole area), the Gulf of Gdańsk, the Gulf of Bothnia, the Gulf of Finland, and the Gulf of Riga, as well as the central part of the Baltic Sea.

From the results presented in Table 2, Tables A1–A3, and Figure 9–Figure 10, a relatively large variability emerges of sea level rise linear trends derived from the altimetric data. This large variability is clearly visible between the following 5-year periods and between different parts of the Baltic Sea. The largest positive secular changes in sea surface level come from 2016–2021 and they exceed 1 cm/yr in almost all studied areas except for the Gulf of Gdańsk, whose sea level rise trend is 0.8 cm/yr. The period 2006–2011 is considerably distinguishable because we can perceive at that time a negative sea level rise trend in all areas, which oscillates around the value of -1.8 cm/yr. The observed anomaly could probably be caused by high air temperatures and repeated heat waves during this period. For example, the 2006 heatwave that affected a large part of Europe resulted in increased water evaporation and drying up of riverbeds that are tributaries of the Baltic Sea (Rebetez, Dupont and Giroud, 2009; Chiriaco et al., 2014). A reflection of this phenomenon can also be found in Figure 20 with a clear pattern of increased sea surface temperatures in all areas of the Baltic Sea in 2003–2008.

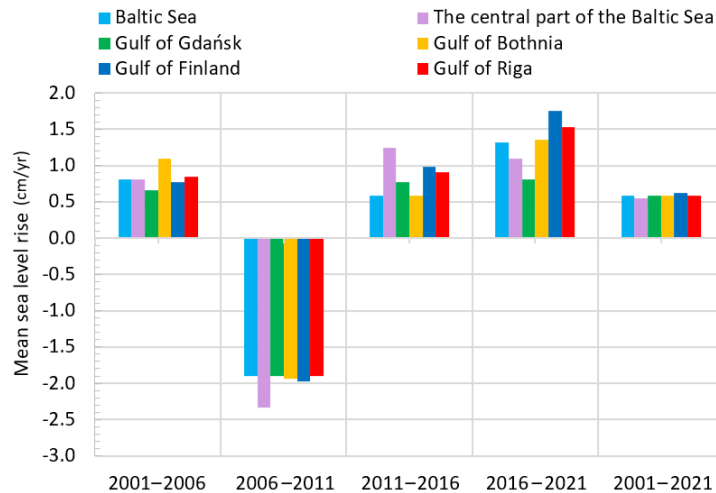


Figure 9. Mean sea level rise linear trends of Baltic Sea in 2001–2021 from altimetric data (SSHA) after removal of seasonal signals

When comparing the results of the 5-year time series from 2001–2021, we can notice that short 5-year periods are characterized by irregular and divergent values. This may be due to the great sensitivity of these data to seasonal effects and short-term factors, such as rapid changes in weather and climate, wave heights, or freshwater inflows into the sea.

Conversely, the values of the sea level rise trend from the entire 2001–2021 period present a great consistency between various parts of the Baltic Sea. The results range from 0.55 to 0.62 cm/yr, with the slowest sea level rise trend observed in the central part of the Baltic Sea and the fastest in the Gulf of Finland, where post-glacial rebound effects additionally occur. Obtained values from this study are greater than the results of Łyszkowicz and Bernatowicz (2019) for

the southern coast of the Baltic, which oscillated between 0.26 and 0.36 cm/yr (Łyszkowicz and Bernatowicz, 2019). They also surpass the global sea level rise trend ranging between 0.24 and 0.36 cm/yr (Milne et al., 2009; Chen, Wilson and Tapley, 2013; Watson et al., 2015), but considered different time spans.

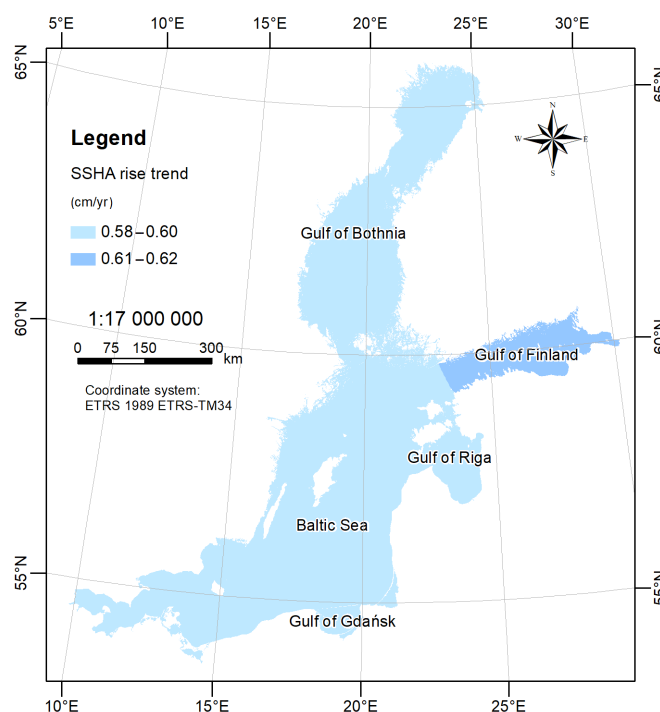


Figure 10. Choropleth map of linear trends of Baltic Sea level rise in 2001–2021 from altimetric data (SSHA) after removal of seasonal signals

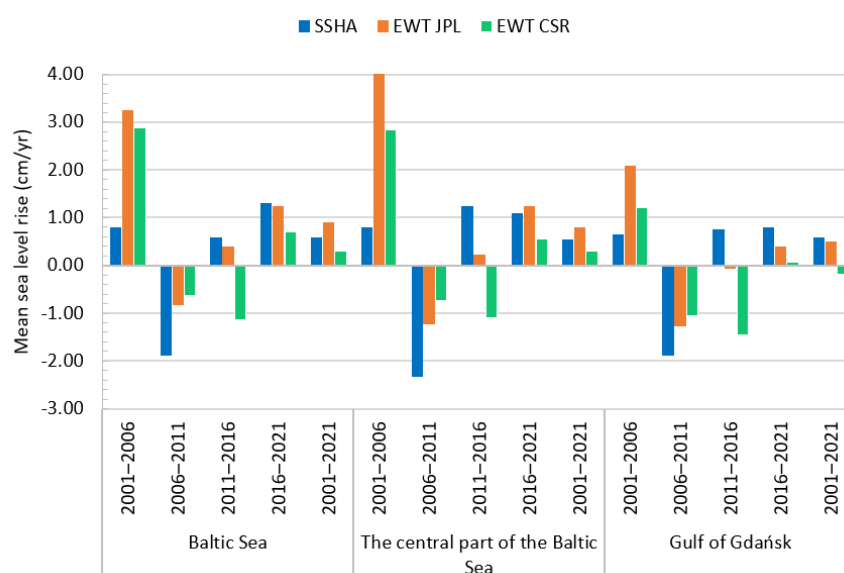


Figure 11. Sea level rise linear trends of the Baltic Sea, the central part of the Baltic Sea, and the Gulf of Gdańsk in 2001–2021 from altimetric (SSHA) and gravimetric data (EWT) after the removal of seasonal signals

