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Probabilistic Modelling and Prediction of Sea Level Dynamics in the Southern Baltic Sea

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Abstract. This paper presents a probabilistic approach to the analysis of non-stationary sea level measurement series in the southern Baltic Sea based on tide gauge data for Swinoujscie, Kolobrzeg, Ustka, Wladyslawowo and Gdansk stations. Harmonic analysis (HA), Continuous Wavelet Transform (CWT), AR(1) autoregressive model and Monte Carlo uncertainty propagation were applied to identify trends, multiscale variability and the stochastic structure of the measurement data. The results indicate a spatially consistent sea level rise trend of 1.8–2.2 mm/yr, modulated by multiscale periodic variability and short-term stochasticity. The model used allows for a probabilistic forecast of sea level changes. In addition, the analysis of extremes using the Gumbel distribution indicates an increase in the probability of extreme sea levels along the southern Baltic coast. The proposed methodology extends conventional sea level analysis by integrating probabilistic interpretation, classical uncertainty estimation, and multiscale signal analysis, thereby providing a useful tool for coastal hazard and flood risk assessment and climate change adaptation in coastal regions.

1 Introduction

Historical solutions in sea level measurements date back to the 18th century. Celsius (1743) estimated the rate of sea level changes based on so-called seal rocks along the Baltic Sea coast. Water levels were marked on these rocks, reflecting both postglacial land uplift and regional hydrological changes. Stones with markings were found at a considerable distance from the current shoreline, which further documented historical changes in sea level and offsets in the shoreline (Weisse et al., 2021). Changes in sea level are important indicators of contemporary climate change and are analyzed at both the global and regional scales. Global sea level rise is mainly driven by the thermal expansion of the oceans and the contribution of melting glaciers and ice sheets (Intergovernmental Panel On Climate Change (IPCC), 2023). On a global scale, the mean sea level is rising by a few millimetres per year, and this rate has accelerated in recent decades (Church and White, 2011). However, at the regional scale, there are significant deviations from the global trend value due to local dynamic processes such as atmospheric circulation, wind speed and direction, atmospheric pressure and isostatic movements (Slangen et al., 2016).

The existing literature demonstrates that sea level variability in the Baltic Sea is highly cyclical. In addition to the dominant annual and semi-annual components, interannual oscillations (~3–8 years) have been identified, which are related to large-scale atmospheric variability, including the North Atlantic Oscillation (NAO). The NAO impacts sea level by modulating westerly winds and water mass transport in this region (Hünicke and Zorita, 2008; Hurrell, 1995).

Analyses of sea level variability from long-term tide gauge observation also indicate significant non-stationarity in the annual cycle and variability in its amplitude on a multi-decadal scale (Hünicke and Zorita, 2008). Satellite altimetry data confirm changes in the amplitude of seasonal components over the past decades, depending on variations in atmospheric circulation (Stramska et al., 2013). Contemporary sea level assessments extend beyond the classical trend-based approach, focusing on the variability of cyclical component amplitude and their modulation over time. The amplitude of seasonal and interannual components is not constant but change in terms of trends and accelerations, indicating a nonlinear character of the ocean–atmosphere system (Hünicke and Zorita, 2008; Hurrell, 1995). This means that analyzing the sea level trend is not sufficient to describe the changes occurring in the system. Simultaneously conducted studies of sea level extremes indicate an increased risk of storm surges as the mean sea level rises. These analyses commonly apply the Gumbel distribution, which is a standard method in hydrology and oceanography for modeling maximum sea levels and estimating the return periods of extreme phenomena (Coles, 2001). In recent years, increasing importance has been attributed to the non-stationarity of oceanic processes and their multiscale temporal structure, analyzed using wavelet methods and time-frequency approaches (Metropolis and Ulam, 1949). Based on the above studies, the analysis of sea level in the southern Baltic Sea requires a multimethod approach that considers both long-term trends and cyclical variability, as well as their modulation over time. In this study, this variability was assessed not only through classical estimates of sea level trends but also through an analysis of changes in the amplitude of individual periodic components and their accelerations over time. This approach allows for the identification of potential changes in the dynamics of climate cycles that are not visible in the analysis of mean sea level trends. Due to significant autocorrelation in sea level time series, an AR(1) model-based analysis was applied, which allows for the correct estimation of parameter uncertainty. To better assess the stability of the results, modified Monte Carlo simulations were used, allowing for the generation of process realizations based on the distributions of model parameters and their estimation uncertainties (Bos et al., 2014; Royston et al., 2018). This study aims to investigate long-term sea level variability, considering both trends in mean values and changes in the dynamics of periodic components and extreme phenomena. The study is based on the assumption that contemporary sea level changes include not only a systematic rise in the mean level but also modulations in the amplitude and accelerations of periodic cycles, which may reflect changes in the climate system (Church and White, 2011; Haigh et al., 2014). An analysis of extreme phenomena was carried out using the Gumbel distribution, applied to modeling maximum sea levels and estimating the return periods (Coles, 2001). The study applied a statistical approach that included the autocorrelation of sea level time series by using an AR(1) model, which allowed for the correct estimation of parameters and their uncertainties. The consistency of the results was verified using Monte Carlo simulations, which allowed for an assessment of the impact of estimation uncertainty on the character of the analysed processes (Guthrie, 2020; Robert and Casella, 2004). The research hypothesis was that climate change affects not only the rise in mean sea level, but also the intensity and dynamics of periodic processes and the frequency of extreme events. It is expected that the research methods applied will enable the identification of changes in sea level dynamics that are not visible in classical linear trend analyses, and will also allow for the assessment of changes in the risk of extreme phenomena under contemporary climate change conditions.

2 Study Area

The study area covers the Polish section of the Baltic Sea coast and the nearby shelf zone. The Baltic Sea is a semi-enclosed basin with limited water exchange with the North Sea through the Danish Straits, which causes that sea level is strongly dependent on local atmospheric conditions, particularly wind fields and atmospheric pressure (Börgel et al., 2026; Carlsson, 1998; Pham et al., 2024). The Polish Baltic coast is highly sensitive to hydrodynamic variability caused by atmospheric interactions and regional circulation (Börgel et al., 2026; Medvedev and Medvedeva, 2021; Wolski and Wiśniewski, 2021). Sea level fluctuations in this region are highly modulated by storm and variability in westerly winds, leading to significant deviations from average values (Kudryavtseva and Soomere, 2017; Paprotny, 2014).

The study used five tide gauge stations representing the western, central and eastern parts of the southern Baltic Sea: Swinoujscie, Kolobrzeg, Ustka, Wladyslawowo and Gdansk. These stations are part of one of the longest and most consistent sea level measurement series in the region (Church et al., 2010). Analyses of tide gauge data indicate that sea level variability in the Baltic Sea region is not spatially homogeneous, and local differences are due to seafloor topography, effects of water dam and variability in the regional wind field and atmospheric pressure (Meier, 2005). At the same time, high spatial coherence in the sea level trend signal is observed along the southern Baltic Sea, indicating the dominance of regional processes.

To extend the analysis of the transition from the coastal zone to the open sea, altimetry data from satellites were used. These data allow for the analysis of spatially homogeneous sea level signals and the comparison with coastal observations, especially in regions where tide gauges may be affected by local hydrodynamic effects (Zakharchuk et al., 2022). The combination of tide gauge with satellite data allows for the analysis of both the local response of the coastal system and regional sea level variability in the southern Baltic Sea. This approach is consistent with the current state of knowledge, which highlights the need to combine multiple data sources in analyses of sea level variability in semi-enclosed basins (Intergovernmental Panel on Climate Change (IPCC) 2023). The study area is presented in Fig. 1.

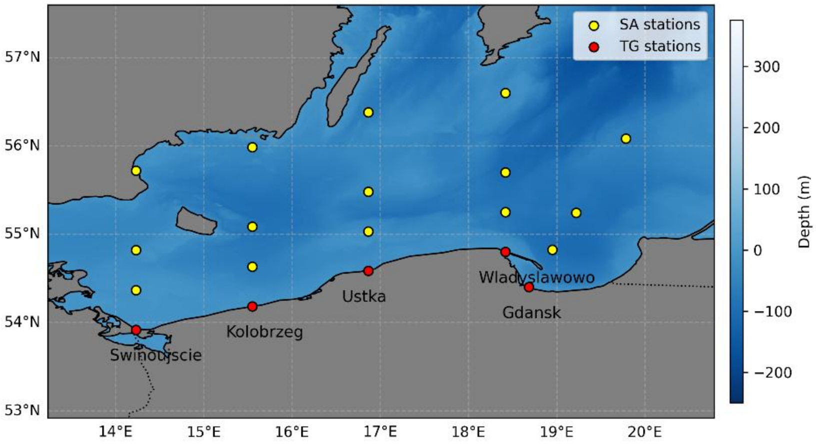

Figure 1: Study area – the south part of the Baltic Sea. Red dots mean the tide gauge stations, yellow dots mean the stations 50 km, 100 km and 200 km from the coast.

3 Datasets

This study employed a set of parameters describing long-term and periodic sea level variability, including trends and acceleration of sea level change. These parameters were determined using time series from tide gauge (TG) data (1951–2025 and 1993–2024) and time series from satellite altimetry (SA) data (1993–2024). Multi-approach research was carried out for coastal stations and points located at specific distances (50 km, 100 km, 200 km) from the coast, which allowed for an assessment of the impact of coastal and open-sea processes on the character of sea level changes. Trends and amplitude determined by harmonic analysis (HA) and verified using Continuous Wavelet Transform (CWT) were used to monitor and forecast sea level dynamics in the southern part of the Baltic Sea, with particular emphasis on the impact of climatic factors and lunar cycles. Table 1 presents the trend and acceleration values for the stations.

