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Sea level along the Polish coast (southern Baltic Sea): Comparison of satellite altimetry and tide gauge observations (1995–2019)

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Abstract

This study examines sea level observations along the Polish coast from 1995 to 2019, combining in situ measurements from tide gauge stations with radar satellite altimetry data. The research is driven by developing new satellite products under the Baltic + SEAL project, specifically tailored for the Baltic Sea. These innovative products utilise advanced algorithms for sea level estimation, enhanced radar waveform processing, and high-resolution sea level data collected in Synthetic Aperture Radar (SAR) mode by multiple satellites during the analysed period. The study's primary aim is to validate and assess the performance of the Baltic + SEAL product against the standard sea level data provided by the Copernicus Marine Environment Monitoring Service (CMEMS) and observations from nine tide gauges distributed along the Polish coast. The evaluation focuses on long-term trends, seasonal variations, and statistical metrics across various time scales, from daily to decadal. The results underscore both the strengths and limitations of the Baltic + SEAL product in capturing spatial and temporal variations in sea levels. This study contributes valuable insights into sea level change dynamics along the Polish coast, providing essential information for coastal monitoring, management, and future research in the Baltic Sea region.

Keywords

Tide gauges; Satellite altimetry; Baltic Sea; Sea level; Validation

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1. Introduction

The Polish coastal zone is thought to be the most exposed to sea level rise in Europe (Kapsi et al., 2023) suffering from severe coastal erosion which exceeds 1 m per year (Luijendijk et al., 2018; Weisse et al., 2021). This vulnerability is further amplified by storm surges associated with northerly winds during the autumn and winter (Musielak et al., 2017). With climate change expected to raise mean sea levels between 26 and 200 cm by the end of the century (IPCC, 2022), and storms increasing in severity and duration, accurate estimates of sea level changes are necessary. The rising sea levels generate a variety of challenges for coastal areas worldwide, necessitating precise and comprehensive monitoring systems. Sea-level rise generates a variety of impacts on coastal areas: change in the coastline location and shape (erosion and accretion), coastal inundation and degradation of coastal vegetation. Along the Polish coast, the situation is compounded by a warming trend, with water temperatures increasing by 0.17°C per decade (Zalewska et al., 2023), particularly the most pronounced warming occurs in Gdańsk Bay between March and May.

The future sea-level rise will modify sediment transport along the coast through changing water currents, and different sources of sediments and deposition areas. These changes will lead to spatially variable rates of erosion and accretion (Musielak et al., 2017). According to coastal change future scenarios, the pessimistic variant assumes a loss of 15.5 ha of land per year (Zaucha and Matczak, 2015). For the Baltic Sea, an increase in absolute mean sea level from 3.3 mm y^{-1} to 4.1 mm y^{-1} was estimated based on available multi-mission satellite altimetry data by different studies over different time periods (Stramska and Chudziak, 2013; Pająk and Kowlaczyk, 2019; Passaro et al., 2021a). Passaro et al. (2021a) demonstrated a statistically significant sea level rise across the entire study region, with a higher increase in winter than summer, revealing a gradient exceeding 3 mm y^{-1} – greater in the north and east than in the southwest – partly explained (about 1 mm y^{-1}) by wind contributions based on regression analysis.

Despite significant advances in satellite altimetry, classical altimeter data in coastal zones face challenges due to land contamination and degraded geophysical corrections, limiting their accuracy near the coast (Abdalla et al., 2021). Recent progress in coastal altimetry data processing, including multi-sensor data integration, presents new opportunities for measuring sea level change close to the coastline. The Baltic + SEAL project introduced the Baltic + SEAL product – an innovative satellite altimetry dataset tailored for the Baltic Sea. This product incorporates advanced algorithms, including the ALES + retracker (Passaro et al., 2014), novel geophysical correction methods (Passaro et al., 2018), and high-resolution Synthetic Aperture Radar (SAR) data of 300 m resolution. These advancements allow observations closer to the coastline, addressing limitations of earlier satellite products.

However, the Baltic + SEAL product has not been sufficiently validated along the Polish coast due to the limited availability of the long-term in situ tide gauge (TG) data during its development phase. This study aims to fill that gap by evaluating the Baltic + SEAL product against the well-established Copernicus Marine Environment Monitoring Service (CMEMS) satellite altimetry (SA) products and in situ TG observations. The primary objectives are to validate the Baltic + SEAL product's performance, assess its ability to capture long-term trends, seasonal cycles, and sea level variability, and identify its advantages and limitations.

This research integrates data from nine strategically located TG stations and two SA products – Baltic + SEAL and CMEMS – spanning from 1995 to 2019. The comprehensive analysis focuses on spatial and temporal sea level dynamics along the Polish coast, evaluating their representation in satellite-derived datasets. By addressing gaps in the validation of coastal altimetry products, the findings contribute valuable insights for coastal monitoring and management. Furthermore, they provide a nuanced perspective on the challenges and opportunities for adapting to ongoing climate change in the Baltic Sea region. This research contributes to our understanding of how the spatial and temporal variabilities (i.e., from daily to decadal) near the coast are linked to the measured offshore change.

2. Data

2.1 Sea level anomalies (SLA) from CMEMS

Daily and Monthly SLA maps with 0.125° spatial resolutions for the period: 05.1995–05.2019 covering the southern Baltic along the Polish coast (53–58°N, 10–20°E) were obtained from the Copernicus Marine Service (CMEMS) from: https://marine.copernicus.eu/access-data. The product was created by combining the measurements of GFO, ERS1/2, ENVISAT, SARAL/AltiKa, TOPEX/Poseidon, Jason-1,-2, and -3, Cryosat-2, HY-2A, and Sentinel-3A altimetry satellites. According to the product manual, the processing of the altimetry data was done as described in Pujol et al. (2016) by performing an optimal interpolation of the L3 along-track individual satellite measurements from different altimeter missions available in the analysed period. We used the L4 delayed-time regional product (https://doi.org/10.48670/moi-00141) tailored to European seas, which uses measurements from all available missions within the analysed time framework. According to the product manual (Pujol, 2023), all data gaps in time and space were interpolated by optimal interpolation creating a complete daily 2D coverage. The quality of the merged L4 products directly depends on the quality of the L3 along track products used as input in the L4 processing. Nevertheless, the main source of error comes from the sampling capability of the altimeter constellation in the particular region and the effective resolution of this product is 190–200 km in the Baltic Sea (Pujol, 2023). As discussed by Pujol et al. (2016), the effective resolution of SLA gridded products is constrained by the altimeter sampling capability and mapping methodology used. The evaluation of this product is available in Ballarota et al. (2019).