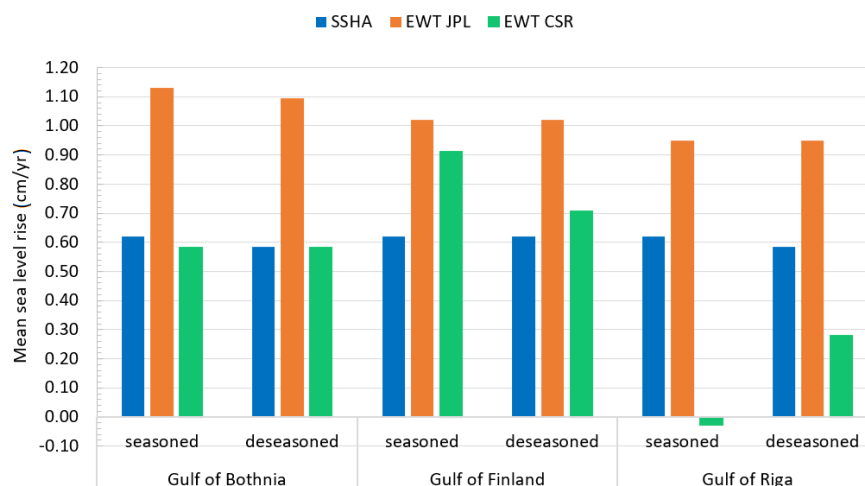


Figure 12. Sea level rise linear trends for the Gulf of Bothnia, the Gulf of Finland, and the Gulf of Riga in 2001–2021 from altimetric (SSHA) and gravimetric data (EWT) before and after removal of seasonal signals

Figures 11 and 12 compare the sea level rise trends derived from altimetric (SSHA) and gravimetric data – EWT from JPL and CSR centers. Figure 11 shows substantial linear trends for EWT in the period 2001–2006. The values exceed SSHA results by 2.45 cm/yr for JPL and by 2.00 cm/yr for CSR, for the entire area of the Baltic Sea. However, a distinct outlier in gravimetric anomaly observation from JPL can be observed in the central part of the Baltic Sea in the same period. There, the trend reaches the value of 39.06 cm/yr. Such high values of linear trends for EWT data in 2001–2006 are due to measurement discontinuities in GRACE missions, which lasted until March 2002, and due to poor data quality in the first months of the mission. In subsequent 5-year periods, the values of the annual sea level rise trends for the gravimetric data are already comparable or lower than the trend values from the altimetric data. In general, we can observe that for most of the analyses, the absolute values of linear trends are higher for the JPL center than for the CSR center. This may be caused by different processing strategies and the background models, as well as differences in outlier elimination methods and corrections for the Earth's oblateness value between these two analysis centers.

Figure 12 shows the sea level rise trends for the Gulf of Bothnia, the Gulf of Finland, and the Gulf of Riga, considering the presence of the seasonal signal in 2001–2021. The seasonal signal has a negligible effect on considered time series with the exception of EWT data from CSR in the Gulf of Finland and the Gulf of Riga. In the Gulf of Riga, after removing the seasonal signal from EWT data from CSR, the linear trend reversed, changing from -0.03 to 0.28 cm/yr. The large gravity anomaly values from the JPL center are evident once again. In comparison to the Gulf of Finland and the Gulf of Bothnia, the value of EWT JPL for the Gulf of Gdańsk is lower by about 0.5 cm/yr. This difference is likely caused by the land uplift of Scandinavia and Finland due to post-glacial rebound. We can also notice this dependency in Figure 13.

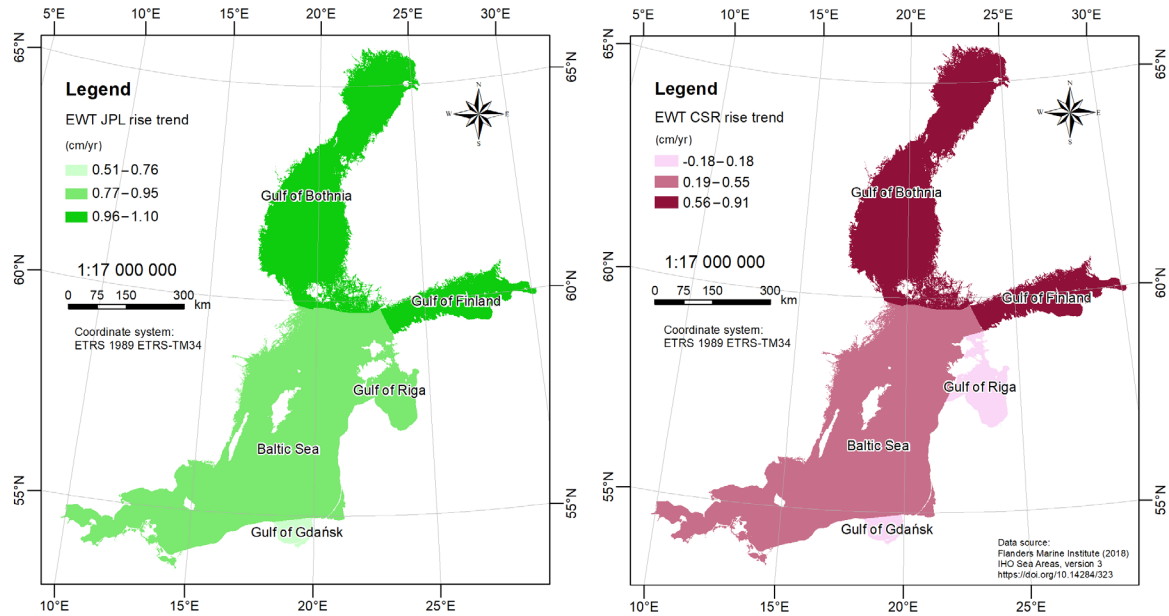
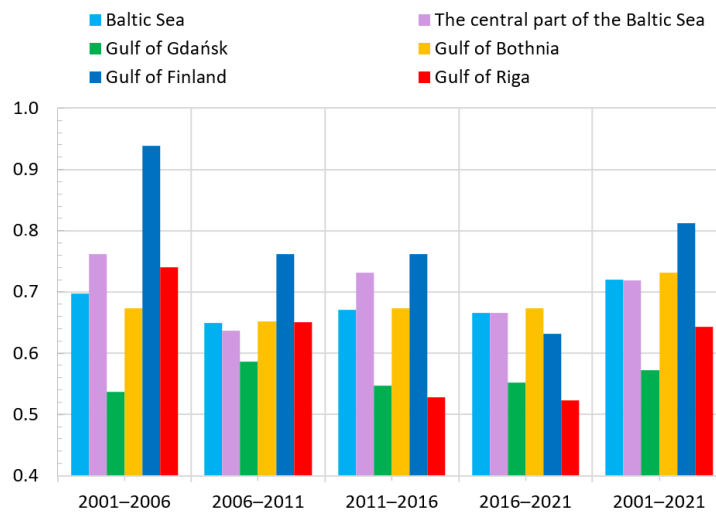