Table 1. Summary of the input datasets

SLR trend [mm/yr] **SLR acceleration [mm/yr^2]**	**Coastal stations**				
	Swinoujscie	**Kolobrzeg**	**Ustka**	**Wladyslawowo**	**Gdansk**
TG (1951-2025) (HA)	2.0 ± 0.1 0.02	1.8 ± 0.1 0.01	1.9 ± 0.1 0.00	2.2 ± 0.1 0.01	2.0 ± 0.1 -0.03
TG (1951-2025) (CWT)	2.1 ± 0.0 0.03	1.9 ± 0.0 0.01	1.9 ± 0.1 0.01	2.2 ± 0.1 0.01	2.0 ± 0.1 -0.03
TG (1993-2024) (HA)	3.4 ± 0.2 0.00	2.4 ± 0.2 -0.09	2.9 ± 0.2 -0.10	2.3 ± 0.2 0.11	0.2 ± 0.2 -0.08
TG (1993-2024) (CWT)	4.0 ± 0.2 0.00	2.4± 0.2 -0.07	3.2 ± 0.2 -0.10	3.2± 0.2 0.11	1.1 ± 0.2 -0.08
SA (1993-2024) (HA)	4.2 ± 0.1 0.05	4.2 ± 0.1 0.05	4.3 ± 0.2 0.07	4.2 ± 0.2 0.03	4.3 ± 0.2 0.04
SA (1993-2024) (CWT)	4.5 ± 0.1 0.04	4.6 ± 0.1 0.04	4.7 ± 0.1 0.06	4.6 ± 0.2 0.02	4.7 ± 0.2 0.04
Stations + 50 km					

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SA (1993-2024) (HA)	4.3 ± 0.1 0.03	4.1 ± 0.1 0.04	4.1 ± 0.2 0.03	4.2 ± 0.2 0.03	4.4 ± 0.2 0.02
SA (1993-2024) (CWT)	4.5 ± 0.1 0.02	4.6 ± 0.1 0.03	4.5 ± 0.2 0.02	4.7 ± 0.2 0.03	4.8 ± 0.2 0.01
Stations + 100 km					
SA (1993-2024) (HA)	4.2 ± 0.1 0.03	4.1 ± 0.1 0.05	4.3 ± 0.2 0.03	4.4 ± 0.2 0.03	4.1 ± 0.2 0.03
SA (1993-2024) (CWT)	4.5 ± 0.1 0.02	4.6 ± 0.1 0.03	4.8 ± 0.2 0.02	4.9 ± 0.2 0.03	4.6 ± 0.2 0.02
Stations + 200 km					
SA (1993-2024) (HA)	4.6 ± 0.1 0.02	4.3 ± 0.1 0.04	4.3 ± 0.2 0.03	4.1 ± 0.2 0.03	4.4 ± 0.2 0.04
SA (1993-2024) (CWT)	4.9 ± 0.1 0.00	4.7 ± 0.1 0.03	4.7 ± 0.2 0.01	4.5 ± 0.2 0.02	4.8 ± 0.2 0.03

The data applied in this study indicate that the spatial consistency of trends increases with distance from the coast. In the coastal zone, higher signal variability is observed due to local hydrodynamic processes, whereas areas distant from the coast are characterized by a more consistent trend in sea level change. Altimetry data indicate a higher rate of sea level rise and higher spatial coherence compared to tide gauge data, particularly outside the coastal zone. Differences between SA and TG results are related to both the local effects of processes occurring in the coastal zone and the influence of GIA (Glacial Isostatic Adjustment) (Peltier, 2004). Tide gauge data refer to relative sea level concerning vertical land movements, while altimetry measurements represent changes in absolute sea level relative to a geocentric reference frame (Church et al., 2008). As a result, vertical crustal movements associated with postglacial isostatic adjustment can lead to differences between trends determined from tide gauge and satellite observations (Vestøl et al., 2019). The analysis also used the GEBCO (General Bathymetric Chart of the Oceans) global bathymetric model, with a spatial resolution of 15″ × 15″ to define the bathymetric character of the seafloor. The GEBCO model provides information on water elevation in a standardized spatial grid, allowing for the analysis of the relationship between sea level variability and local bathymetry. Depth values were assigned to the analyzed points using linear interpolation, which ensured spatial consistency of the data and consistency with the model's resolution. Based on GEBCO data, depths were determined for the stations and a comparison of the amplitude of selected harmonic components in relation to bathymetric conditions was carried out. The effect of the seafloor topography on the spatial variation of amplitude was assessed and relationships between depth and the intensity of periodic signals were identified (GEBCO Compilation Group, 2025).

4 Methodology

4.1 Cyclical analysis (Harmonic and CWT Analysis)

To identify periodic components, harmonic analysis and the continuous wavelet transform (CWT) were used, which allows for the analysis of non-stationary signals in the time-frequency domain (Parker, 2007; Schureman and U.S. Coast and Geodetic Survey, 1971; Torrence and Compo, 1998). The combination of these two methods provides a complementary approach to sea level variability: harmonic analysis allows for precise estimation of the amplitude and phases of selected components with defined periods, while CWT enables tracking the evolution of these components over time and identifying changes across various time scales. Harmonic analysis was performed by fitting a model consisting of a sum of sinusoidal functions with specific frequencies corresponding to the main physical cycles present in the sea level signal (Foreman, 1977). The model parameters were estimated using the least squares method, which allowed for the determination of amplitude, phase and their changes over time. A Continuous Wavelet Transform was performed using the Morlet wavelet. The following cycles were identified: an annual cycle, associated mainly with the seasonality of atmospheric forces (temperature, wind, pressure); a semi-annual cycle, reflecting seasonal asymmetry and transitional circulation phases and interannual oscillations, interpreted as the effect of climate variability on a regional scale and high-frequency signals, potentially associated with lunar cycles and short-term atmospheric variability (Cheng et al., 2018; Zakharchuk et al., 2022). For each of the identified components, the amplitude and its variability over time were determined. The application of the wavelet transform additionally allowed for the verification of the temporal stability of individual components and the identification of periods of their amplification and attenuation, which constitutes an essential element of the interpretation of multiscale variability in the Baltic Sea region.

4.2 Harmonic-Wavelet Analysis of Amplitude Modulation

The study employed a hybrid method for analyzing non-stationary signals defined as harmonic-wavelet analysis of amplitude modulation; this is a multiscale method for analyzing non-stationary signals, combining nonlinear trend decomposition, the continuous wavelet transform (CWT), harmonic analysis, and estimation of statistical uncertainty (Barache et al., 1997; Katsavrias et al., 2022; Tary et al., 2018). The method allows for the study of the global dynamics of the system and the temporal dynamics of periodic components, along with an assessment of their amplitude modulation and acceleration. The analyzed time series is modeled as the sum of a nonlinear trend and harmonic components of variable amplitude:

$$MSL\ (t) = trend\ (t) + \sum_{i=1}^{N} harmonics + \varepsilon(t)\ , \qquad (1)$$

where: MSL (t) is mean sea level in time t and ε(t) is random component/noise The long-term deterministic component is described by a second-order polynomial:

$$trend\ (t) = at^2 + bt + c + \varepsilon(t)\ , \qquad (2)$$

where: b is linear trend component t, a is acceleration, c is a constant offset and ε(t) means the residual stochastic component. The parameters were estimated using the ordinary least squares (OLS) method. A Morlet's wavelet was used for the time-frequency analysis (Wallisch et al., 2009):

$$\psi(t) = \pi^{-\frac{1}{4}} e^{-\frac{1}{2}t^2} e^{-i\omega_0 t}\ , \qquad (3)$$

The transform is defined as:

$$(a,b) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} f(t)\psi^{*}\left(\frac{t-b}{a}\right)dt\ , \tag{4}$$

where: a is scale parameter, b is time translation parameter, ψ^{*} means mother wavelet parameter.

The result of the transformation is a time-frequency representation (scalogram), which allows for the identification of periodic components and their variation over time (Percival and Walden, 2000). Extraction of harmonic parameters based on CWT coefficients is a recognized method for identifying periodic components (Liu et al., 2007). Amplitude was determined as the average value of the magnitude of CWT coefficients in the scale ranges:

$$A_i(t) = \langle |W_x(a,b)| \rangle_{a\in\Delta a_i}\ , \tag{5}$$

This approach corresponds to the analysis of amplitude modulation in non-stationary signals (Lilly and Olhede, 2010). A second-order nonlinear model was used to model amplitude trends:

$$\mathrm{A_i(t)} = \alpha_i \mathrm{t}^2 + \beta_i \mathrm{t} + \gamma_i + \eta_i(t)\ , \tag{6}$$

where: α_i is acceleration of amplitude modulation, β_i is linear trend of the harmonic amplitude, γ_i means constant term and $\eta_i(t)$ is the residual noise. The obtained functions $\mathrm{A_i(t)}$ represent the temporal amplitude modulation of individual cycles (Huang et al., 1998). Parameter uncertainties were estimated using the block bootstrap method (Kunsch, 1989). Confidence intervals were determined using the percentile method:

$$\mathrm{CI}_{95\%} = [\mathrm{P}_{2.5}, \mathrm{P}_{97.5}]\ , \tag{7}$$

This resulted in statistically robust conclusions in conditions of significant autocorrelation and non-stationarity of the data. The application of a hybrid harmonic-wavelet method to amplitude modulation analysis enables the identification and quantitative assessment of the temporal amplitude modulation of harmonic components, considering their multiscale variability. This allows for the detection of trends and accelerations in amplitude changes, which provides information about the dynamics and processes occurring in the analyzed sea level variability.