2.2 Baltic + SEAL altimetry sea level products

We use products developed during the Baltic + SEAL project (http://balticseal.eu/) that were specifically processed for the Baltic Sea using specialized algorithms for the coastal altimetry described in detail in Passaro et al. (2021a). These products include monthly gridded maps of sea surface height (SSH) known as L4 gridded products that consist of various altimetry missions (Table 1). Detailed information on the methodology, project documentation, and validation efforts can be found in Passaro et al. (2020 and 2021a,b) and Rautiainen et al. (2020). The Baltic + SEAL project improved the processing of the available satellite missions by performing four advancements: i) unsupervised waveform classification to detect sea ice and leads, ii) performing direct range estimate from the waveform using

Table 1. The products marked with * were specifically processed using ALES+ retracker as part of the Baltic SEAL project (from Passaro et al., 2020).

Altimetry mission	Timeframe	ALES+ processed
TOPEX/Poseidon	1995–2005	○
ERS-2	1995–2010	✓
Envisat	2002–2012	✓
Jason-1	2001–2013	✓*
Jason-2	2008–2019	✓*
Alti-Ka	2013–2019	✓*
CryoSat-2	2010–2019	✓*
Sentinel-3A	2016–2019	✓*
Sentinel-3B	2018–2019	✓*
Jason-3	2016–2019	✓*

ALES + retracker, iii) directly estimated sea state bias correction from the waveform, iv) performed a multi-mission cross-calibration (Müller et al., 2020). The processing used different satellite missions listed in Table 1. The time span of the Topex and Jason series covers the entire dataset, i.e., 24 years and 32 passes over 948 cycles. The time span of the ERS-2 and ENVISAT extends up to 18 years starting from May 1995 until May 2012. In the L4 gridded monthly product, the SA observations are interpolated on an unstructured triangular grid (i.e., geodesic polyhedron) with a spatial resolution of 6–7 km. The SSH was corrected by standard geophysical corrections specified in detail in Passaro et al. (2021a) in their Table 1, the corrections included wet and dry tropospheric, ionospheric, dynamic atmospheric, solid earth tide, pole tide, sea state bias and radial orbit and ocean tide and load tide using FES2014 tidal model (Lyard et al., 2021). We used only data with good quality flags, which, according to the product validation report, provide a better estimation of trends and smaller root mean squared error (RMSE) when compared to other TG measurements in the Baltic.

2.3 Tide gauges measurements

We use data from nine TG stations located along the Polish coastline (Figure 1) that measured relative sea level in the overlapping period to the satellite observations in 1995–2019. These data were provided by IMGW (Gdynia) as an hourly-averaged measurement referenced to Normaal Amsterdams Peil (NAP) reference frame. Four stations (Gdańsk, Ustka, Władysławowo, Kołobrzeg) had complete temporal coverage during the analyzed period. For the remaining stations, there were some periods of missing data in Szczecin from 01.11.2015 to 31.10.2016, in Hel station the whole of 2017 was missing, and in Łeba 65 days were missing during 2016. At Darłowo station, TG measurements began later on 07.12.2006, therefore the calculated trend and statistics cannot be compared with other stations over the whole period of the study, although we still use these data to compare to the SA measurements in the overlapping shorter (13 years) period.

TG measured relative sea level change, which is the height of the sea surface relative to the land at a specific location. Satellite altimeters measured absolute sea level change, which is the height of the sea surface relative to the Earth's centre of mass and independent from the vertical land motion (VLM):

$$\mathrm{VLM} = \mathrm{SA} - \mathrm{TG} + \mathrm{error} \tag{1}$$

SA together with TG measurements can be used to derive VLM as was demonstrated by Oelsmann et al. (2021, 2024) and Kowalczyk et al. (2021). However, according to Glacial Isostatic Adjustment (GIA) models of the Baltic Sea the land uplift is very small along the Polish coast ranging from about -0.06 to $0.13\ \mathrm{mm\ y^{-1}}$ (Mostafavi et al., 2024; Kapsi et al., 2023; Vestøl, 2019). This is an order of magnitude smaller than the sea level rise (e.g. about 1 mm vs 1–4 cm per decade) and therefore can be neglected in the comparison. Nevertheless, this affects only a small part of the comparison, particularly the assessment of the long-term sea level trends. The error due is only a few per cent of the sea level trend.

3. Methods

To validate the gridded dataset, the closest grid point from every TG was located (Figure 1 see Table 2 for exact distances). As the gridded Baltic + SEAL dataset had a monthly temporal resolution, the TG data were monthly averaged to match this resolution. Only TG data with the good quality flag were used for the averaging and 20 days worth of data were needed to calculate the mean of each month. Furthermore, there is a clear difference in the sea level reference frame as the altimeter sea level height is tied to the TOPEX ellipsoid, and TG sea level height data to Normal Amsterdams Peil (NAP) reference frame. Hence, the means were removed for both datasets to make the comparison possible. This however inhibits the comparison of the means.

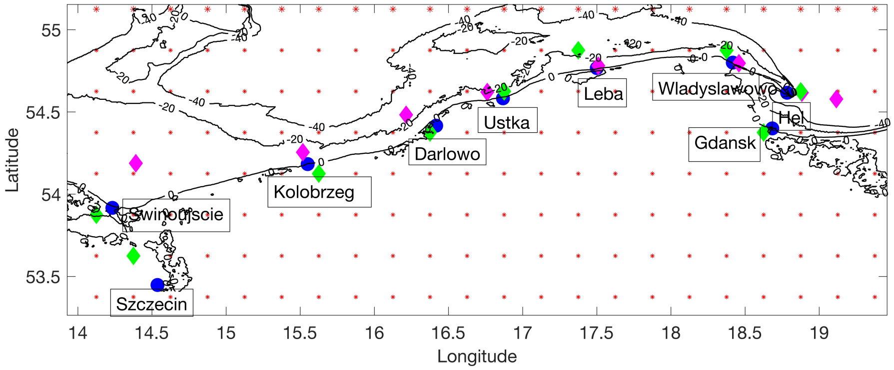

Figure 1. Location of TG stations (blue), Baltic + SEAL grid (pink), and CMEMS grid (green) points used for the comparison. The red dots show the CMEMS grid and the bathymetry contour is plotted for 0 m, 20 m and 40 m depths.

Table 2. Characteristics of average daily sea level values measured by tide gauges along the Polish coast in 05.1995–05.2019.