Figure 13. Choropleth maps of linear trends of Baltic Sea level rise in 2001–2021 from gravimetric data (EWT) after the removal of seasonal signals

Figure 14 and 15 show linear regression coefficients between altimetric anomalies and gravimetric anomalies. When analyzing results from Figure 14, we can state that the largest linear dependency occurs in the Gulf of Finland, the central part of the Baltic Sea, and the whole Baltic Sea area. The Gulf of Riga and the Gulf of Gdańsk are characterized by the weakest linear dependency, which can be related to the size of these gulfs, which can hardly be separated in GRACE data. We can observe similar patterns in all studied periods from Figure 14. The highest linear regression coefficients appear in 2001–2006; for the Gulf of Finland, the regression coefficients reach even 0.9. The second highest values of linear correlations come from 2001–2021. We can assume that this is due to the long-term nature of the observations, which makes the correlation between the analyzed data more visible. Further observation is a slight variation between different periods in Figure 14, which can be the result of weaker sensitivity of linear dependency between SSHa and EWT to short-term seasonal signals.



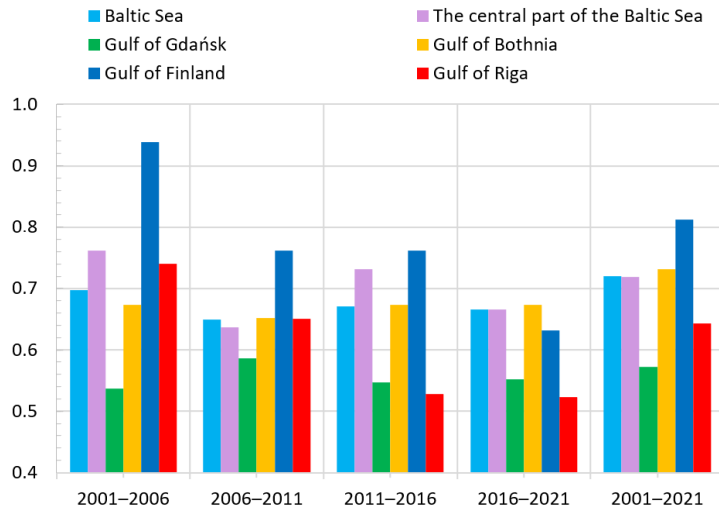


Figure 14. Linear regression coefficients between altimetric anomalies (SSHA) and gravimetric anomalies (EWT JPL) for the Baltic Sea in 2001–2021 after the removal of the seasonal signal

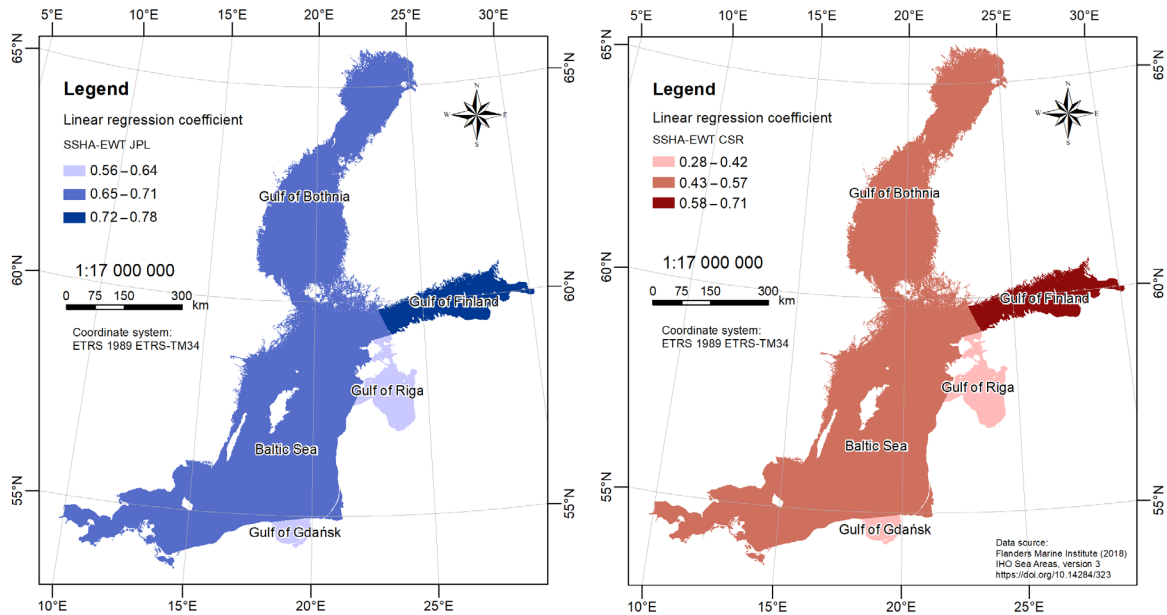


Figure 15. Choropleth maps of linear regression coefficients between altimetric anomalies (SSHA) and gravity anomalies (EWT JPL/CSR) of the Baltic Sea in 2001–2021 after the removal of seasonal signals

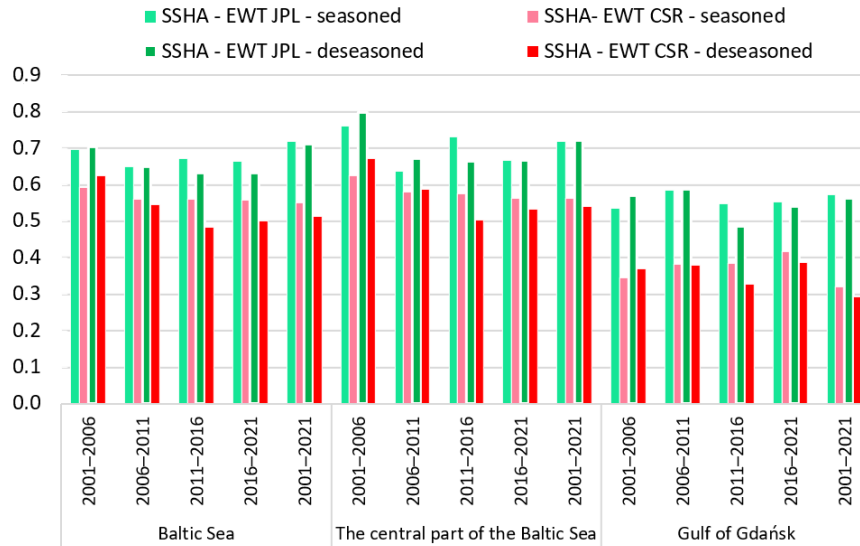


Figure 16. Linear regression coefficients between altimetric anomalies (SSHA) and gravity anomalies (EWT JPL/CSR) of the entire area of the Baltic Sea, the central part of the Baltic Sea, and the Gulf of Gdańsk in 2001–2021

By examining Figure 16, we can assess the effect of the choice of gravimetric data processing center and the removal of the seasonal signal on the strength of the linear correlations. The analysis reveals a stronger linear relationship between the SSHA-EWT JPL data and the SSHA-EWT CSR data. For instance, in the Baltic Sea between 2001 and 2021, the linear regression coefficient for the SSHA-EWT JPL data is 0.71, while for the SSHA-EWT CSR data set it is only 0.51. This dependency is consistent across all periods and areas analyzed in the figure.