4.3 Extreme value analysis (Gumbel distribution)

Sea level extremes were analyzed using the Gumbel distribution for maximum values. The Gumbel model was used to estimate maximum annual sea levels and to analyze the return periods of extreme phenomena. The analysis of extreme sea levels was based on the Gumbel distribution, extended to include a non-stationary component, and uncertainty assessment procedures using the bootstrap method. In the first step, annual maxima series were determined from daily time series, which serve as the basis for estimating the parameters of the extreme distribution. The model parameters were estimated using the maximum reliability method. Then, a non-stationary variant was examined, in which the distribution location parameter was defined as a linear function of time:

$$\mu(t) = \mu_0 + \beta t\ , \tag{8}$$

enabling the incorporation of a long-term trend in changes of sea level extremes. In contrast to the classical stationary approach, the scale parameter was retained as constant over time, allowing for the isolation of the effect of changes in the mean level of extremes. For the defined models, extreme levels were calculated for return periods (2–100 years), and their changes over time were analysed by accounting for the observed climate trend. To assess the uncertainty of the estimates, a bootstrap procedure (n = 1000–2000 iterations) was applied, involving sampling with replacement from the set of annual maxima and refitting the Gumbel distribution for each sample. On this basis, empirical 95% confidence intervals were determined for the extreme levels (Cheng and Huang, 2010; Coles, 2001; Pajer et al., 2020). In addition, the rate of change of extremes (β) was compared with the trend of the mean sea level (Vousdoukas et al., 2018; Wahl et al., 2015). This analysis assessed whether extreme sea levels are changing at the same rate as the mean sea level. The results of this procedure provide the basis for assessing the stationary character of extreme processes and their potential acceleration under a changing climate.

4.4 Modified Monte Carlo simulations

A probabilistic forecasting approach was used to predict sea level changes. For each of the selected locations, an analysis of daily sea level changes over a 31-year period was carried out. To estimate the long-term trend and seasonality, a deterministic model of the following form was used:

$$y(t) = a + bt + ct^2 + \sum_{i=1}^{3}[A_i \cos(\omega_i t) + B_i \sin(\omega_i t)] + \varepsilon_t \, , \tag{9}$$

where a means the bias, b means the linear trend, c means the trend acceleration and the sine and cosine components represent cyclical fluctuations (annual, semi-annual and long-term). The parameters A represent the amplitude of the individual components and ω represent the frequencies of the cycles. The model residuals ε are described using a first-order autoregressive process AR(1), which accounts for the temporal autocorrelation and memory of the process. A_i parameters means the amplitude of the individual components, ω correspond to the cycle frequencies. The residuals of the model ε_t are defined by autoregressive AR(1) model (Wang, 2023).

The model parameters were estimated using the Least Squares method, followed by probabilistic propagation through Monte Carlo simulation. As part of this approach, 1000 model realizations were generated, in which the parameters were selected from normal distributions corresponding to their estimation errors. Based on this, uncertainty intervals (5th–95th percentiles) were determined for sea level projections. For each point, the trend (b) and acceleration (c) parameters, along with their corresponding uncertainty intervals, were determined. The approach used represents an integrated, multi-component sea level forecast model, combining a deterministic component (trend and seasonality) with a stochastic model (AR(1) and Monte Carlo), providing a more realistic assessment of sea level change forecasts in the southern Baltic Sea region(Ansari et al., 2024; Grandey et al., 2023; Ruckert et al., 2017; Wang, 2023).

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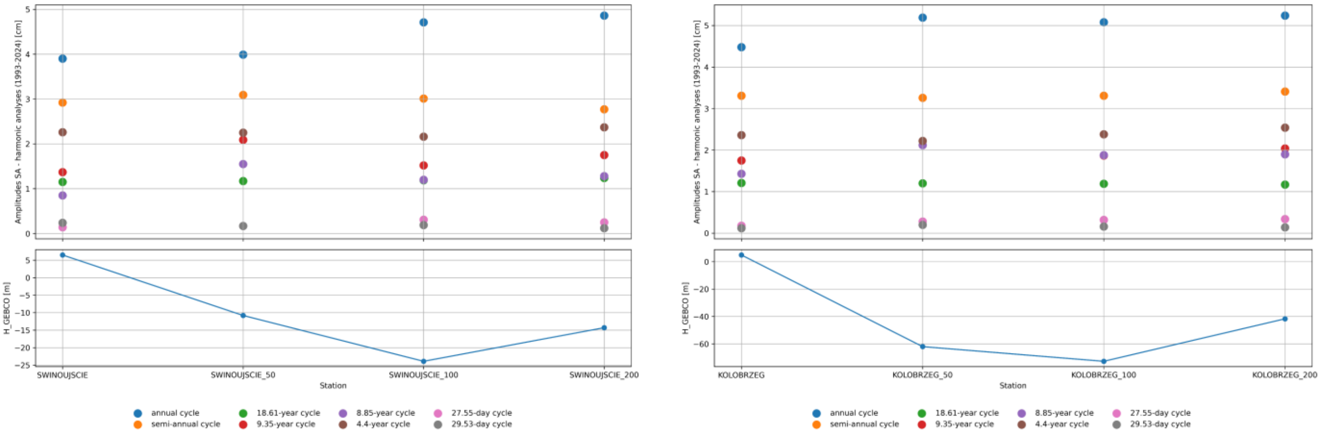
5 Results

5.1 Seasonal amplitude profiles as a function of depth

The study analyzed the amplitude of selected cyclical components of sea level, including both seasonal (annual and semi-annual cycles) and long-term (18.61-, 9.35-, 8.85-, 4.4-year cycles) and short-term (27.55- and 29.53-day cycles), which allowed for a comprehensive assessment of the influence of astronomical, atmospheric, and oceanic processes on the formation of sea level variability depending on distance from the coastal zone. Analysis of the amplitude of these cycles also enabled the identification of spatial differences and an assessment of the role of local and regional factors. Analysis of the amplitude of individual cycles in altimetry (SA, 1993–2024) and tide gauge (TG, 1993–2024 and 1951–2025) revealed distinct variations depending on both distance from the coast and water depth. The results obtained allow for the identification of the mechanisms responsible for sea-level variability on different time scales. Vertical profiles were generated – presenting changes in amplitude values across various cycles, starting from coastal points and extending to points 200 km from the southern Baltic coast (Fig. 2), as well as horizontal profiles—that is, a representation of how amplitude vary across different cycles along successive points at a given distance from the SA time series (1993–2024) and how amplitude vary across different cycles along the southern coast of the Baltic Sea based on SA (1993–2024) and TG (1993–2024 and 1951–2025) data (Fig. 3).