Station	Longitude	Latitude	Number of missing days	Temporal coverage [%]	Linear trends [mm/year]	Mean value [cm]	Standard deviation [cm]	Exceeded warning/alarm levels [days]	Max [cm]	Min [cm]	Range [cm]
Gdańsk PP	18.6830	54.4000	0	100	0.6	511.9	19.6	308 / 51	620	422	198
Hel	18.7833	54.6166	365	96	−0.7	505.7	19.4	158 / 20	604	431	173
Władysławowo	18.4170	54.8000	9	100	1.5	507.4	20.2	226 /39	621	426	195
Łeba	17.5000	54.7666	65	99	1.5	506.5	19.6	29 / 1	606	427	179
Ustka	16.8670	54.5830	0	100	4.3	506.7	19.9	33 / 1	611	427	184
Darłowo*	16.4166	54.4166	4328	54	−6.9	512.4	19.7	41 / 1	614	423	190
Kołobrzeg	15.5500	54.1830	0	100	2.7	505.8	19.3	45 / 1	619	416	203
Świnoujście	14.2330	53.9170	153	98	3.3	504.2	19.6	79 / 17	616	399	216
Szczecin	14.5372	53.4481	365	96	2.1	516.6	19.6	94 / 9	633	428	205

* Observations at this station started later on 07.12.2006.

Daily and monthly averages, standard deviations, long-term linear trends from 1995 to 2019, and the mean seasonal cycle described by an annual amplitude and the time of maximum sea level (phase) in a year were calculated for each data type (in situ vs altimetry) for daily and monthly-averaged values. For the SA, the flag value indicating good data was used. The distance of the closest altimetry grid point to each station was determined. Furthermore, interpolation and extrapolation methods of SA data to the location of the TGs were investigated. The seasonal cycle was determined by fitting an annual harmonic function simultaneously with a linear trend to daily and monthly time series using a least-square fitting approach, similarly as was done in Passaro et al. (2021a) and Karimi et al. (2021):

$$\eta(t) = a_0 + a_1 t + [b_i \sin(\omega_i t) + c_i \cos(\omega_i t)] + \varepsilon \quad (2)$$

where η is dynamic SLA, a, b, and c are coefficients to be estimated, t is time, ω_i is the frequency corresponding to annual harmonics and ε is the residual signal. The trend estimate is found solving the fitting by linear least squares. The trend uncertainty of our estimates is assumed to be of the order of 1 mm y^{-1} when accounting for the autocorrelation in the time series, as demonstrated by Passaro et al. (2021a) for the Baltic + SEAL in the southern Baltic Sea.

The amplitude represents the difference between the maximum and minimum sea level of the annual cycle, and the phase represents the day when the sea level reaches its maximum. The resulting outcomes were compared with satellite measurements from the nearest points to the monitoring stations (Figure 1). Satellite measurements have their limitations, especially near the coast. Therefore, the comparison used the nearest points with over 250 months of good-quality satellite data in the analyzed period.

3.1 Sea level variability from tide gauge observations in 1995–2020

In the Baltic Sea, there is a strong salinity decrease from the southwest to the northeast of the basin, which results from the along-basin separation between the main saltwater and freshwater sources leading to a sea level gradient of about 35–50 cm across the Baltic Sea (Weisse et al., 2021). Table 2 shows that the average sea level increases towards the East from Świnoujście, at the most westerly station, to Władysławowo located at the East, which is in agreement with the overall increase of mean sea level from the southwestern to the northeastern Baltic. However, our results show that the highest mean daily sea level in the analyzed period occurs in Szczecin and Gdańsk, which are the areas strongly influenced by freshwater sources such as the Odra and Vistula rivers. The Hel station also stands out from this pattern with smaller mean sea levels than expected, as the station is located on the southern coast of the Hel Peninsula measuring sea

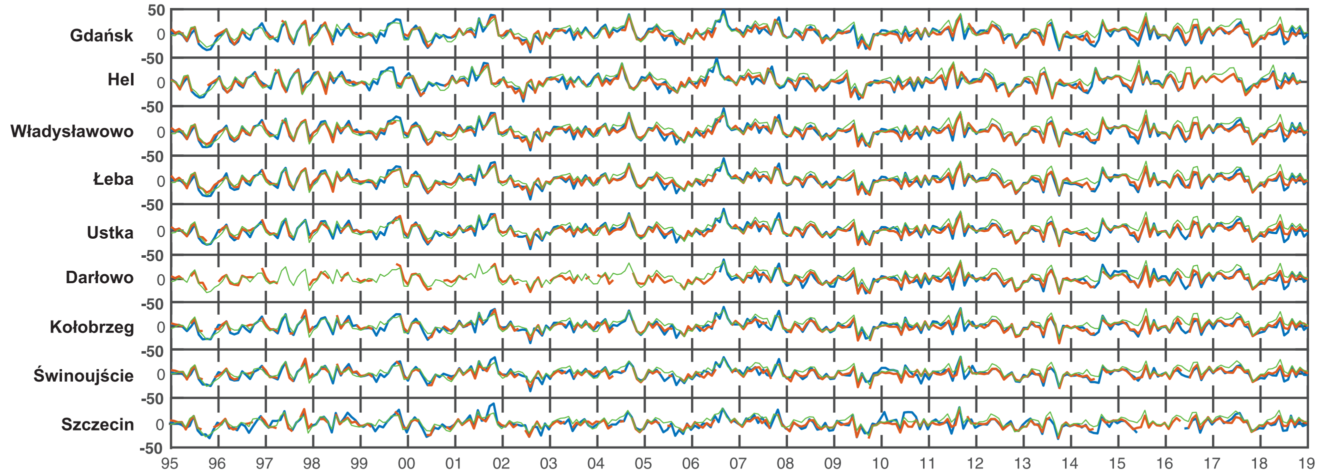

Figure 2. Monthly time series of sea level (cm) for TG (blue), Baltic + SEAL (red) and CMEMS (green) at 9 locations along the Polish coast.

level inside the Gdańsk Bay, which is also affected by the freshwater coming from the Polish rivers. The greatest daily sea level variability, expressed by the standard deviation in Table 2, occurs on the central coast in Władysławowo (20.2 cm), and the largest daily range of fluctuations during the analyzed period was observed in Świnoujście (216 cm). Linear absolute sea level trends over the 24 years (05.1995–05.2019) calculated for daily-averaged TG ranged from 1 mm y^{-1} in Gdańsk to 4.1 mm y^{-1} in Ustka.

The warning and alarm levels vary across the different stations. In Gdańsk, Hel, and Wladyslawowo, the warning level is set at 550 cm, and the alarm level at 570 cm. For Darłowo and Kołobrzeg, these levels are 570 cm and 610 cm, respectively, while in Leba, Ustka, and Szczecin, they are 570 cm and 600 cm. The Świnoujście station has a warning level of 560 cm and an alarm level of 580 cm. During the studied period, Gdańsk experienced the highest frequency of exceeded warning and alarm levels (Table 2), with these thresholds surpassed on 51 and 308 days, respectively. Despite the high frequency of alarm levels, no significant trend was identified across the stations. This lack of observed change may be attributed to the insufficient length of the data record for detecting variations in extreme sea levels.