The influence of the removal of the seasonal signal on the value of the linear regression coefficient is more apparent in the SSHA-EWT CSR dataset. Excluding the 2001–2006 period, the removal of the seasonal signal generally slightly weakens the linear correlation between the data. This is particularly noticeable for the 2011–2016 period, where the difference between the linear regression coefficients is typically around 0.1.

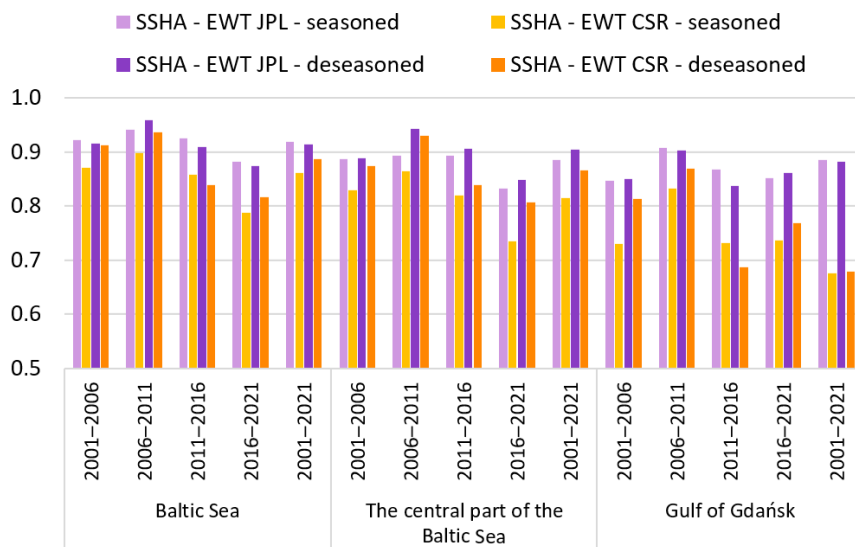


Figure 17. Pearson correlation coefficients between altimetric anomalies (SSHA) and gravity anomalies (EWT JPL/CSR) of the entire area of the Baltic Sea, the central part of the Baltic Sea, and the Gulf of Gdańsk in 2001–2021

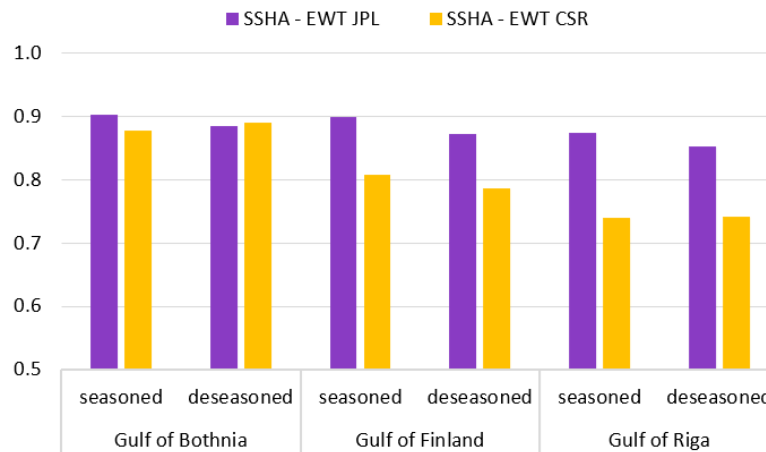


Figure 18. Pearson correlation coefficients between altimetric anomalies (SSHA) and gravity anomalies (EWT JPL/CSR) of the Gulf of Bothnia, the Gulf of Finland, and the Gulf of Riga in 2001–2021

Figure 17–19 show the distribution of Pearson correlation coefficients between different sets of altimetric and gravimetric data. Similar to the linear regression coefficient, the EWT JPL data exhibits a stronger correlation with the SSHA compared to the EWT CSR. However, the differences are not as significant as in Figure . An exception to this is the Gulf of Gdańsk from 2001–2021, where the correlation after removal of the seasonal signal between the SSHA-EWT JPL data is 0.88, while the SSHA-EWT CSR correlation is only 0.68.

We can see both in Figure 15 and Figure 19 that the Gulf of Gdańsk and the Gulf of Riga are distinguished by a weaker linear dependency between altimetric and gravimetric anomalies. This may be due to the greater vulnerability of these bays to the effect of sea temperature on the increase in sea surface elevation, which is not included in gravimetric measurements, as well as the small areas of these gulfs. We can confirm this assumption in Figure 23 and Figure 24, where the Gulf of Gdańsk and the Gulf of Riga stand out with the highest Pearson correlation coefficients between sea surface temperature and altimetric anomalies in 1993–2018.