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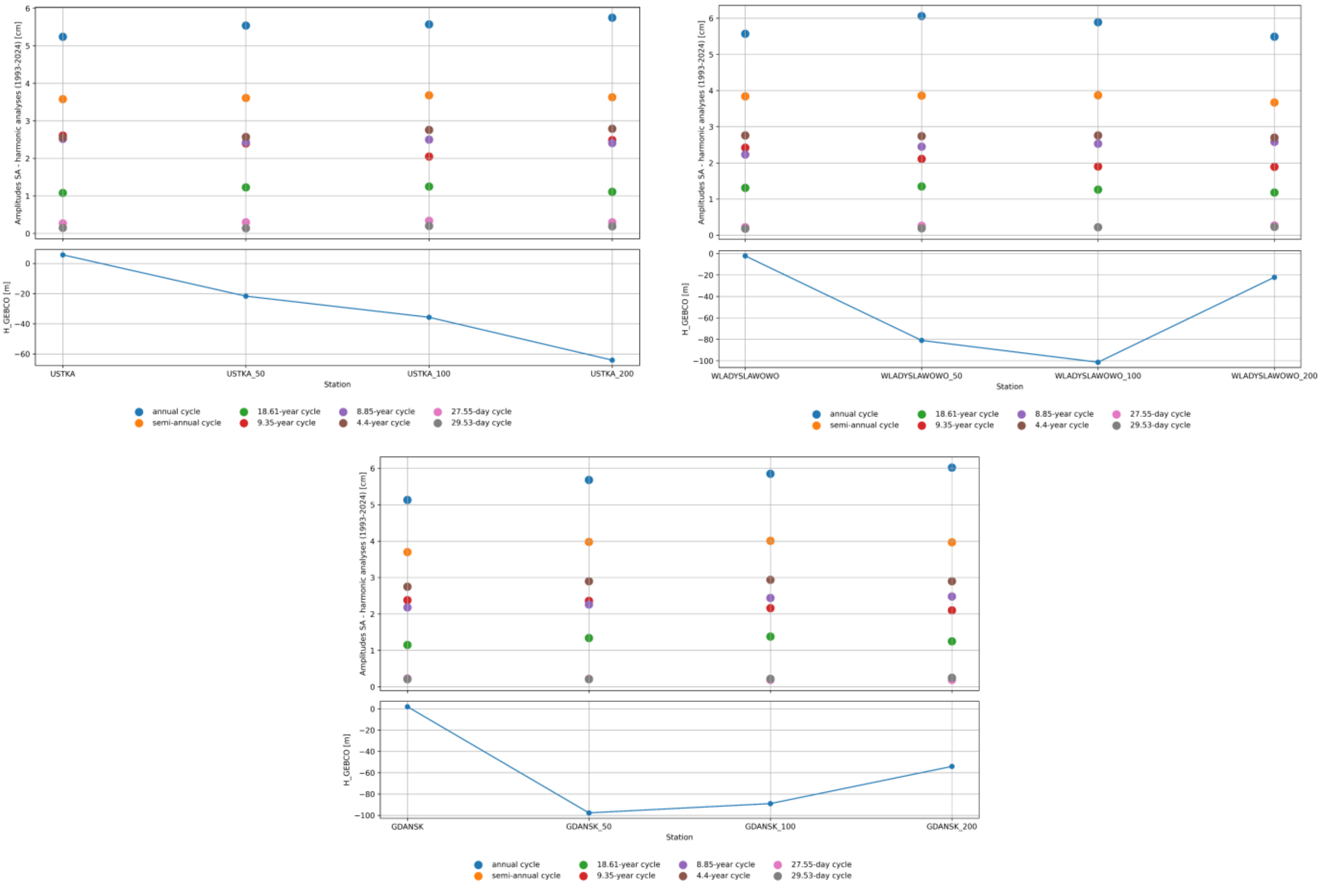
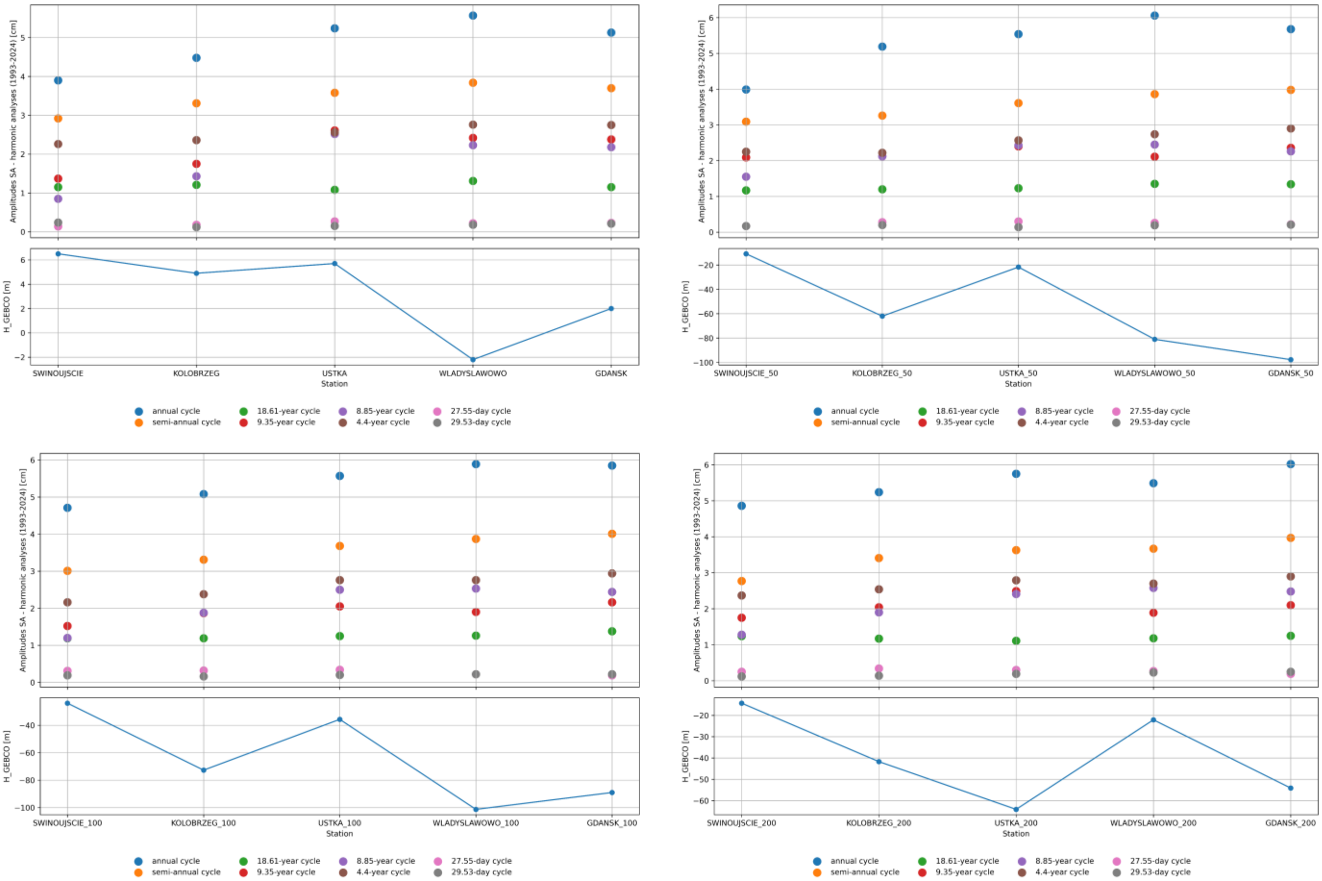


Figure 2: Vertical profiles – changes in amplitude values from SA data (HA analysis) – coastal stations and stations located 50 km, 100 km, and 200 km from the southern Baltic coast. The units are centimeters.

For altimetry data, a systematic increase in the amplitude of most of the analyzed cycles is observed with increasing distance from the coast. The most pronounced trend concerns the annual cycle, whose amplitude increases from approximately 3.9 in the coastal zone to over 5.5–6.0 in areas 50–200 km offshore. This increase can be interpreted as the result of the diminishing influence of local coastal processes, such as bottom friction, shoreline interaction, or river inflows, which lead to the attenuation of the seasonal signal. A similar, though weaker, trend is observed for the semi-annual cycle, whose amplitude is more spatially homogeneous. This indicates its partially regional nature and lower sensitivity to local hydrodynamic conditions. Multiannual cycles present varied behavior. The 18.61-year component remains relatively stable regardless of its distance from the coast, confirming its astronomical origin and global nature. In contrast, cycles with periods of about 9–10 years (9.35 and 8.85 years) show a marked increase in amplitude towards the offshore waters , suggesting their relationship with large-scale ocean and atmospheric circulation processes, which are better represented in data from deep-water areas. Also, short-term cycles (day 27.55 and day 29.53) reach higher amplitude as they move away from the coast. This is in line with expectations for tidal and lunar components, which are strongly suppressed in the coastal zone due to interaction with the seafloor and complex topography.

The results obtained indicate a significant relationship between the amplitude of the analyzed cycles and depth. As depth increases, the amplitude of most components increases, particularly that of the annual cycle, the decadal cycles, and the monthly cycles. This phenomenon results from the reduced influence of bottom and coastal processes and the better preservation of long-period wave energy in deep-sea areas. The 18.61-year cycle exhibits the lowest sensitivity to changes in depth, which further confirms its independence from local conditions and the dominant influence of astronomical factors.



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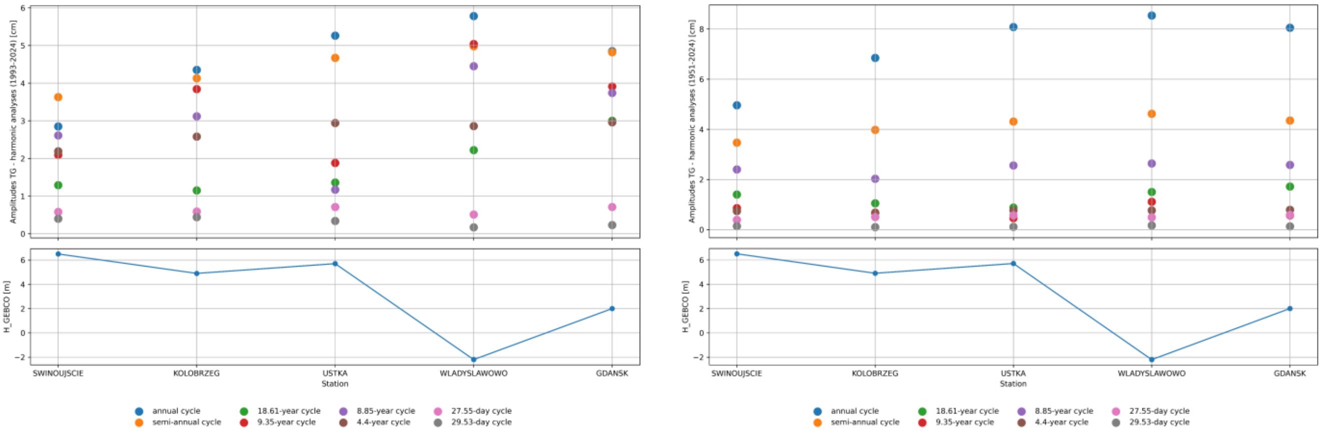

Figure 3: Horizontal profiles - changes in amplitude values from SA data (HA analysis) – coastal stations, stations 50 km, 100 km and 200 km away from the South Baltic coast and changes in amplitude values from TG data (HA analysis) – coastal stations. The units are centimeters.