3.2 Validation of the monthly gridded altimetry products from CMEMS and Baltic + SEAL

The linear trends were calculated over 24 years (05.1995–05.2019) for the monthly averages for three types of data including TG observations and two gridded altimetry products (Table 3). For the SA data, linear trends are more consistent and higher, ranging from 3.3 mm y^{-1} in Świnoujście to 4.4 mm y^{-1} in Władysławowo, Hel, and Ustka (Table 3). The average long-term trends in the analysed period along the Polish coast are 2.3, 3.8, and 3.9 mm y^{-1} for TG, Baltic + SEAL, and CMEMS satellite products, respectively. The greatest differences of about 3 mm y^{-1} between the two types of measurements were found in Hel, and Gdańsk, which are located in the Gdańsk Bay, in the areas strongly influenced by freshwater output from the rives especially the largest among them, Vistula River. Very small differences (about 1 mm y^{-1}) between TG and SA trends were found for Świnoujście, Kołobrzeg and Ustka with the Baltic + SEAL providing overall better agreement with the mean difference of 1.8 mm y^{-1} comparing to 2.6 mm y^{-1} found for CMEMS. Both satellite products overestimate the trends compared to TG observations. The Darłowo TG station is notable in trend comparisons with only negative trends over a much shorter period compared to other stations. Its records show exceptionally high sea levels at the beginning of its data set in December 2006 (Figure 2), while both SA datasets had periods of missing data during that time. This example highlights the importance of caution when comparing trends from different data types, as high-frequency variability with extremely low values, which may not be captured by certain datasets, can lead to significant discrepancies in trend estimation. Therefore, to ensure accurate trend comparisons, it is crucial to use long-term data, ideally spanning more than 20 years. What stands out from the analysis, is that TG data have slightly larger (by 1–2 cm) standard deviations and ranges (on average by about 10 cm) of monthly variability when compared to SA products. This suggests that the extreme lowest and highest sea level events are not well represented in the satellite data, which could be an effect of the effective resolution of these products and smoothing during gridding. The Pearson correlation coefficient was calculated for i) monthly data with the trend and the overall mean removed and ii) for the same data pairs with also

Table 3. Comparison statistics for monthly altimetry data sets and tide gauge observations along the Polish coast.

Station name	Trend [mm/year]	STD [cm]	RANGE	R (raw data/seasonality removed)	No. of months	Distance [km] to TG	RMSE [cm]
	TG / BalticSEAL / CMEMS			BalticSEAL / CMEMS	TG / BalticSEAL / CMEMS	BalticSEAL / CMEMS	BalticSEAL / CMEMS
Gdańsk PP	1/3.6/4.3	14.8/14.0/13.3	89.4/76.1/71.5	0.91/0.90 0.94/0.95	289/252/289	34/5	6.4/5.7
Hel	1.2/4.4/4.2	14.8/13.9/13.6	88.0/74.6/74.8	0.92/0.92 0.95/0.95	277/263/289	6./6	6.0/5.4
Władysławowo	2.7/4.4/4.1	14.9/13.8/13.5	86.2/75.2/75.9	0.93/0.92 0.94/0.94	289/284/289	3/8	5.7/5.3
Łeba	2.1/4.4/3.9	14.9/13.2/13.0	87.3/71.9/72.1	0.93/0.93 0.94/0.94	288/282/289	2/14	5.6/5.3
Ustka	4.0/3.7/4.0	14.2/12.5/12.7	82.3/71.1/70.1	0.93/0.92 0.91/0.94	289/263/289	8./4	5.0/4.7
Darłowo*	−5/1.8/2.2	14.0/12.1/12.4	76.9/68.1/67.3	0.90/0.88 0.93/0.90	150/252/289	15./5	6.6/6.4
Kołobrzeg	3.1/3.4/3.9	13.1/11.8/11.8	74.4/70.0/65.2	0.90/0.89 0.93/0.92	289/251/289	8/8	5.4/5.0
Świnoujście	2.9/3.3/3.4	11.9/10.9/10.8	72.2/65.8/63.3	0.87/0.86 0.89/0.90	289/257/289	32/8	5.6/5.3
Szczecin	2.1/3.5/3.4	12.6/10.9/10.9	74.6/65.8/63.2	0.80/0.83 0.81/0.85	278/257/289	83//22	7.4/7.5

* Observations at this station started later on 07.12.2006.

mean seasonal cycle removed (Table 3). Its value ranged from 0.80 in Szczecin to 0.93 along the central coast (between Ustka and Władysławowo), with an overall area average of 0.90 for both satellite products. The removal of the Darłowo station with the shortest time period caused an increase in the mean correlation to 0.96 for CMEMS but did not change the correlation for Baltic + SEAL which remained at 0.90. Despite similar correlation coefficients for the two SA products, the CMEMS product has much lower variability, with standard deviations and ranges on average 5.6 cm and 11 cm smaller than TG. On the other hand, the Baltic + SEAL product shows very similar variability to TG with standard deviation and range only about 1 cm smaller, which is a significant improvement.

To sum up, for Gdańsk station experiencing large freshwater fluxes and located in a bay, the Baltic + SEAL exhibits a higher linear trend, lower standard deviation, and a smaller range of fluctuations compared to CMEMS, suggesting a better precision. Similarly, at the Hel station, Baltic + SEAL shows a higher linear trend, lower standard deviation, and a smaller range, indicating better conformity with in situ data. The Władysławowo, Łeba, and Ustka stations also demonstrate higher linear trends and lower variability for Baltic + SEAL, emphasizing its potential superiority over CMEMS. Darłowo, despite some discrepancies, highlights Baltic + SEAL's ability to capture short-term trends more accurately. Kołobrzeg, Świnoujście, and Szczecin further showcase Baltic + SEAL's tendency to align better with in situ measurements in terms of linear trends, standard deviation, and range. However, it is essential to note that variations exist among stations, potentially influenced by local conditions. Overall, Baltic + SEAL appears to offer slightly better alignment with in situ measurements, particularly in capturing long-term trends and variability in the Gdańsk Bay area.

3.2.1 Interpolation effects

Various methods of extrapolating data to the coordinates of TG stations for the Baltic + SEAL product were tested to examine the impact of interpolation/extrapolation on the comparison and selection of the most appropriate points and methods for comparison. In the previous section, the nearest points were compared, but they turned out to be significantly distant (up to 80 km) from some stations which motivated us to check whether interpolation improves the statistics of the comparison.