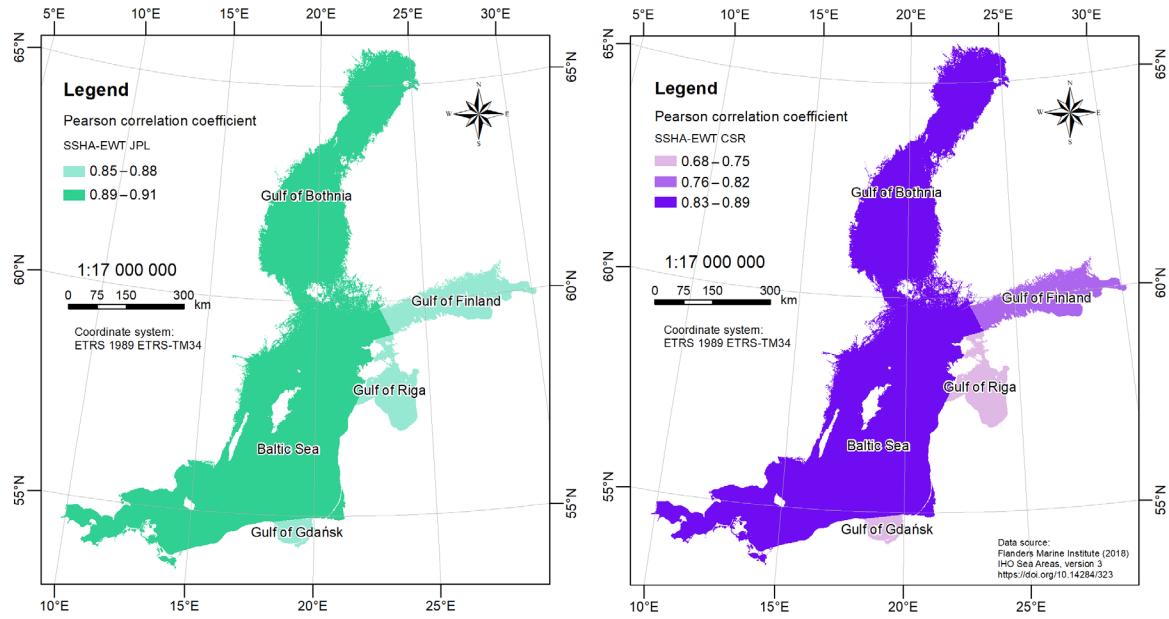


Figure 19. Choropleth maps of Pearson correlation coefficients between altimetric anomalies (SSHA) and gravity anomalies (EWT JPL/CSR) of the Baltic Sea in 2001–2021 after the removal of seasonal signals

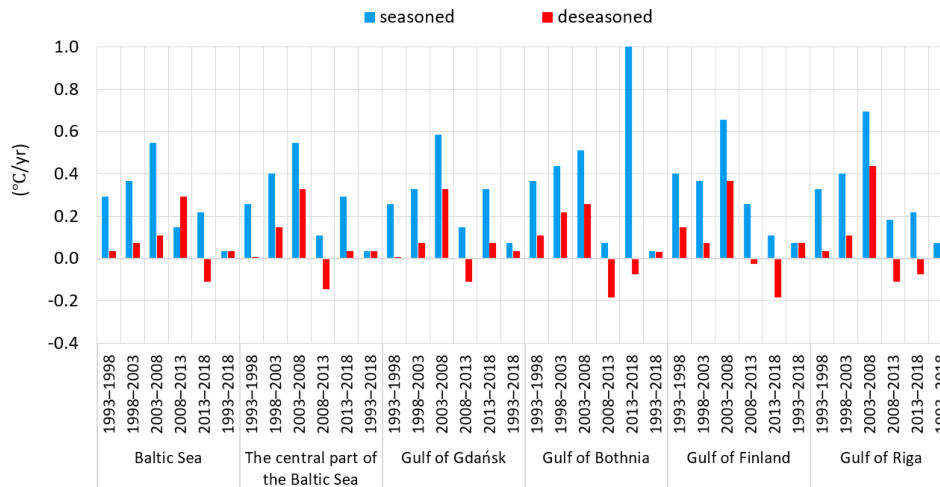


Figure 20. Sea surface temperatures (HRRST) linear trends of the Baltic Sea in 1993–2018

Figure 20–24 show the results of analyses of sea surface temperature rise and its impact on altimetry anomalies measured in 1993–2018. In Figure 20, we can perceive the high sensitivity of the 5-year time series of sea surface temperature to the removal of seasonal signals, resulting in a significant decrease in the values of the linear trend. This is apparent in 2003–2008, where, as a result of removal of the seasonal signal, the linear trend falls from $0.55^{\circ}\text{C}/\text{yr}$ to $0.11^{\circ}\text{C}/\text{yr}$. The linear trend results for the long-term time series (1993–2018) are characterized by substantial high resistance to the impact of removing the seasonal signal. In most of the considered Baltic Sea regions, these results remain essentially unchanged. Nonetheless, the Gulf of Gdańsk shows a deviation from this pattern, as the linear trend after the removal of the seasonal signal decreased from $0.07^{\circ}\text{C}/\text{year}$ to $0.04^{\circ}\text{C}/\text{year}$ during the period 1993–2018.

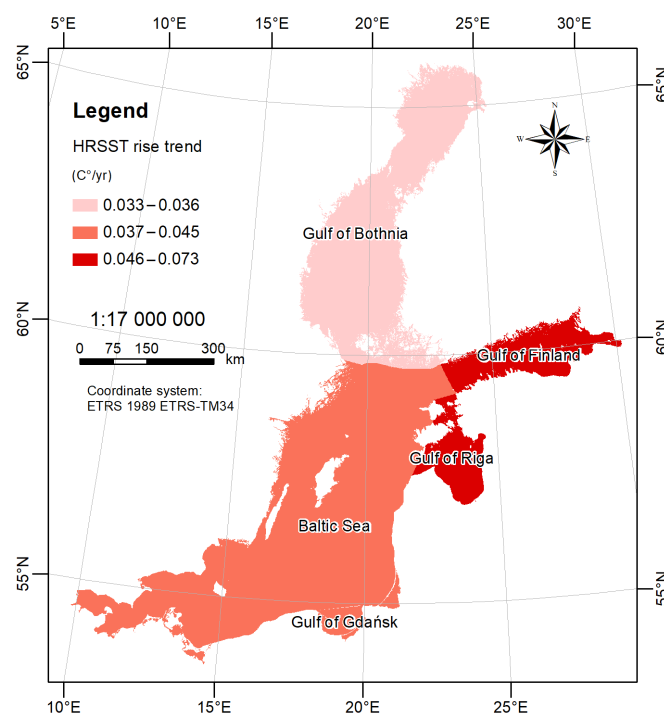


Figure 21. Choropleth map of sea surface temperatures (HRRST) linear trend of the Baltic Sea in 1993–2018 after the removal of seasonal signals

The highest values of sea surface temperature linear trend occur in 2003–2008. It can be associated with factors such as weather variabilities and climate changes, the inflow of hot tropical air, the inflow of warm waters from the North Sea, or human activities (Dutheil et al., 2022). The heat waves that affected Europe in 2006 are worth mentioning again (Rebetez, Dupont and Giroud, 2009; Chiriaco et al., 2014). While analyzing the 1993–2018 period, we can conclude that the largest trend of sea surface temperature rise takes place in the Gulf of Finland and the Gulf of Riga and it reaches $0.07^{\circ}\text{C}/\text{yr}$. This may be due to the shallowness of the mentioned gulfs. The average depth of the Gulf of Finland is 38 m, while that of the Gulf of Riga is 26 m. In the shallow gulf, the warming of seawater may occur faster and more intensely.