Significant differences are observed between the results of amplitude changes derived from altimetry (SA) and tide gauge (TG) data. Altimetry data are characterized by higher spatial homogeneity and more clearly reflect regional and oceanic signals. In contrast, tide gauge data exhibit higher variability and larger amplitude for certain cycles, particularly in the time series for the period 1993–2024, where significant amplitude of semi-annual and multi-year cycles (especially 9.35 and 8.85 years) are noticeable, which locally reach values significantly higher than in the altimetry data series. This may result from the strong influence of local factors, such as wind effects, changes in atmospheric pressure, and resonance phenomena (e.g., swells), which are recorded by tide gauge stations but are less evident in satellite data. Short-term cycles (27–29 days) also exhibit significantly higher amplitude in time series derived from TG data than in SA data, confirming the significant role of local hydrodynamic processes in the coastal zone.

A comparison of the results for the time series derived from tide gauge measurements for the periods 1993–2024 and 1951–2025 indicates that the length of the analyzed period has a significant impact on the obtained amplitude. In the time series covering the period 1951–2015, a clear amplification of the annual cycle is observed, with its amplitude reaching values even above 8.0 cm, which indicates its dominant and stable nature on a long-term scale. At the same time, the amplitude of medium-term cycles (4–10 years) decrease significantly, suggesting that their high values in the shorter time series may result from temporal instability or the influence of episodic events. Short-term cycles in the time series for the period 1951–2025 exhibit lower amplitude than in the time series for the period 1993–2024, which can be interpreted as an effect of averaging and noise reduction in the longer data series. The analysis indicates that sea level variability is strongly dependent on the spatial and temporal scale of observations. As distance from the coast increases and depth rises, the contribution of regional and global processes grows, whereas local processes dominate in the coastal zone, leading to higher variability and signal distortion.

5.2 Trends and acceleration of seasonal amplitude

Changes in sea level result from overlapping processes: steric, dynamic and atmospheric. In addition to the mean trend (SLR), changes in the amplitude of periodic cycles are of significant importance, as they reflect the dynamics of the ocean–atmosphere system. Of particular importance are: the annual cycle (seasonal forcing), the semi-annual cycle, interannual oscillations (~4–5 years) and tidal signals (~27–30 days). Therefore, the study included an analysis of sea level time series, which revealed a spatially coherent signal of Baltic Sea level rise and a complex, nonlinear reorganization of periodic variability. This study analyzes the trends and rate of change in the amplitude of selected periodic components of sea level for five measuring stations, as shown in Fig.4.

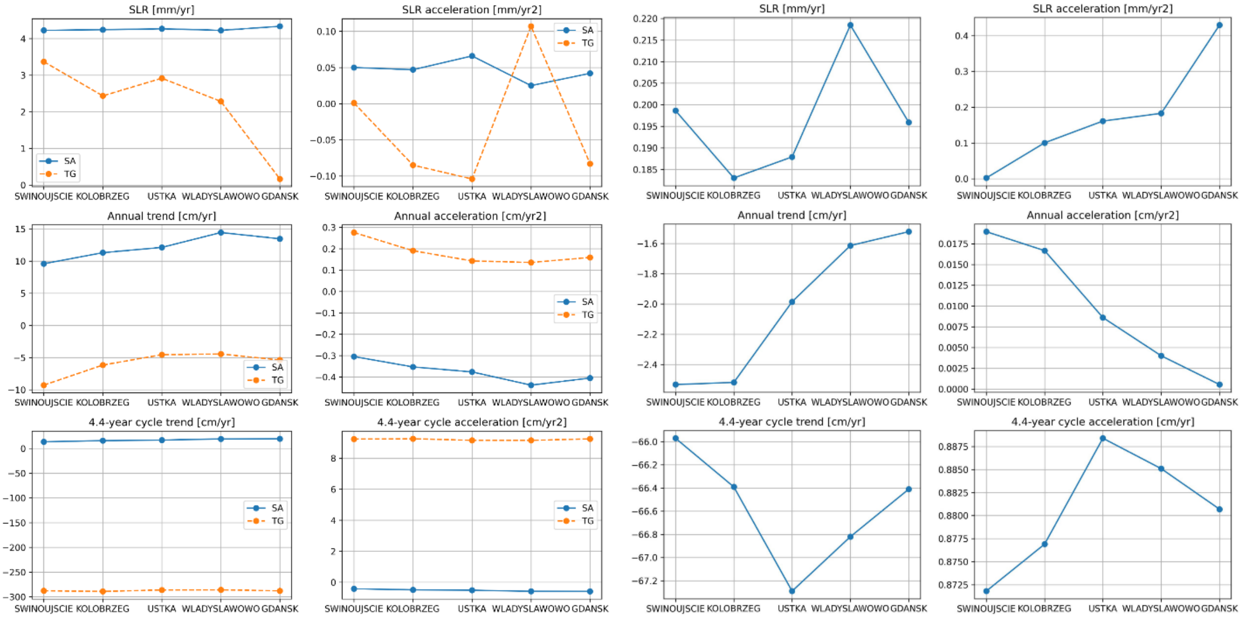

Figure 4: Analysis of trends and accelerations of selected periodic sea level components for 5 measuring stations based on data from SA/TG (1993–2014) (a), and TG (1951–2025) (b). The units are centimeters.

At all locations (Swinoujscie, Kolobrzeg, Ustka, Wladyslawowo, Gdansk), an almost identical trend of sea level rise is observed from SA data (1993–2024), at a rate of ~4.2–4.3 mm/yr, indicating the dominance of a common, regional forcing mechanism. The acceleration of sea level change is positive but low, suggesting a stable, albeit slightly strengthening, long-term signal. An analysis of cyclical variability shows that the annual component exhibits a clear and statistically significant increase in amplitude (on the order of ~9.6–14.4 cm/yr), accompanied by negative acceleration (~−0.30 to −0.44 cm/yr²). This means that although seasonal sea level variability is increasing, the rate of increase is decreasing over time. A similar but even stronger signal is observed for oscillations with a period of ~4.4 years, where the increase in amplitude reaches values of ~13.5–19.7 cm/yr, and the negative acceleration is more pronounced (~−0.42 to −0.58 cm/yr²). The consistency of these results across all stations and their statistical significance (confirmed by the bootstrap method) indicates the presence of a strong, large-scale mechanism modulating interannual variability. The semi-annual cycle exhibits no significant trends or accelerations, and the signals for monthly periods (27.55 and 29.53 days) are characterized by low explained variance (R^2 ~0.07–0.12) and a lack of statistical significance. This suggests that short-term fluctuations are dominated by stochastic variability or tidal processes that do not undergo systematic reorganization during the analyzed period.

A major result of the analysis is the co-occurrence of increasing amplitude of the main cycles and their negative acceleration. This combination indicates nonlinear dynamics of change, in which this variability occurs across time scales, which may be caused by physical mechanisms, such as changes in atmospheric and oceanic circulation, modulation of mass transport and steric properties, and the influence of interannual climate changes. The results indicate that the amplitude of the annual component shows a systematic decreasing trend at all analyzed locations based on TG data (1993–2024), with trend values ranging from approximately –4.4 to –9.3 cm/yr. At the same time, the estimated accelerations of amplitude are positive, but in no case do they reach statistical significance, suggesting that the observed decline is linear and does not show a marked intensification over time. This phenomenon can be interpreted as a potential weakening of the seasonal sea level cycle, which may be related to changes in the seasonality of atmospheric forcings, such as wind or pressure distribution.

The trends in the semi-annual amplitude remain negative; however, their uncertainty is so high that they include 0 within their confidence intervals, indicating no significant changes over time. The acceleration of this component's amplitude is positive but also statistically insignificant. The most pronounced and clear signal of change concerns the component with a period of approximately 4.4 years. For all stations, a strong, negative amplitude trend of approximately -286 to -290 cm/yr was identified, accompanied by high values of the coefficient of determination (R^2 ~0.81), indicating a very well-fitting model. Importantly, the acceleration of this component's amplitude is positive and statistically significant, reaching values of approximately 9.1–9.3 cm/yr². This means that the amplitude changes of this cycle vary over time.

In contrast to the above results, the short-term components with periods of approximately 27.55 and 29.53-days do not show any significant trends or accelerations in amplitude. The values of the estimated parameters are close to 0; furthermore, the low values of the coefficient of determination indicate that the variability of these components is highly random. This can be interpreted as the absence of long-term reorganization of the energy of signals associated with lunar cycles and other high-frequency processes. For all analyzed stations, a negative trend in the annual cycle amplitude (–2.5 to –1.5 cm/yr) was observed in the TG data (1951–2025), indicating a systematic weakening of seasonal sea level variability. At the same time, slight positive accelerations in amplitude (0.001–0.02 cm/yr²) were observed, suggesting a nonlinear nature of the changes and a potential deceleration of this trend.

In summary, the results indicate that the nature of the changes varies depending on the time scale. While the annual and semi-annual components present weak or insignificant changes, the multi-year cycle (~4.4 years) undergoes distinct and significant changes, making it a key component of the observed variability. The absence of significant trends in the short-term components further underscores that the main transformations occur in the low-frequency range. These results suggest the need for further research aimed at identifying the physical mechanisms responsible for the observed changes, in particular through the analysis of correlations with climate indices and the application of methods enabling the study of signal non-stationarity in the time and frequency domains. The results obtained indicate a clear separation, like sea level variability in the Baltic Sea region. These results are consistent with the current state of knowledge, according to which the Baltic Sea functions as a system strongly dependent on atmospheric forcing, and its sea level variability is largely determined by climatic processes on a regional and supra-regional scale (Raudsepp et al., 2025).

