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Temporal Analysis of Mean Sea Level and Characterization of Extreme Climate Events in Guanabara Bay, Rio de Janeiro (1989–2021)

Análise Temporal do Nível Médio do Mar e Caracterização dos Eventos Extremos na Baía de Guanabara – Rio de Janeiro (1989–2021)

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Abstract: Coastal management aimed at mitigating the effects of sea level rise and extreme events has become an increasing concern. This requires strategies based on risk assessments, vulnerabilities, and impacts associated with various climate scenarios. In this context, the present study aims to evaluate changes in mean sea level and characterize the occurrence of extreme events in the Guanabara Bay. The focus is on the seasonality and evolution of the time series recorded by the tide gauge at Ponta da Armação in Niterói, RJ, from 1989 to 2021. The study estimates the rate of sea level rise, the frequency of extreme events exceeding ±2 and ±3 standard deviations, and the evolution of harmonic components (amplitude and phase) over both annual and 19-year periods. The average rate of sea level rise was determined to be 2.66 ±0.45 mm/year. Residuals were crucial in identifying anomalies and distinguishing extreme over-elevation events, which predominantly occurred in the autumn (54.62%) and the winter (34.63%). The most intense events, exceeding ±3 standard deviations, displayed strong seasonality, with positive peaks in the autumn (66.20%) and negative peaks in the winter (44.33%). The analysis of harmonic components revealed positive trends in the amplitudes of the annual series for M2 and S2, alongside variations in the phases of M4, N2, and Q1. These results suggest significant changes in the dynamics of sea level variations in the region over the studied period.
Keywords: Sea level. Extreme events. Tide gauge. Seasonality. Guanabara Bay.

Resumo: O gerenciamento costeiro voltado à mitigação dos impactos do aumento do nível do mar e da ocorrência de eventos extremos tem se tornado uma preocupação crescente, exigindo estratégias baseadas na análise de riscos, vulnerabilidades e impactos associados a diferentes cenários climáticos. Neste contexto, o presente estudo tem como objetivo avaliar a variação do nível médio do mar e caracterizar a ocorrência de eventos extremos na Baía de Guanabara, com foco na sazonalidade e evolução da série temporal registrada pelo marégrafo de Ponta da Armação, em Niterói-RJ, entre 1989 e 2021. Foram estimadas a taxa de elevação do nível do mar, a frequência de eventos extremos excedentes a ±2 e ±3 desvios padrão e a evolução das componentes harmônicas (amplitude e fase) para períodos anuais e de 19 anos. A taxa média de elevação do nível do mar foi estimada em 2,66 ±0,45 mm/ano. Os resíduos foram essenciais na identificação de anomalias e na distinção de eventos extremos de sobre-elevação, que ocorreram majoritariamente no outono (54,62%) e inverno (34,63%). Os eventos mais intensos, excedentes a ±3 desvios padrão, apresentaram forte sazonalidade, com picos positivos no outono (66,20%) e negativos no inverno (44,33%). As análises das componentes harmônicas evidenciaram tendências positivas nas amplitudes das séries anuais para M2 e S2 e variações nas fases de M4, N2 e Q1. Esses resultados sugerem alterações significativas na dinâmica das variações do nível do mar na região ao longo do período estudado.
Palavras-chave: Nível do mar. Eventos extremos. Marégrafo. Sazonalidade. Baía de Guanabara.

1 INTRODUCTION

The monitoring, management, and conservation of the coastline and coastal zone have become issues of increasing concern in Brazil in recent years. In response to these challenges, the Federal Government launched the National Coastal Conservation Program (Procosta), established by Ordinance No. 76 on March 26, 2018 (BRASIL, 2018). This program aims to enhance coastal management through long-term strategic actions, considering risk analysis, vulnerabilities, and impacts associated with climate change in current and future scenarios (MMA, 2018).

The Brazilian coastal zone encompasses four major regions of the country, including 17 coastal states and 274 municipalities, where approximately 26.6% of the Brazilian population resides (IBGE, 2011). This area corresponds to about 19% of the Brazilian urbanized areas (IBGE, 2022) and plays a fundamental role in the national economy, concentrating numerous economic activities responsible for 30% of the country's Gross Domestic Product (MMA, 2018). As a result, this region is subject to intense socioeconomic and environmental pressures.