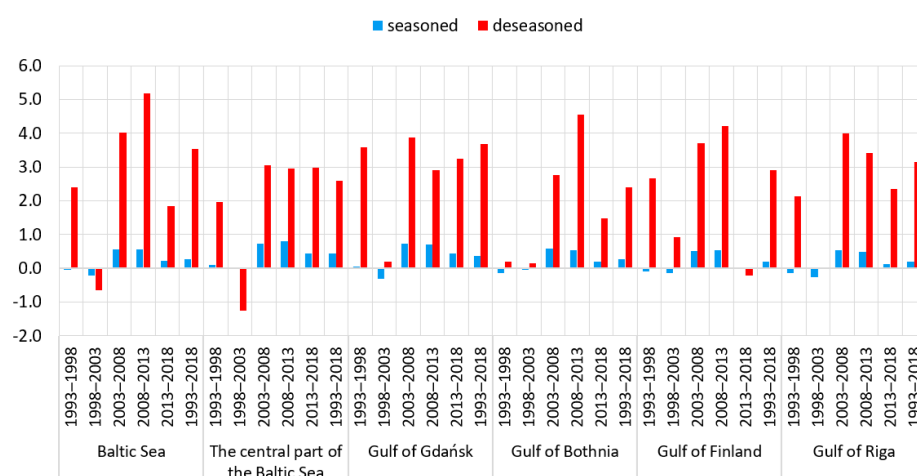


Figure 22. Linear regression coefficients between altimetric anomalies (SSHA) and sea surface temperatures (HRSST) for the Baltic Sea in 1993–2018

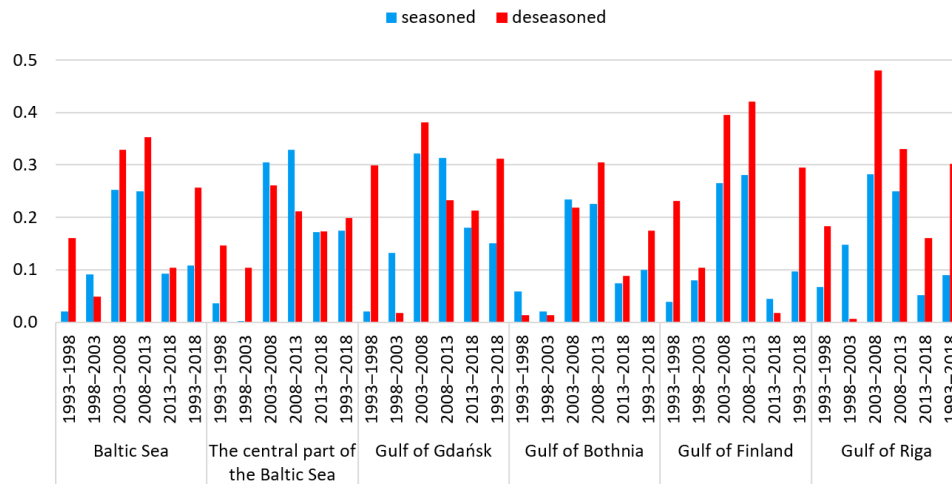


Figure 23. Pearson correlation coefficients between altimetric anomalies (SSHA) and sea surface temperatures (HRSST) of the Baltic Sea in 1993–2018

Figure 22 illustrates linear regression coefficients between altimetric anomalies (SSHA) and sea surface temperatures (HRSST). Because of the distinct advantage and much smaller variations of deseasoned data over seasoned data, sometimes as much as seven times, we can conclude that altimetry anomalies are sensitive to sea surface temperature changes caused by unseasonal, long-term factors such as global warming. Furthermore, while analyzing the results after removing the seasonal signals, we can see a rather irregular distribution of values over consecutive years. This is particularly noticeable in the Baltic Sea and the Gulf of Finland, where the differences are approximately 2.5–3.0 for consecutive periods. Meanwhile, the highest linear regression coefficient is found in the Gulf of Gdańsk for the long-term period of 1993–2018, with a value of 3.69.

In Figure 23, which depicts the values of Pearson correlation coefficients, we can observe a similar trend, where the values of deseasoned data are larger than those including seasonal signals. However, these differences are not so large as in Figure 22. The largest values occur in the Gulf of Riga and the Gulf of Finland, where they can reach up to 0.2. We can also notice that in all areas of the Baltic Sea, the largest correlation coefficients come from the periods of 2003–2008 and 2008–2013. In the long-term 1993–2018 period, the highest correlation between altimetry anomalies and sea surface temperature is found in the Gulf of Gdańsk (0.31), the Gulf of Riga (0.30), and the Gulf of Finland (0.29). Considering the nature of the data, we can assess these results as a positive and moderately strong correlation. In Figure 24, we can see that the Gulf of Bothnia has the smallest linear regression and Pearson correlation coefficients.

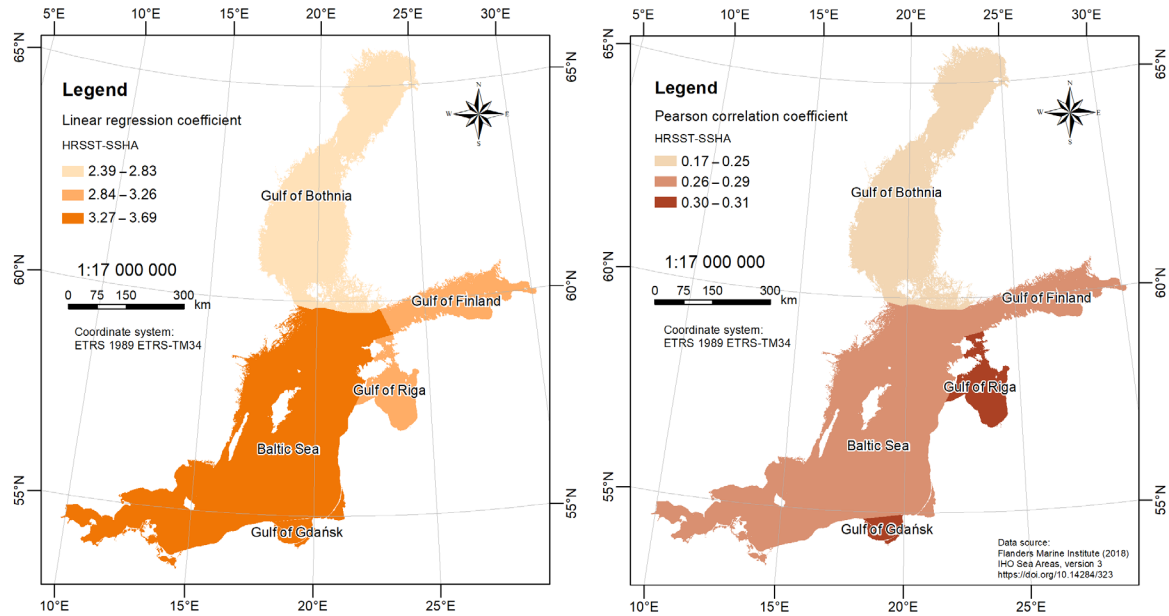


Figure 24. Choropleth map of linear regression and Pearson correlation coefficients between altimetric anomalies (SSHA) and sea surface temperatures (HRSST) for the Baltic Sea in 1993–2018

4. CONCLUSIONS AND DISCUSSION

Through a comparative analysis of altimetric, gravimetric, and sea surface temperature data, we investigated the dynamics of the Baltic Sea surface level changes across specific spatial and temporal units. Our main conclusion is that the trend of the Baltic Sea level rise is 0.58 cm/yr in 2001–2021 and 0.51 cm/yr in 1993–2018. These rates exceed those reported for the southern Baltic coast (0.26–0.35 cm/yr) and the global average (0.24–0.36 cm/yr) cited in the literature (Milne et al., 2009; Chen, Wilson and Tapley, 2013; Watson et al., 2015; Łyszkowicz and Bernatowicz, 2019).