5.3 Extreme value analysis (Gumbel distribution)

An analysis of sea level extremes was carried out for coastal stations (1951–2025 TG time series) using a Gumbel distribution fitted to annual maxima, which allows for estimation of extreme events across various time scales. Including a linear trend also allows assessment of the impact of climate change on future extreme levels (Fig. 5-9).

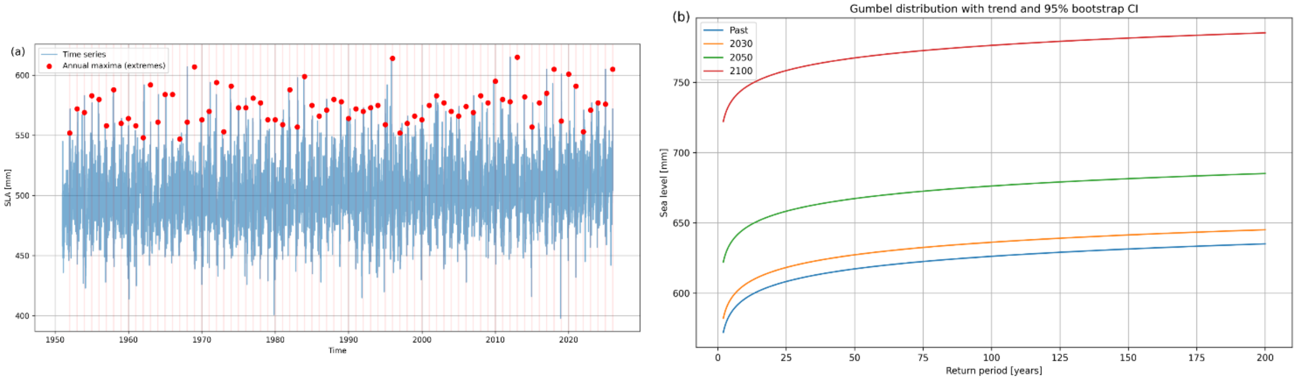

Figure 5: Time series TG (1951–2025) and annual extreme values at the Swinoujscie station (a) and Gumbel distribution of sea level rise to 2100 (b).

The Gumbel distribution fitted to annual maximum values indicates that current extreme levels at the Swinoujscie station range from approximately 572 mm for a 2-year return period to approximately 626 mm for a 100-year return period. The return period refers to the average time between occurrences of an event of a specific magnitude or higher and is equal to the inverse of the probability of exceeding it in a specific year (e.g., a 100-year period corresponds to a 1% chance of occurrence in a particular year). The 95% confidence intervals obtained using the bootstrap method expand as the return period increases, reflecting the growing uncertainty for rare occurrences. Assuming a linear increase of 2.0 mm/yr, all return levels are systematically increased. By 2050, the 100-year level rises to approximately 676 mm, and by 2100 it reaches approximately 776 mm.

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Preprint. Discussion started: 26 June 2026

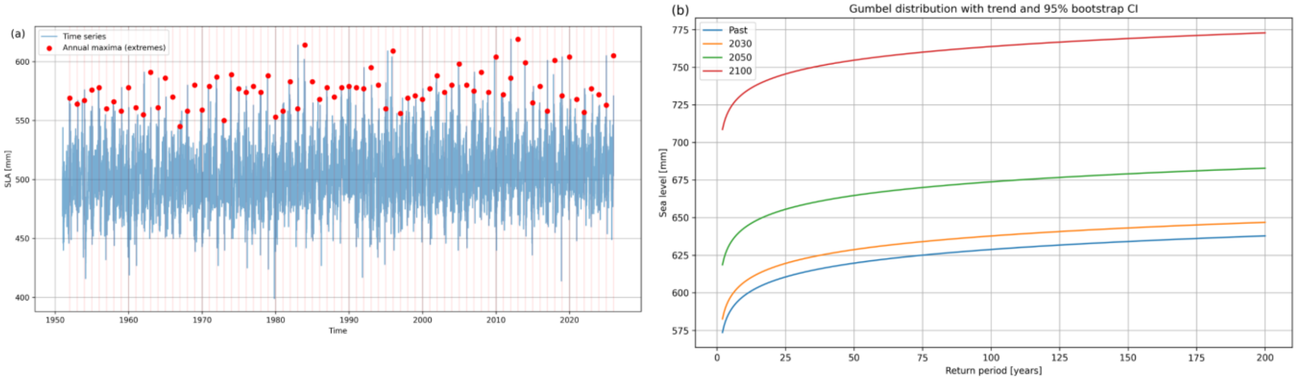

Figure 6: Time series TG (1951–2025) and annual extreme values at the Kolobrzeg station (a) and Gumbel distribution of sea level rise to 2100 (b).

At the Kolobrzeg station, the Gumbel distribution indicates that modern (baseline) extreme levels range from about 574 mm for a return period of 2 years to about 629 mm for a period of 100 years. The 95% confidence intervals determined by the bootstrap method increase in width as the return period increases (e.g. for T = 100 years: 618–639 mm), indicating increasing estimation uncertainty for rarer extreme occurrences. Taking into account the linear growth trend of 1.8 mm/yr leads to a systematic upward shift of the entire distribution of extremes. By 2050, the level corresponding to a 100-year event increases to about 674 mm, and by 2100 it reaches about 764 mm.

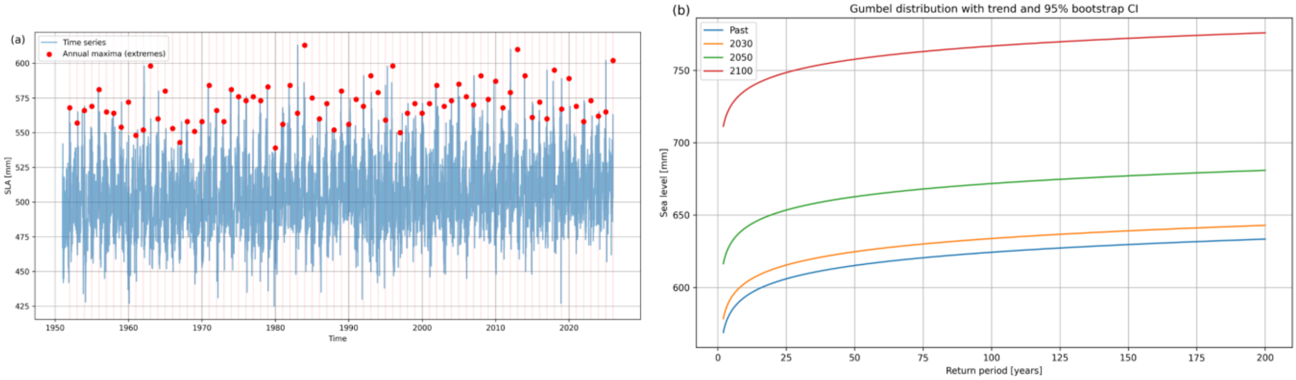

Figure 7: Time series TG (1951–2025) and annual extreme values at the Ustka station (a) and Gumbel distribution of sea level rise to 2100 (b).

At the Ustka station, the Gumbel distribution indicates that modern (baseline) extreme levels range from about 569 mm for a return period of 2 years to about 624 mm for a period of 100 years. The 95% confidence intervals obtained by the bootstrap method increase in width as the return period increases (e.g., for T = 100 years: 613–634 mm), reflecting the increasing uncertainty of estimation for rarer extreme occurrences. Taking into account the linear growth trend of 1.9 mm/yr results in a systematic shift in extreme levels over time. By 2050, the level corresponding to a 100-year event increases to about 672 mm, and by 2100 it reaches about 767 mm.

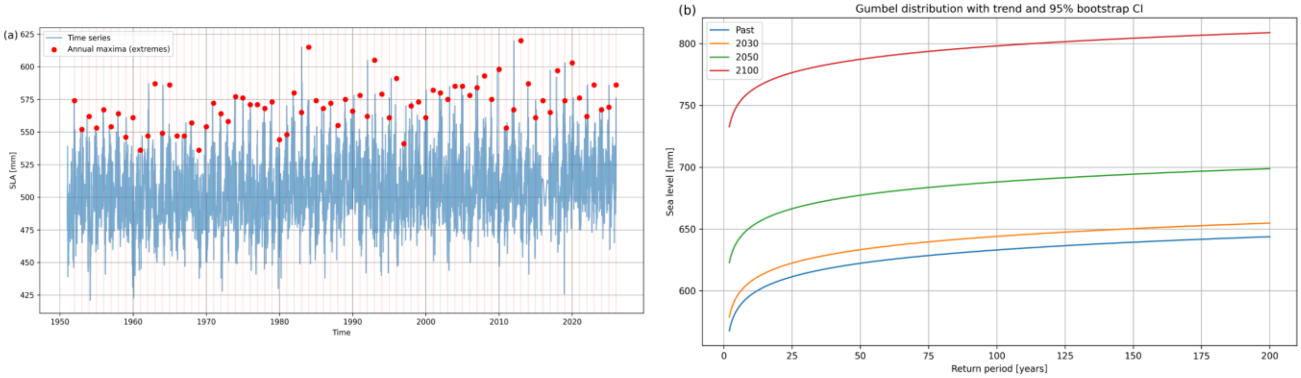

Figure 8: Time series TG (1951–2025) and annual extreme values at the Wladyslawowo station (a) and Gumbel distribution of sea level rise to 2100 (b).