In this context, the Guanabara Bay stands out as an estuarine environment influenced by tidal regimes and the discharge of various rivers originating in the Serra do Mar and Baixada Fluminense. The bay covers an area of 348 km², making it the second-largest bay on the Brazilian coast. Its area of influence includes 11 municipalities entirely and 7 partially, located within the second-largest urban agglomeration in Brazil. This region is home to over 70% of the population of the state of Rio de Janeiro and most large-scale industries, totaling a population of more than 11 million inhabitants (Rangel & Oliveira, 2021). Additionally, according to the National Waterway Transportation Agency (ANTAQ, 2025), the bay houses twenty port facilities, which are susceptible to the impacts of sea level variations.

The rise in sea level and its impacts on coastal zones are fundamental indicators of climate change over medium and long timescales (Vang & Andersen, 2021). Recent studies indicate that the global average rate of sea level rise is 3.3 ± 0.3 mm/year, based on satellite altimetry time series collected since 1993 (Nerem et al., 2018; Cazenave & Moreira, 2022; Guérou et al., 2023; Hamlington et al., 2024).

The current climate change scenario demands transformative actions by governments to mitigate impacts and avoid catastrophic scenarios. The increase in global temperature, coupled with other factors, has directly contributed to changes in coastal dynamics, especially considering projections indicating a sea level rise of between 0.6 and 1.1 meters by 2100, according to the AR6_WGIII report of the IPCC (2022). Furthermore, meteorological factors, combined with rising sea levels, can significantly amplify impacts on wildlife and the economy in regions vulnerable to extreme events (Marone et al., 2017; Araújo et al., 2019).

Different mechanisms influence sea level variations, including wind friction on the ocean surface, atmospheric pressure variations, water density, and river discharges. These factors affect ocean circulation and the distribution of sea level across different spatial and temporal scales (Harari et al., 2021). The oscillations resulting from these forcings, combined with wave action, can amplify impacts on the coastal zone. Such variations, whether positive or negative (Pugh, 2014), can exacerbate socioeconomic damages in densely populated coastal areas (Lima et al., 2021). In practice, local and regional mean sea level variations can differ significantly from the global average, making some regions more prone to extreme events. An important example applied to Brazil can be seen in Daniel et al. (2025).

The study of tide gauge records allows identifying trends in sea level variations at regional and local scales. However, the scientific literature focused on analyzing this phenomenon along the Brazilian coast remains limited, particularly in the surroundings of the Guanabara Bay in the state of Rio de Janeiro. Some studies stand out in this context, such as that of Tecchio (2022), which provides important contributions on the meteorological aspects associated with sea level variations in the bay, and that of Santana (2022), which proposes a methodology for calculating the uncertainty of the chart datum, considering the influence of the period and timing of tide gauge measurements.

Concerning vulnerability, Marone et al. (2017) discuss coastal hazards and risks associated with extreme events in the marine environment, with direct impacts on the environment, science, and society. Regarding astronomical effects, Harari and Camargo (1995) analyzed a 46-year historical series of sea level at the Port of Santos-SP, aiming to characterize its variability and to identify potential changes in the region mean sea level. In addition, Harari et al. (2013) conducted a study on the recovery and analysis of tide gauge records at the ports of Belém-PA, Recife-PE, Santos-SP, and Cananéia-SP, on seasonal, annual, and decadal scales, enabling a comprehensive assessment of mean sea level variability and the main tidal components (M2 and S2). Finally, IBGE (2021) presents an analysis of mean sea level variation and its relative trend for the seven

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locations monitored by the Permanent Tide Gauge Network for Geodesy (*Rede Maregráfica Perpamente para Geodésia* -RMPG).

The present study therefore aims to analyze mean sea level variations and to characterize the occurrence of extreme events, focusing on seasonal oscillations and the evolution of the relative sea level time series recorded by the Ponta da Armação tide gauge in Niterói-RJ, from 1989 to 2021.

2 METHOD

2.1 Datasets and computational tools

The sea level data used in this study were provided by the Brazilian National Oceanographic Data Bank (*Banco Nacional de Dados Oceanográficos* – BNDO) through a request made via the following website: https://www.marinha.mil.br/chm/dados-do-bndo/outros-dados-e-produtos. The time series were obtained from measurements taken by a tide gauge operated by the Navy Hydrographic Center (*Centro de Hidrgrafia da Marinha* - CHM), located at the Ponta da Armação Naval Complex (22°52'59.31"S; 43°08'05.02"W, SIRGAS 2000), in the municipality of Niterói, Rio de Janeiro. The observations have temporal resolutions ranging from 5 to 60 minutes, covering the period from November 1988 to September 2022.