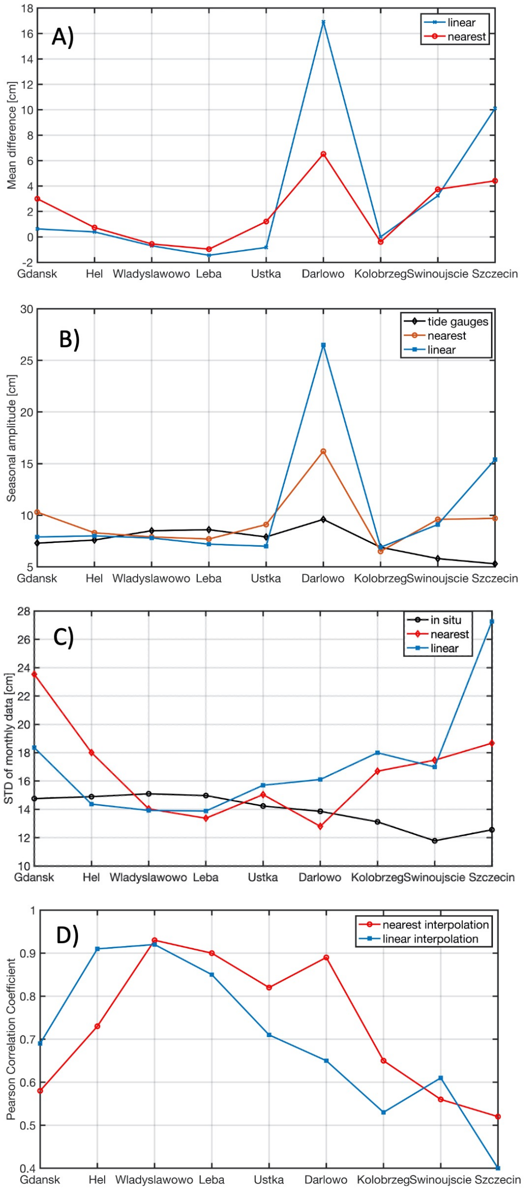

Figure 3. The average monthly difference between in situ data and satellite data for two types of satellite data interpolation to station coordinates (A) – nearest (red) and linear (blue). A comparison of seasonal sea level amplitudes(B) for different interpolation methods and in situ data. Pearson correlation coefficient determined for monthly data from the Baltic + SEAL product interpolated to station positions (C) using the nearest point method (blue) and linear (red). Comparison of standard deviations for in situ stations (blue), the Baltic + SEAL product interpolated to station coordinates (D) using the nearest value method (red), and linear (black).

Each of the extrapolation methods analyzed has its own advantages and disadvantages and can be also a source of additional error. The results, presented in Figure 3, show that the linear extrapolation yields much better correlation coefficients for two eastern stations, Gdańsk and Hel, as well as for Świnoujście, but produces poorer results for the other stations. This method does not perform well for the Szczecin station, which is evident in Figure 3 as a large standard deviation and an increase of mean difference between the two types of data. Similarly, this extrapolation method performs the worst for the Darłowo introducing additional errors. On the central coast, where the satellite data grid is complete temporally and adequately covers the measurement stations, both interpolation methods produce similar results, indicated by mean differences within 1 cm (Hel, Władysławowo, Łeba, Kołobrzeg) and comparable standard deviations to in-situ measured values for stations from Hel to Ustka (Figure 3).

In summary, the analysis shows that the nearest interpolation method generally performs better. Specifically, stations like Darłowo and Szczecin exhibit significant deviations and higher variability with the linear method, resulting in larger errors and standard deviations. In contrast, the nearest method provides more consistent and accurate results across most stations. Gdańsk and Hel are exceptions where both methods perform similarly with minimal differences. Overall, the nearest extrapolation method is more reliable for sea level comparisons in this context. However, direct comparison with values from the nearest points, presented in the previous section, yields similar results for the central stations with good, complete satellite data coverage in time and space, and it performs better for the western stations, as indicated by higher correlation coefficients (0.8–0.93) and lower standard deviations (12–15 cm), which are closer to the in-situ measured values then the one interpolated.

The choice between using extrapolation methods or directly comparing TG measurements with the nearest grid points for sea level analysis depends on the specific characteristics of each station, including accuracy requirements, data variability, and the distance between measurement locations. Extrapolation methods, particularly nearest neighbour extrapolation, can offer improved accuracy in certain situations. For example, stations like Darłowo and Szczecin, which exhibit significant variability and larger distances between TG stations and the nearest satellite grid points, benefit from extrapolation. In these cases, direct comparisons with the nearest grid points often lead to greater discrepancies due to spatial differences. Extrapolation helps mitigate these discrepancies by adjusting for spatial variations, resulting in more accurate comparisons.

Moreover, extrapolation methods are better at handling variability, especially in stations with more complex data patterns. For instance, in Szczecin, where standard deviations and errors are larger when using direct comparisons, nearest neighbour extrapolation provides smoother and more consistent results. This capability to address data variability makes extrapolation particularly valuable in locations where sea level changes are not uniform or where environmental conditions vary significantly across small distances.

However, extrapolation is not without its challenges. In some cases, such as Darłowo when using linear extrapolation, the method can introduce higher errors and greater variability compared to direct comparisons. This highlights that not all extrapolation methods are equally reliable across all stations, and the choice of method must be carefully considered. Additionally, extrapolation methods are more complex to implement, requiring careful validation, especially in regions with sparse data or rapidly changing environmental conditions. This complexity may not always be justified, particularly when the improvements in accuracy are marginal.

On the other hand, direct comparison with the nearest grid point offers simplicity and consistency in well-covered areas. This approach is easy to implement and interpret, especially when the grid points are relatively close to the TG stations, as seen in Hel or Władysławowo. In these locations, where satellite data coverage is good and variability is low, direct comparison yields results similar to those obtained through extrapolation. This suggests that in well-sampled areas with minimal variability, direct comparison with the nearest grid point is often sufficient for accurate analysis.

In conclusion, nearest neighbour extrapolation is recommended for stations where distance or data variability poses challenges, as it offers more accurate comparisons in these cases. However, in well-covered regions with minimal variability and good satellite data coverage, direct comparison with the nearest grid point remains a simpler and equally effective method. The choice between these approaches should be based on the specific characteristics of each station, balancing the need for accuracy with the complexity of the method.

3.3 The mean seasonal cycle

Although the seasonal (annual) variation in sea level is a common feature of oceans, the magnitude of these fluctuations varies regionally and locally. The observed TG seasonal cycle amplitude is the smallest (5.3 cm) on the western Polish coast and increases eastwards, reaching the maximum of about 8.6 cm in Łeba, then decreases again to 6 cm in the Gdańsk Bay. The minimum sea level is usually observed in May on the central and western Polish coast and a month earlier in the Gdańsk Bay (Figure 4). Szczecin station is located more inland in the Odra River in proximity to the Dąbie Lake. Therefore, the overall changes in water level can drive sea level changes further downstream from this station. However, it has not yet been explored whether the sea greatly influences water levels there. This station stands out with an unusually small seasonal cycle with an amplitude of only 0.8 cm, and both satellite products display larger amplitudes as their measurements were acquired outside the river. This suggests that the seasonal cycle is driven mainly by the sea seasonal variability offshore, which is suppressed upstream in the rivers. It is recommended that a specialized processing of the along-track satellite in Zalew Szczeciński and Dąbie Lake (Figure 1) is applied in the future for this region to derive water level changes.