However, it is important to note that our results cannot be directly compared to previous studies, as they cover different periods, areas, and methodologies. The measurements of the southern Baltic coast were obtained from a network of tide gauges (1951–2017) and GNSS observations (2002–2017). They were limited to coastal areas without including open sea measurements (Łyszkowicz and Bernatowicz, 2019). Conversely, the global sea level rise trend of 0.26–0.29 cm/yr reported in a paper by Watson et al. (2015) was for the years 1994–2014 (Watson et al., 2015). The influence of older study periods based on different measurement types may be important in the context of faster sea level rise in recent years.

Altimetric anomalies (SSHA) consistently exhibit variations higher by about 10 cm than gravimetric anomalies (EWT). This is due to different measurement techniques – altimetry includes factors such as sea temperature, salinity, and sea currents, whereas gravimetry does not. We can also see that for both data types, the removal of seasonal signals has a negligible impact, which is around 0.4 cm, that is, close to measurement uncertainty (Chen, Wilson and Tapley, 2013; Watson et al., 2015). For the 2001–2021 period, we find the highest gravimetric anomalies (about 1 cm/yr) in the Gulf of Bothnia and the Gulf of Finland. It is probably caused by the uplift of the Earth’s crust due to the post-glacial rebound in Scandinavia and Finland and the high uncertainty in the background GIA model.

Nevertheless, the coefficient of the EWT trend line may be overestimated because of the lack of GRACE observations in the first months of the considered period. We can also observe that gravimetric data processed by the JPL center has higher compatibility with altimetric data than

the time series from CSR. For the Baltic Sea in 2001–2021, the linear regression coefficient between SSHA-EWT JPL is 0.71, while that between SSHA-EWT CSR is only 0.51. These differences may result from the different processing strategies, background models, outlier elimination methods, and corrections for the Earth's oblateness value between these two analysis centers. The higher linear regression coefficient for the JPL center may also be attributed to the Coastal Resolution Improvement (CRI) filter, which reduces leakage errors across coastlines (Śliwińska and Nastula, 2023).

From the analysis of the sea surface temperature (HRSST) of the Baltic Sea in 1993–2018, we can conclude that for both deseasoned data and those with seasonal signals, the linear trend is $0.04^{\circ}\text{C}/\text{yr}$. The largest growth rate of HRSST can be found in the Gulf of Finland and the Gulf of Riga ($0.07^{\circ}\text{C}/\text{yr}$ for both), which is probably due to their shallowness. We can also see that removal of the seasonal signal from the HRSST has a huge effect on lowering their range of values from $0\text{--}19^{\circ}\text{C}$ to $-2\text{--}2^{\circ}\text{C}$ and changing the character of their variabilities. Deseasoned HRSST data is also characterized by high linear regression and Pearson correlation coefficients with SSHA. For the linear regression coefficient, it is possible to note an over seven times increase in its value. Therefore, we can assume that for long-term periods, the sea level rise is more sensitive to nonseasonal variations of sea surface temperature, caused, for example, by global warming. While analyzing the results of the linear regression between deseasoned HRSST-SSHA, we can find that the change of sea surface temperature by 1°C corresponds to the change of sea level rise by 3.55 cm. Hence, a nonseasonal increase in sea surface temperature from 1993–2018 is responsible for a sea level rise of $0.14\text{ cm}/\text{yr}$. It is 28% of the total annual sea level rise trend.

Our findings are crucial for assessing altimetric (TOPEX/Poseidon, Jason-1, Jason-2, Jason-3) and gravimetric (GRACE and GRACE-FO) missions. They offer insights into forecasting Baltic Sea level changes and potential flood risks. Areas at risk of flooding in the future may require measures such as reinforcing existing flood defenses and natural barriers. Restoring wetlands can also help with water absorption. It is important to continuously monitor coastal flood risk, which may require relocating populations and infrastructure. Long-term sea level forecasting is, therefore, essential for conducting appropriate preventive actions.

Statement of Competing Interests. The authors declare that there is no conflict of interest.

Acknowledgements. We acknowledge NASA, CSR, JPL, and altimetry data providers.

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Received: 2024-07-11

Reviewed: 2024-08-07 (undisclosed name); 2024-08-19 (undisclosed name)

Accepted: 2024-09-05

APPENDIX A

Table A1. Results of statistical analyses of sea level changes from altimetric (SSHA) and gravimetric (EWT) data after removal of seasonal signals

Region	Period	Sea level rise trend (cm/yr)			Linear regression coefficient		Pearson correlation coefficient	
		SSHA	EWT JPL	EWT CSR	SSHA – EWT JPL	SSHA – EWT CSR	SSHA – EWT JPL	SSHA – EWT CSR
Baltic Sea	2001–2006	0.80	3.25	2.88	0.70	0.62	0.92	0.91
	2006–2011	–1.90	–0.84	–0.62	0.65	0.55	0.96	0.94
	2011–2016	0.58	0.40	–1.13	0.63	0.48	0.91	0.84
	2016–2021	1.31	1.24	0.69	0.63	0.50	0.87	0.82
	2001–2021	0.58	0.91	0.29	0.71	0.51	0.91	0.89
The central part of the Baltic Sea	2001–2006	0.80	39.06	2.85	0.80	0.67	0.89	0.87
	2006–2011	–2.34	–1.24	–0.73	0.67	0.59	0.94	0.93
	2011–2016	1.24	0.22	–1.10	0.67	0.50	0.91	0.84
	2016–2021	1.10	1.24	0.55	0.67	0.53	0.85	0.81
	2001–2021	0.55	0.80	0.29	0.72	0.54	0.90	0.87
Gulf of Gdańsk	2001–2006	0.66	2.08	1.20	0.57	0.37	0.85	0.81
	2006–2011	–1.90	–1.28	–1.06	0.59	0.38	0.90	0.87
	2011–2016	0.77	–0.07	–1.46	0.49	0.33	0.84	0.69
	2016–2021	0.80	0.40	0.07	0.54	0.39	0.86	0.77
	2001–2021	0.58	0.51	–0.18	0.56	0.29	0.88	0.68
Gulf of Bothnia	2001–2006	1.10	3.39	3.94	0.66	0.65	0.91	0.91
	2006–2011	–1.93	–0.44	–0.58	0.64	0.56	0.95	0.92
	2011–2016	0.58	0.66	–0.69	0.61	0.48	0.90	0.86
	2016–2021	1.35	1.57	1.24	0.62	0.52	0.87	0.82
	2001–2021	0.58	1.10	0.58	0.71	0.56	0.89	0.89
Gulf of Finland	2001–2006	0.77	4.89	6.35	0.90	1.03	0.88	0.81
	2006–2011	–1.97	–0.80	0.84	0.74	0.66	0.92	0.81
	2011–2016	0.99	–0.04	–1.50	0.69	0.51	0.81	0.68
	2016–2021	1.75	1.39	1.61	0.60	0.55	0.78	0.71
	2001–2021	0.62	1.02	0.91	0.78	0.71	0.87	0.79
Gulf of Riga	2001–2006	0.84	3.50	1.86	0.72	0.44	0.87	0.85
	2006–2011	–1.90	–0.47	–0.84	0.64	0.41	0.91	0.91
	2011–2016	0.91	0.33	–0.99	0.46	0.23	0.81	0.71
	2016–2021	1.53	1.17	0.44	0.50	0.30	0.83	0.77
	2001–2021	0.58	0.95	–0.04	0.62	0.28	0.85	0.74