At the Wladyslawowo station, the adjusted Gumbel distribution to annual maxima indicates that modern (base) extreme levels range from about 568 mm for a return period of 2 years to about 633 mm for a period of 100 years. The 95% confidence intervals obtained by the bootstrap method increase in width with increasing return period (e.g. for T = 100 years: 621–644 mm), indicating increasing estimation uncertainty for rarer extreme occurrences. Taking into account the linear growth trend of 2.2 mm/yr leads to a systematic shift in extreme levels over time. By 2050, the level corresponding to a 100-year event increases to about 688 mm, and by 2100 it reaches about 798 mm.

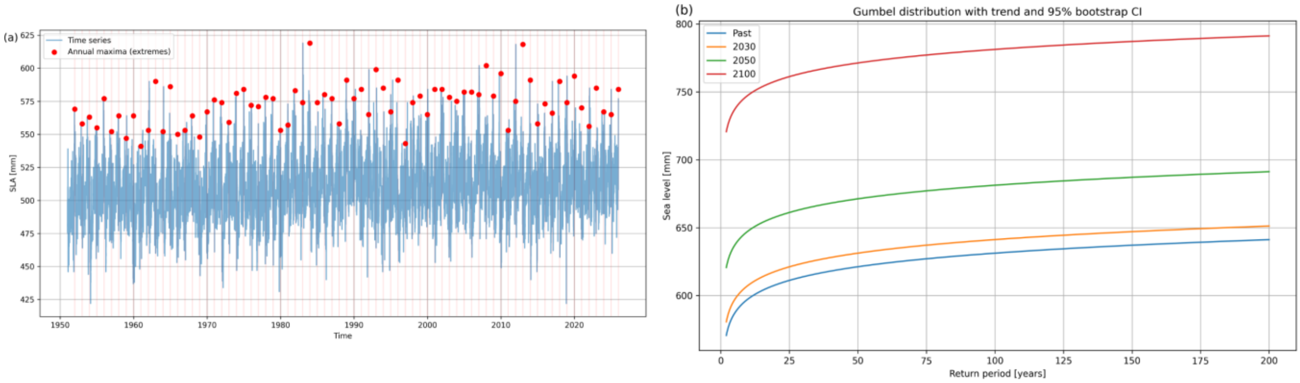

Figure 9: Time series TG (1951–2025) and annual extreme values at the Gdansk station (a) and Gumbel distribution of sea level rise to 2100 (b).

At Gdansk station, the adjusted Gumbel distribution to annual maximums indicates that modern (baseline) extreme levels range from about 571 mm for a return period of 2 years to about 631 mm for a period of 100 years. The 95% confidence intervals obtained by the bootstrap method increase in width as the return period increases (e.g., for T = 100 years: 621–641 mm), reflecting the increasing uncertainty of estimation for rarer extreme occurrences. Taking into account the linear growth trend of 2.0 mm/yr leads to a systematic shift in extreme levels over time. By 2050, the level corresponding to a 100-year event increases to about 681 mm, and by 2100 it reaches about 781 mm. The results indicate a systematic increase in

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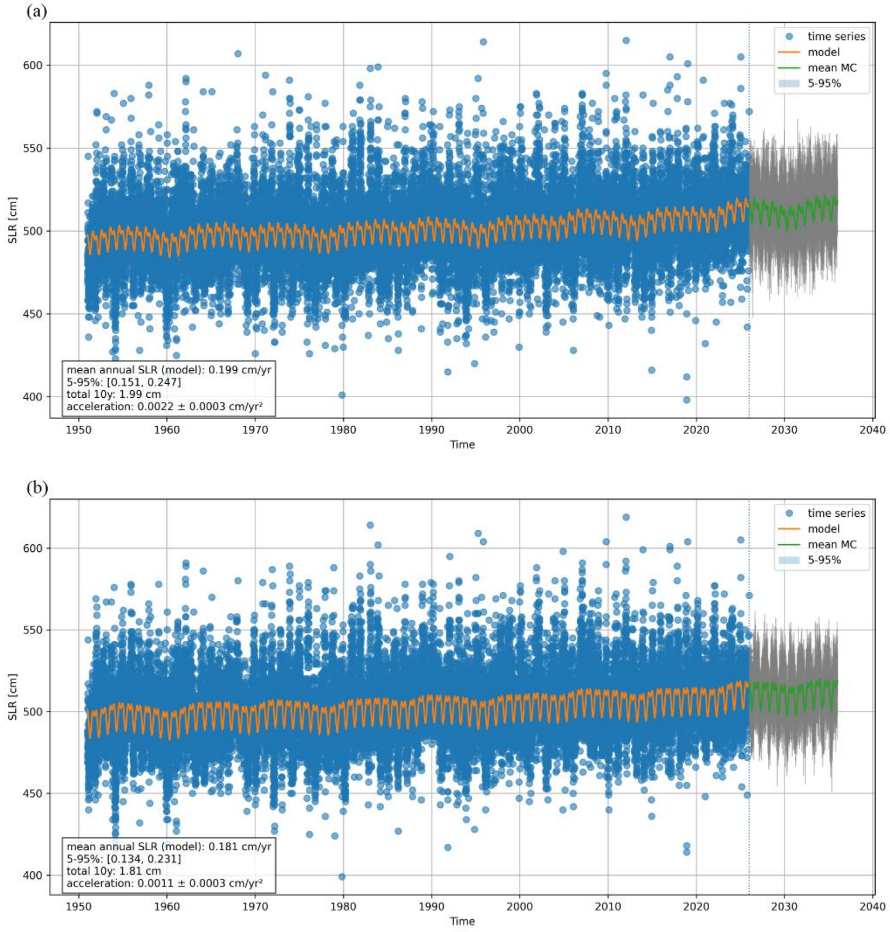
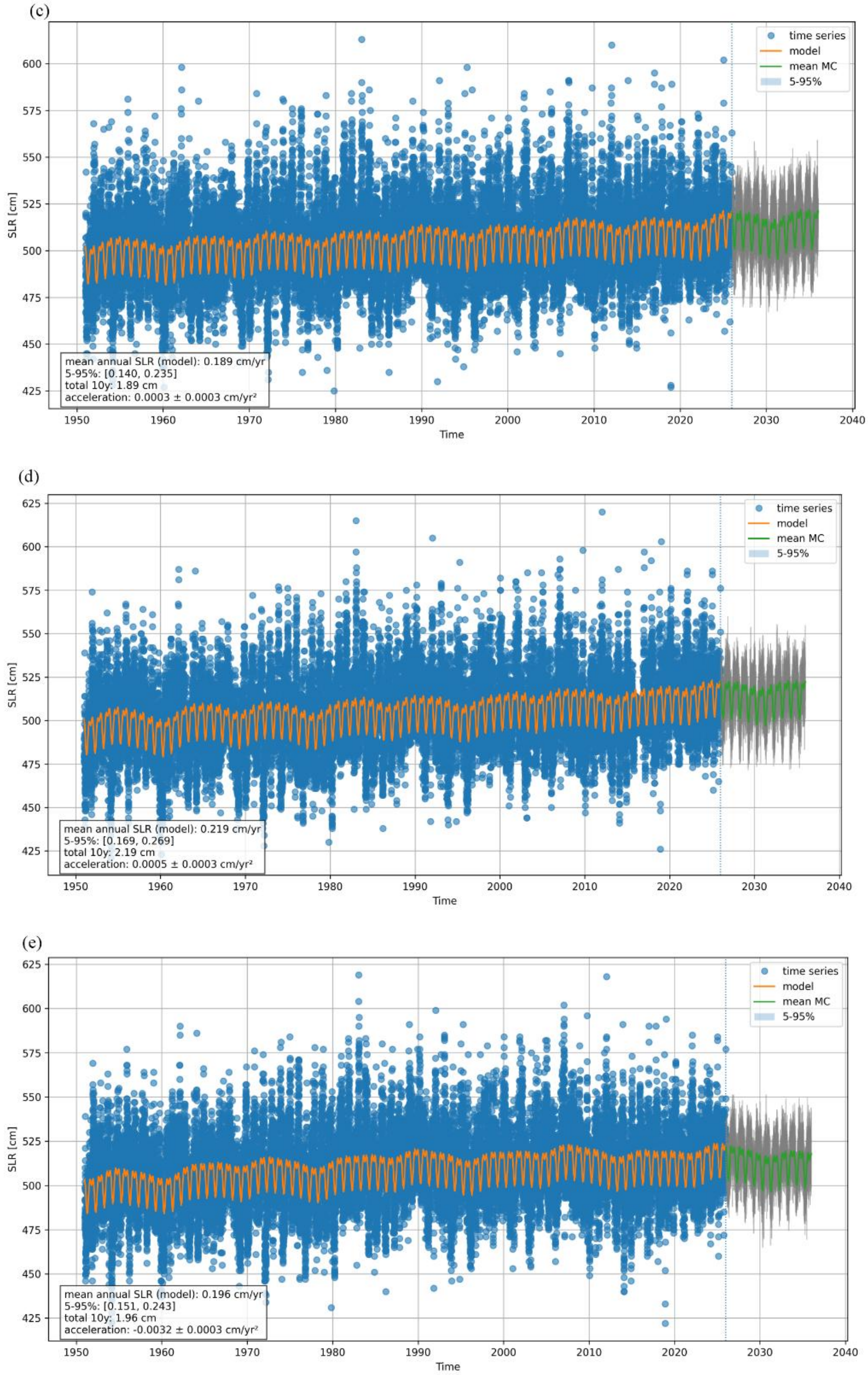
Preprint. Discussion started: 26 June 2026

extreme sea levels, both currently and in projected scenarios. This means an increasing frequency of events previously considered rare, as well as a growing risk of their consequences in the future.