The seasonal amplitude in satellite data is comparable on the central coast, and in this region, the differences be-

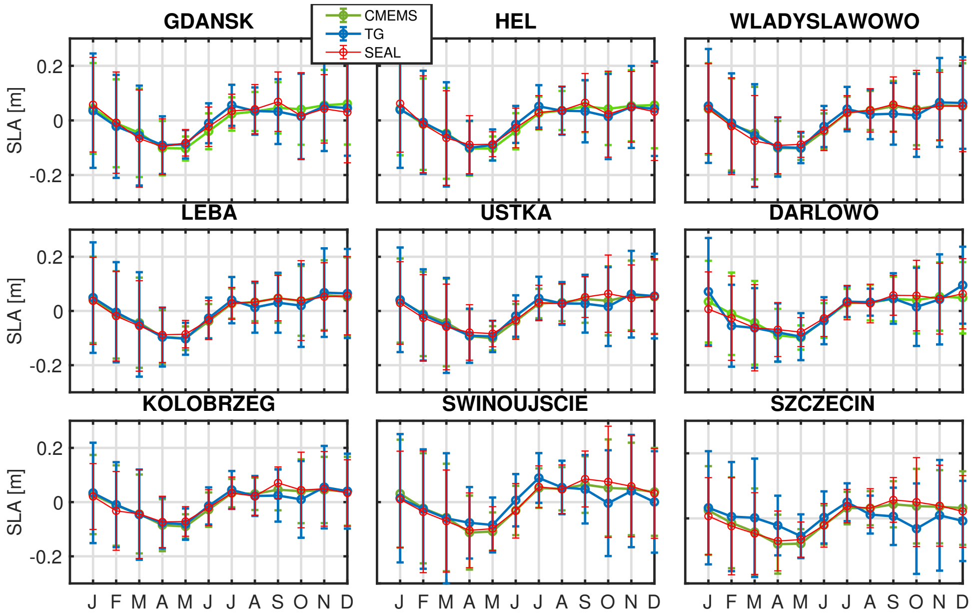

Figure 4. Mean seasonal variations of sea level at 9 stations from TG, Baltic + SEAL and CMEMS in 1995–2019.

tween seasonal amplitude between SA and TG are below 1 cm for both satellite products, which is a very good agreement. However, in Gdańsk and Hel, both located inside the Gdańsk Bay, the amplitude of the seasonal cycle is larger for satellite data by approximately 1.4–1.7 cm. In the case of Szczecin, the differences range from 4.8 to 5.8 cm for Baltic + SEAL and CMEMS products, because the source of their data is from the sea and not from the rivers, where these stations are located.

The amplitude of the seasonal sea level change in SA products is on average 1.3 and 1.2 cm larger for CMEMS and Baltic + SEAL in the Gdańsk Bay. The seasonal cycle in the Baltic + SEAL product has been improved, with seasonal amplitudes more closely matching those measured in situ by TGs at Gdańsk and Hel stations. The maximum sea level is reached the earliest in Świnoujście, a month later in Gdańsk and Hel, and the latest on the central coast. On the other hand, the phase of the seasonal cycle in satellite products is on average 10 and 18 days earlier in CMEMS and Baltic + SEAL products but within the same month. We can summarize the comparison of the seasonal cycle as follows: Baltic + SEAL generally exhibits amplitudes closer to the in situ values in Gdańsk and Hel, suggesting a better agreement in capturing the seasonal variability in Gdańsk Bay.

The sea level variability along the coast is the largest in the autumn and winter, from October until March, and greatly reduced by about 60–70% from April until September. The obvious source of this variability is direct atmospheric forcing by winds and frequent storms and storm surges that occur in those seasons. Figure 4 shows that while satellite products can capture the general seasonal sea level variation, Baltic + SEAL generally provides a more accurate representation than CMEMS, especially in complex coastal regions influenced by rivers. Nonetheless, both SA datasets tend to overestimate the seasonal amplitude compared to TG observations. In most stations, the Baltic + SEAL product (red line) generally follows TG data more closely than CMEMS, indicating better performance in capturing seasonal variability, especially in regions like Gdańsk and Szczecin, where the agreement between Baltic + SEAL and TG is more pronounced. Stations like Szczecin (which is strongly influenced by the Odra River) show significant deviations between the satellite data and TGs, especially during the spring and summer months. This suggests that satellite products may struggle to capture the impact of freshwater inputs and local hydrodynamics in river-influenced regions.

3.4 Validation of daily gridded CMEMS altimetry product

Daily sea level anomalies measured by SA from 05.1995 to 05.2019 were used for comparison with data from TG stations. Only data from CMEMS were used here for comparison to TG because Baltic + SEAL did not provide a daily multi-mission product. The closest points to the stations were selected for comparison (Figure 1). The Pearson correlation coefficient for daily anomalies varies between 0.66 for Szczecin to 0.84 in Łeba and Hel (Table 4) and is very similar for the same data with the seasonal cycle removed (0.68–0.84). This agreement is lower by about 10–20% when compared to the previously described (Section 4.2), monthly averaged data providing clues about temporal scales resolved by SA. For SA, the amplitude of seasonal sea level variations is the smallest in the west

Table 4. Comparison statistics for daily sea level observations from CMEMS satellite product and TG stations along the Polish coastline.

Station	R	R for data with seasonality removed	Annual Amplitude TG/CMEMS [cm]	Phase of seasonal cycle [day] TG/CMEMS	Standard deviation [cm]	Range [cm]	Standard deviation of the difference between two data types [cm]	Trends [mm y^{-1}] TG/ CMEMS
Gdańsk PP	0.83	0.83	5.7 / 7.1	292 / 304	15.3	102.2	10.9	1 / 5
Hel	0.84	0.84	5.8 / 7.1	295 / 301	15.7	103.0	10.4	1.3 / 5
Władysławowo	0.82	0.81	6.5 / 7.0	306 / 301	15.7	101.4	11.5	2.7 / 4.9
Łeba	0.84	0.83	6.6 / 6.8	307 / 302	15.4	101.7	10.8	2.2 / 4.6
Ustka	0.80	0.79	6.0 / 6.7	301 / 303	15.1	100.2	11.5	4.1 / 4.7
Darłowo*	0.77	0.76	6.7 / 6.5	306 / 301	14.8	95.9	12.5	−5 / 4.8
Kołobrzeg	0.74	0.73	5.0 / 5.9	298 / 296	14.2	93.7	13.1	3.2 / 4.5
Świnoujście	0.68	0.68	3.8 / 4.9	262 / 288	13.1	92.2	14.0	3.0 / 4
Szczecin	0.66	0.68	0.5 / 5.3	287 / 292	12.9	86.6	14.7	2.2 / 4