Table A2. Results of statistical analyses of sea level changes from altimetric (SSHA) and sea surface temperature (HRSST) data before removal of seasonal signals

Region	Period	Sea surface temperature rise trend (HRSST) (C°/yr)	Sea level rise trend (SSHA) (cm/yr)	Linear regression coefficient (HRSST – SSHA)	Pearson correlation coefficient (HRSST – SSHA)
Baltic Sea	1993–1998	0.29	–0.29	–0.05	0.02
	1998–2003	0.37	–0.66	–0.20	0.09
	2003–2008	0.55	2.63	0.57	0.25
	2008–2013	0.15	2.08	0.56	0.25
	2013–2018	0.22	3.58	0.23	0.09
	1993–2018	0.04	0.51	0.26	0.11
The central part of the Baltic Sea	1993–1998	0.26	0.00	0.09	0.04
	1998–2003	0.40	–0.69	0.00	0.00
	2003–2008	0.55	2.15	0.74	0.30
	2008–2013	0.11	1.61	0.80	0.33
	2013–2018	0.29	3.07	0.44	0.17
	1993–2018	0.04	0.47	0.45	0.17
Gulf of Gdańsk	1993–1998	0.26	0.03	0.05	0.02
	1998–2003	0.33	–0.29	–0.31	0.13
	2003–2008	0.58	2.66	0.72	0.32
	2008–2013	0.15	2.41	0.70	0.31
	2013–2018	0.33	3.65	0.44	0.18
	1993–2018	0.07	0.55	0.37	0.15
Gulf of Bothnia	1993–1998	0.37	–0.62	–0.15	0.06
	1998–2003	0.44	–0.66	–0.05	0.02
	2003–2008	0.51	2.85	0.57	0.23
	2008–2013	0.07	1.93	0.54	0.23
	2013–2018	1.83	3.80	0.21	0.07
	1993–2018	0.04	0.55	0.26	0.10
Gulf of Finland	1993–1998	0.40	–0.37	–0.08	0.04
	1998–2003	0.37	–0.62	–0.14	0.08
	2003–2008	0.66	2.77	0.52	0.27
	2008–2013	0.26	2.08	0.54	0.28
	2013–2018	0.11	3.47	–0.03	0.04
	1993–2018	0.07	0.51	0.20	0.10
Gulf of Riga	1993–1998	0.33	–0.26	–0.14	0.07
	1998–2003	0.40	–0.62	–0.26	0.15
	2003–2008	0.69	2.74	0.54	0.28
	2008–2013	0.18	2.37	0.49	0.25
	2013–2018	0.22	3.58	0.13	0.05
	1993–2018	0.07	0.58	0.19	0.09

Table A3. Results of statistical analyses of sea level changes from altimetric (SSHA) and sea surface temperature (HRSST) data after removal of seasonal signals

Region	Period	Sea surface temperature rise trend (HRSST) (C°/yr)	Sea level rise trend (SSHA) (cm/yr)	Linear regression coefficient (HRSST – SSHA)	Pearson correlation coefficient (HRSST – SSHA)
Baltic Sea	1993–1998	0.04	0.51	2.40	0.16
	1998–2003	0.07	–0.69	–0.65	0.05
	2003–2008	0.11	–1.06	4.02	0.33
	2008–2013	0.29	2.26	5.18	0.35
	2013–2018	–0.11	1.68	1.84	0.10
	1993–2018	0.04	0.51	3.55	0.26
The central part of the Baltic Sea	1993–1998	0.01	–0.40	1.97	0.15
	1998–2003	0.15	–1.10	–1.25	0.10
	2003–2008	0.33	1.75	3.05	0.26
	2008–2013	–0.15	1.20	2.95	0.21
	2013–2018	0.04	2.66	2.98	0.17
	1993–2018	0.04	0.47	2.60	0.20
Gulf of Gdańsk	1993–1998	0.01	–0.33	3.59	0.30
	1998–2003	0.07	–0.66	0.20	0.02
	2003–2008	0.33	2.30	3.87	0.38
	2008–2013	–0.11	2.04	2.91	0.23
	2013–2018	0.07	3.29	3.25	0.21
	1993–2018	0.04	0.55	3.69	0.31
Gulf of Bothnia	1993–1998	0.11	–1.06	0.21	0.01
	1998–2003	0.22	–1.06	0.14	0.01
	2003–2008	0.26	2.45	2.77	0.22
	2008–2013	–0.18	1.53	4.56	0.30
	2013–2018	–0.07	3.36	1.49	0.09
	1993–2018	0.03	0.51	2.39	0.17
Gulf of Finland	1993–1998	0.15	–0.77	2.66	0.23
	1998–2003	0.07	–1.02	0.92	0.10
	2003–2008	0.37	2.37	3.69	0.40
	2008–2013	–0.03	1.68	4.21	0.42
	2013–2018	–0.18	3.07	–0.21	0.02
	1993–2018	0.07	0.51	2.90	0.29
Gulf of Riga	1993–1998	0.04	–0.69	2.14	0.18
	1998–2003	0.11	–1.02	–0.01	0.01
	2003–2008	0.44	2.34	4.00	0.48
	2008–2013	–0.11	1.97	3.42	0.33
	2013–2018	–0.07	3.18	2.35	0.16
	1993–2018	0.07	0.55	3.16	0.30