5.4 Statistical Sea Level Rise Forecast

To estimate future sea level changes in the southern Baltic Sea, a probabilistic forecasting approach was used, which allows for both long-term trends and natural temporal variability (Fig.10). The analysis used a model combining a quadratic trend, a seasonal component and autocorrelation described by an AR(1) model.





390 **Figure 10: Projected sea level changes in the southern Baltic Sea obtained from a probabilistic model that accounts for long-term trends, seasonality, and AR(1) autocorrelation, along with forecast uncertainty intervals. Swinoujscie TG station (a) Kolobrzeg TG station (b), Ustka TG station (c), Wladyslawowo TG station (d), Gdansk TG station (e).**

The results indicate that there is a consistent, increasing trend in sea level rise in the analyzed area, with a rate of 1.8–2.2 mm/yr. This result remains stable within the estimation uncertainty and represents a dominant, long-term signal in the analyzed time series. At the same time, the estimated acceleration of sea level change presents significant spatial variability, taking on both positive and negative values (ranging from approximately −0.03 to +0.02 mm/yr²). An analysis of periodic components demonstrated a significant predominance of annual and semi-annual oscillations; additionally, an interannual signal with a period of approximately 4.4 years was identified. Oscillations of approximately 18.6-year and components of ~27–30 days are also present, which may be related to the nodal cycle, lunar modulation and short-term atmospheric variability. Forecasts indicate a further progressive rise in sea level at a rate consistent with the estimated trend; however, it should be emphasized that the results obtained are regional in nature. The results indicate a dominant, positive, and spatially consistent trend of sea level rise in the southern Baltic Sea during the analyzed period, highly modulated by multiscale periodic variability and short-term stochasticity. The model accurately captures the statistical characteristics of the time series and enables the generation of consistent probabilistic forecasts. However, some of the long-term components and the estimated acceleration are difficult to interpret and are sensitive to the method of time series decomposition.

6 Discussion

The results of the study identify the dominance of seasonal components and their variability over time. Changes in the amplitude of multi-year oscillations indicate a change in the dynamics of the ocean–atmosphere system and a change in the contribution of processes affecting sea level. Trends determined by using satellite and tide gauge observations indicate a significant impact of local coastal processes and vertical movements of the Earth's crust associated with GIA (Glacial Isostatic Adjustment) on the observed differences in trends. This suggests that both regional hydrodynamic conditions and geodynamic processes must be considered in further analysis of sea level variability. The study presented that the most significant components are related to annual, semi-annual, and interannual (~4.4-year) oscillations. The model also identified short-term oscillations related to lunar modulation, tidal processes, and short-term atmospheric variability. However, in contrast to low-frequency components, high-frequency components do not demonstrate significant trends or changes in amplitude. This is consistent with the understanding of the Baltic Sea as a micro-tidal basin, where the astronomical signal is highly suppressed by the dominance of meteorological processes (Hünicke and Zorita, 2008). The results indicate that the ~4.4-year interannual oscillation is statistically most significant. The high spatial coherence of this signal suggests a association with climatic processes, rather than with local hydrodynamic effects alone. In the context of sea level extremes, the application of the Gumbel distribution allows for the assessment of changes in the risk of extreme events. The analysis of extremes confirms that even a slight increase in mean sea level can significantly increase hydrological risk and hazards to coastal infrastructure. The use of an AR(1) model in the analysis of residuals allowed for the significant temporal autocorrelation characteristic of sea level processes to be accounted. The introduction of an autoregressive structure improved the representation of short-term variability and increased the reliability of parameter estimates and their

https://doi.org/10.5194/egusphere-2026-3383
Preprint. Discussion started: 26 June 2026

uncertainties. Monte Carlo simulations indicate that, assuming the current statistical structure of the system remains intact, further sea level rise is expected in the coming decades. At the same time, the projections are conditional and assume the stationarity of model parameters. This means that the simulations do not account for potential climate changes or future changes in atmospheric dynamics, which may lead to random fluctuations in sea level. The probabilistic approach used in this study is consistent with the recommendations of contemporary climate research, which emphasizes the need to use probabilistic methods rather than deterministic point forecasts (Intergovernmental Panel On Climate Change (IPCC), 2023). The results indicate that sea level variability in the southern Baltic Sea cannot be described using only a linear upward trend. The system is characterized by a clearly multi-scale and non-stationary dynamics, in which processes related to regional atmospheric circulation dominate. An innovative aspect of this study is the multi-approach to sea level analysis in the southern Baltic Sea, combining trend analysis, cyclical variability, and stochastic components. The application of harmonic analysis, the continuous wavelet transform (CWT), and the AR(1) model with uncertainty propagation using the Monte Carlo method allowed for a transition from classical deterministic analysis to a probabilistic approach. An additional innovation is the use of extensive daily time series (1951–2025), which enabled the analysis of processes across a range of timescales—from short-term oscillations to multi-year trends. The study also introduced a probabilistic sea level forecast and an analysis of extremes using the Gumbel distribution and bootstrapping, which allowed for the simultaneous assessment of trends, variability, and the risk of extreme events under climate change conditions. The results of this study have significant practical implications, as they provide a better assessment of long-term sea-level changes and the associated risks of hydrological extremes in the southern Baltic Sea. The probabilistic forecasts obtained can be used in coastal protection planning, the design of hydrotechnical infrastructure, and in storm surges risk analyses. Additionally, the approach used allows for a more reliable consideration of climate and stochastic variability, which can support adaptation decision-making in the context of climate change and long-term coastal zone management.

7 Conclusions

The study of multiscale sea-level variability in the southern Baltic Sea provided a comprehensive assessment of short-term fluctuations and their climatic and hydrodynamic determinants. The application of statistical and spectral methods allowed for the identification of significant patterns in the signal structure. The results obtained indicate the complex nature of sea level changes, resulting from the simultaneous interaction of atmospheric and oceanic processes as well as local factors, which forms the basis for the following conclusions.

The study identified a positive trend in sea level in the southern Baltic Sea, consistent with regional and global observations and indicative of ongoing climate change. Sea level variability is highly modulated by atmospheric circulation, particularly the NAO index, confirming the significant impact of atmospheric forcing on the hydrodynamic conditions of the Baltic Sea. Seasonal and interannual components dominate, with the ~4.4-year oscillation providing the most statistically significant low-frequency signal, associated with climate processes on regional and hemispheric scales. A nonlinear evolution of the amplitude of periodic components was observed (an increase in amplitude with negative acceleration), indicating a reorganization of the ocean–atmosphere system dynamics and a possible transition to a new balance condition. CWT analysis confirmed the significant non-stationarity of the sea level signal, particularly in the low-frequency range, indicating variability in the system's energy structure over time.

Satellite and tide gauge data are consistent in terms of major variability trends, although differences in trends result, among other factors, from local effects and vertical movements of the Earth's crust. The highest consistency is observed in high-frequency components (periods of ~27–30 days), which demonstrate no significant trends or changes in amplitude. The AR(1) model and Monte Carlo simulations confirm significant autocorrelation and the probabilistic character of sea level changes, and indicate a further rise in sea level in the future, assuming the current system structure remains intact. Extreme value analysis (Gumbel) indicates that a rise in mean sea level results in a non-linear increase in the risk of storm surges, even without a change in the intensity of weather events. The results confirm the hypothesis that climate change affects not only the mean trend of sea levels but also the dynamics of periodic cycles and the character and frequency of extreme events. Sea level variability in the southern Baltic Sea is multiscale, non-stationary, and nonlinear, and the observed changes include simultaneous increases in mean sea level, a reorganization of cyclical dynamics, and an increase in the risk of hydrological extremes.

Code and data availability

Daily sea level anomalies were provided by the Copernicus Marine Environment Monitoring Service (https://data.marine.copernicus.eu/products)— accessed on 6 February 2026.

GEBCO_2025 model was provided by the General Bathymetric Chart of the Oceans (https://www.gebco.net/data_and_products/gridded_bathymetry_data/) —accessed on 7 February 2026.

Tide gauge time series was provided by the Institute of Meteorology and Water Management – National Research Institute (IMGW-PIB)—accessed on 9 February 2026.

Author contributions

Conceptualization, K.P.; methodology, K.P. and M.I.; software, K.P. and M.I.; validation, K.K.; formal analysis, K.P. and M.I.; investigation, K.P.; resources, K.P. and M.I.; data curation, K.P. and M.I.; writing—original draft preparation, K.P. and M.I.; writing—review and editing, K.K.; visualization, K.P. and M.I.; supervision, K.K. All authors have read and agreed to the published version of the manuscript.

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