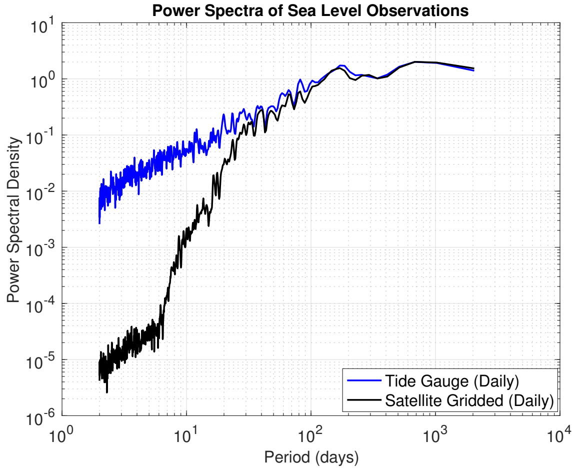

Figure 5. Power spectra density [m^{2} cycle^{-1} day^{-1}] of daily detrended and – sea level observations from SA (CMEMS) and TG station from the central Polish coast (Kołobrzeg).

(4.9 cm) and increases eastwards to 7.1 cm. On the other hand, TGs show very small (0.5 cm) seasonal variations in Szczecin, an increase in seasonal amplitude to 6.6 cm towards the central coast, and a slight decrease in the Gdańsk Bay to 5.7 cm. Satellite observations show that the phase of the seasonal cycle, daily variability, and the range of daily variability increase eastwards. Linear trends calculated from daily SA measurements over the 24 years also increase eastwards from 4 mm y^{-1} in Świnoujście to 5 mm y^{-1} in Gdańsk and Hel. However, the standard deviation of differences between the two types of data increases westward. In Świnoujście and Szczecin, both types of data differ the most from each other. In the CMEMS product daily SA along-track data are merged by optimal interpolation, smoothed in time and space and gaps in the data are filled in the interpolation process. Therefore, SA standard deviations and ranges of daily fluctuations reach only 50% of the same parameters obtained using TGs. TG observations are characterized by greater station variability and smaller long-term trends (1–4.1 mm y^{-1}). Satellite data are more spatially homogeneous and have much less spatial variability along the Polish coast. Figure 5 shows that most of the energy in the SA data is concentrated in periods greater than 30 days, while TGs show more red noise type spectrum where the power spectral density is proportional to the inverse of its frequency squared. Overall, all of the above results demonstrate that the high frequency (<30 days) sea level variability is very important and reaches about 50% of the total variance. Still, it is not represented well in the SA CMEMS product.

4. Discussion

Satellite altimetry provides a unique and consistent long-term observational dataset, enabling the characterization of how sea level variability evolves from the open ocean to the coastal zone. While tide gauges offer high-frequency time series data at specific points but are predominantly located in sheltered environments that may not accurately represent offshore conditions. Sea level variability observed in this study aligns with earlier research, which identifies a general sea level increase from the southwestern to the northeastern Baltic, primarily influenced by regional salinity gradients (Weisse et al., 2021) and winds (Passaro et al., 2021a). This trend is evident in the results presented in Section 4.1 about the TGs observations, where mean sea levels increase from Świnoujście to Władysławowo. However, we demonstrated that the highest mean daily sea levels were recorded in Szczecin and Gdańsk, regions strongly impacted by significant riverine inputs from the Odra and Vistula rivers. This suggests that local freshwater fluxes play a crucial role in sea level variability in the coastal areas. An unexpected divergence from this general pattern is seen at the Hel station, where mean sea levels are notably smaller despite its location in Gdańsk Bay, a region significantly influenced by freshwater inputs. This anomaly may be attributed to the unique geographic and bathymetric characteristics of the Hel Peninsula, which shield the bay from some of the external forces that impact other stations. The variability observed in Władysławowo highlights the influence of local factors, with this station displaying the greatest daily sea-level fluctuations along the Polish coast during the study period. These findings are consistent with Wolski and Wiśniewski (2020), who emphasized that seasonal sea level variability along the Polish coastline is heavily influenced by storm surges, particularly during the fall and winter months.

When comparing TG data with SA products, this study found that satellite measurements tend to overestimate sea level trends compared to in situ observations, a finding consistent with Madsen et al. (2019) who analysed sea level trends over a much shorter period (1993–2014). TG data from Gdańsk show a long-term trend of 1 mm y^{-1}, whereas SA reveals trends ranging from 3.3 to 4.4 mm y^{-1}. These discrepancies likely stem from the resolution and gridding processes used in satellite data, which may smooth over localized sea level variations captured by TGs, as well as the lack of data close to TG stations in the Gdańsk Bay. The better agreement between TG and SA trends was found in the central coast, where trends differ by less than 1 mm y^{-1}. Our results show that the Baltic + SEAL product demonstrates superior alignment with in situ data compared to CMEMS, particularly in areas like Gdańsk Bay, where the Vistula River contributes significant freshwater input. This suggests that Baltic + SEAL's enhanced processing techniques and higher effective resolution make it more suitable for regions with complex hydrodynamics, such as semi-enclosed bays. Passaro et al. (2021a) reported a 9% overall improvement in the agreement between trends computed using SA Baltic + SEAL and TGs in the Baltic Sea. Our findings indicate an even greater improvement of up to 12% (0.5 mm y^{-1}) for the Łeba and Kołobrzeg stations and a maximum of 16% (0.7 m y^{-1}) for the Gdańsk station.

The difference in trends between the two altimetry products, of approximately 1 mm y^{-1} for most stations, and high Pearson correlations ranging from 0.8 to 0.96 – is consistent with findings from other studies e.g. Pająk and Kowalczyk (2019), who reported monthly correlations between TGs and SA data (but over different time-period and using only the monthly CMEMS product) ranging from 0.88 to 0.94. In this study, similarly high correlations were observed, reaching up to 0.96 for CMEMS, highlighting the value of long-term, high-resolution data in accurately capturing sea level trends, as emphasized by Mostafavi et al. (2024). The SA Baltic + SEAL product also compared favourably to TG measurements in the other areas of the Baltic Sea, with correlations ranging from 0.8 to 0.95 and an average RMSE of 5.9 cm for Baltic + SEAL and 5.6 cm for CMEMS. Passaro et al. (2021a,b) found that out of 67 TG and gridded altimetry pairs, 62 had correlations higher than 0.6, and 61 had an RMSE below 9 cm. Overall, when compared across the entire Baltic region, our findings show strong agreement with in situ observations, indicating that SA can be reliably used for sea level research along the Polish coast.

The seasonal sea level variations observed in this study are consistent with those reported in previous research by Pająk and Kowalczyk (2019). Our results demonstrate more complete picture using more TG stations located not in the central coast but also the Gdańsk Bay and Zalew Szczecinski. In addition, we demonstrate the differences between observations on the land (TG) and more offshore as measured by SA. Along the Polish coast, seasonal amplitudes increase from west to east, peaking at 8.6 cm in Łeba and declining to 6 cm in the Gdańsk Bay. The Szczecin station, however, stands out with an unusually small seasonal amplitude of 0.8 cm, which contrasts sharply with the larger amplitude captured by satellite data. This discrepancy suggests that Szczecin's seasonal sea level cycle is primarily driven by upstream freshwater inputs, while satellite data reflect offshore sea variability. This finding highlights the need for specialized processing of satellite data in riverine regions, a point also raised by Pająk and Kowalczyk (2019), who noted the limited availability of satellite data for such areas. We recommend special processing of the SA tailored to the inland waters for this area to better represent water height variations.

Comparisons between SA and TG observations of seasonal cycles revealed that satellite products generally capture accurately the seasonal changes in sea level in the central coast but tend to overestimate the amplitude by approximately 1.4–1.7 cm in the Gdańsk Bay as demonstrated in Table 5 for Gdańsk and Hel stations. This observation indicates that while SA performs well in capturing general

Table 5. Comparison of amplitude and phase of the seasonal cycle for three types of data.

Station	TG amplitude [cm]	BalticSEAL/CMEMS amplitude [cm]	In situ TG Phase [day]	BalticSEAL/CMEMS Phase [day]
Gdańsk PP	6.0	6.6 / 7.4	292	288/304
Hel	6.0	6.7 / 7.4	296	285/301
Władysławowo	6.7	7.4 / 7.4	306	285/301
Łeba	6.8	7.2 / 7.1	307	286/302
Ustka	6.2	7.1 / 7.0	300	287/303
Darłowo*	7.2	6.8 / 6.8	287	285/301
Kołobrzeg	5.2	6.4 / 6.3	298	280/296
Świnoujście	3.8	5.9 / 5.3	261	274/288
Szczecin**	0.8	5.9 / 5.6	287	276/292

* data available only from 12.2006, ** Station located in the Odra river 80 km from the altimetry grid point.

trends, it may struggle to fully resolve finer-scale seasonal variations driven by local freshwater inputs and the complex geometry of the bay. Baltic + SEAL, with its smaller range of fluctuations, appears to provide a slight improvement over CMEMS in capturing the seasonal cycle in the Gdańsk Bay, consistent with its better overall performance in river-influenced regions.

Daily sea level anomalies from CMEMS were compared with TG data, revealing lower correlations for daily data (ranging from 0.66 to 0.84) than for monthly averages. This finding shows that high-frequency variability, such as storm surges, is not always well captured by SA gridded products due to spatial and temporal smoothing and interpolation of the along-track SA data that is available over a particular region every 10–30 days depending on a satellite and region. This study confirms that daily satellite data exhibit lower variability, with standard deviations around 50% smaller than those from TGs. These discrepancies underscore the limitations of SA in capturing short-term sea-level fluctuations, particularly during extreme events. We present a comparison of the power spectra of daily detrended and deseasonalized SA and TGs in Figure 5. The results show that for SA, the energy at temporal scales shorter than 30 days is very low. However, both spectra align closely for periods exceeding 30 days. The SA data is corrected by the Dynamic Atmospheric Correction (DAC) signal induced by wind and pressure forcing, what additionally reduces the short-term wind contribution in SA data.

Finally, this study explored the impact of different interpolation methods on sea level comparisons, concluding that nearest-neighbour interpolation generally outperforms linear extrapolation, particularly for stations like Darłowo and Szczecin, which exhibit higher data variability. This finding aligns with the recommendations of Pająk and Kowalczyk (2019), who advised caution when comparing trends from different data sources. The differences between SA and TG trends may be attributed to VLM and crustal movements. To validate Geostatic Isostatic Adjustment (GIA) models along the Polish coastline, it is advisable to incorporate co-located GNSS measurements in both space and time, which provide a direct method of measuring VLM with the best accuracy. Kowalczyk et al. (2021) estimated VLM between 1993 and 2017 by comparing linear trends from daily CMEMS SA products and four TGs, reporting values ranging from about 1 mm y^{-1} in Kołobrzeg to about 2 mm y^{-1} in Władyslawowo and Gdańsk. However, our findings suggest caution when interpreting these results. Different SA processing methods can significantly impact trends, with the Baltic + SEAL product generally yielding smaller discrepancies between TG and SA trends, as well as VLM estimates. Additionally, careful consideration must be given to factors such as the choice of SA point for TG comparisons, interpolation methods, and the proximity of the along-track satellite data to TG stations.

5. Conclusions

- Significant daily sea level variability is observed, with the highest standard deviation recorded in Władysławowo and the widest range in fluctuations in Świnoujście. This variability underscores the dynamic nature of sea level changes along the Polish coast, influenced by local and regional factors. The high-frequency signal (<30 days) contributes to about 50% of the variance in the detrended and deseasonalised TG data.

- Over 24 years, TG measurements reveal varying linear sea level trends from 1 mm y^{-1} in Gdańsk to 4.1 mm y^{-1} in Ustka. SA products, such as Baltic + SEAL and CMEMS, generally show higher trends, with Baltic + SEAL demonstrating better agreement with TG data, especially in the Gdańsk Bay.

- Seasonal cycles in sea level amplitude vary regionally, with the smallest observed on the western coast and the largest in Łeba. Satellite data generally show larger seasonal cycle amplitudes compared to TG observations.

- Baltic + SEAL SA product demonstrates improvements in capturing seasonal variability in Gdańsk and Hel, aligning more closely with in situ measurements and is a more accurate and reliable satellite product for capturing the seasonal cycle of sea level changes along the Polish coast.

- The Pearson correlation for daily sea level anomalies between satellite data and TGs ranges from 0.66 to 0.84. Satellite data show lower variability and smaller seasonal amplitudes compared to in situ measurements, indicating limitations in capturing extreme sea level events. The high-frequency variability (<30 days) is not well represented in the SA CMEMS product.

Author contributions

AIB: conceptualization, management, visualization, data analysis and interpretation, writing of the first draft and revision, funding acquisition; LDG: funding acquisition, writing and editing; BK: IMGW tide gauge data preparation.

Data availability

The Baltic + SEAL dataset is available from |urlhttp://baltic-seal.eu/, and sea level tide gauge observations are available from IMGW https://www.imgw.pl/. CMEMS satellite gridded L4 product SEALEVEL_EUR_PHY_L4_MY_008_068 is available from: https://data.marine.copernicus.eu/product/SEALEVEL_EUR_PHY_L4_MY_008_068/services.

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Conflict of interest

None declared.

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