The observations used have temporal resolutions ranging from 5 to 60 minutes and cover the period from November 1988 to September 2022. For the analyses in this study, only the subset from 1989 to 2021, corresponding to complete years, was considered. However, observations outside this interval are incorporated into the processing, as they assist in the application of the 168-hour filter.

The tide gauge station is equipped with two sea level sensors: one of the stilling well type and the other of the radar type. Additionally, the station includes a standard Hidromec tide staff, made of aluminum, 4.0 meters long, graduated every 2 cm, and fixed to the dock near the station shelter. The monitoring is complemented by a set of Benchmarks associated with the Brazilian Geodetic System (e.g IBGE, 2021). The reference sheet for the chart datum used is F-41 50141, which was most recently updated in 2022, based on the observation period from February 8, 2018, to February 7, 2020, allowing for determining tidal elements (DHN, 2022).

The analysis of mean sea levels was conducted using the SLP64 software package (Caldwell, 2014), developed by the Joint Archive for Sea Level, a joint initiative between the University of Hawaii Sea Level Center (UHSLC) and the US National Oceanographic Data Center (US NODC). The inputs and outputs of SLP64 were generated using the CRITNM and SLPLAC software (Luz, 2008). Additionally, specific scripts developed in the Matlab environment, based on the work of Harari (2021), were adapted to the needs of this study. Furthermore, the Harmonic Prediction and Tide Analysis software - PACMARÉ (Franco, 2009) was used for complementary analyses.

2.2 Determination of local mean sea level variation

To ensure the standardization of data from the BNDO, an initial data cleaning step was performed. A detailed analysis of the data and metadata revealed the presence of discontinuities in the time series, variations in data collection platforms, differences in temporal resolution, and the use of different sensors over the analyzed period. Given these inconsistencies, procedures were implemented to harmonize the data.

Initially, a preliminary critique of the observations was applied, followed by the filtering of daily sea level data for each dataset using the CRITNM software (Luz, 2008). Observations recorded at 5-minute intervals were reformatted into annual hourly series using the double application of a 13-point moving average, considering previous and subsequent values, followed by cubic spline filtering. This procedure allowed identifying gaps in the time series and discrepant observations, such as heights recorded as zero and outliers. Gaps shorter than 3 hours were filled by cubic spline interpolation, based on 20 filtered observations before and after the missing data.

In the next step, quality control of the observations was performed. Harmonic components were generated with reference to 2009. That year was adopted as a reference because it is common to the three main subdivisions of the analyzed time series, as illustrated in Figure 1. From these components, astronomical predictions were generated for the entire period of the series (1988 to 2022). Subsequently, residuals were calculated, defined as the differences between predicted values and recorded observations. This analysis was conducted using the SLP64 software (Caldwell, 2014).

After organizing the predictions and observations, the information was concatenated into two files, covering the entire period of the time series. These files served as input for the SLPLAC software (Luz, 2008), used for filtering the high-frequency components of sea level. A 168-hour filter was applied, following the methodology proposed by Pugh (1987), resulting in filtered hourly averages, which were subsequently used to calculate monthly mean sea levels through the simple average of all valid values within the analyzed period.

To ensure the standardization of the results, the time series were aligned to a single reference, considering that they originally presented vertical misalignments. This procedure allowed for consistently calculating monthly and annual averages, the complete series, and the trend. During this step, discrepancies in specific segments of the series were identified, characterized by "jumps" resulting from sensor replacements over time. These discontinuities were analyzed and corrected, ensuring data homogeneity. The identification and treatment of these inconsistencies followed the methodological guidelines established by IBGE (2021). As a result, a consolidated time series was obtained, containing monthly and annual averages and the associated residuals.

For estimating the trend, simple linear regression was used, as recommended by Zervas (2001; 2009), where X_i and Y_i represent the month and the corresponding monthly mean sea level, respectively, after subtracting their respective means. In Eq. (1), the slope of the line, represented by b, provides the inclination of the linear regression line, indicating the trend of the series. Its standard error (S_b) is found using Eq. (2).

$$b = \frac{\sum_i X_i Y_i}{\sum_i X_i^2} \tag{1}$$

$$S_b = \frac{S_{xy}}{\sqrt{\sum_i X_i^2}} \tag{2}$$

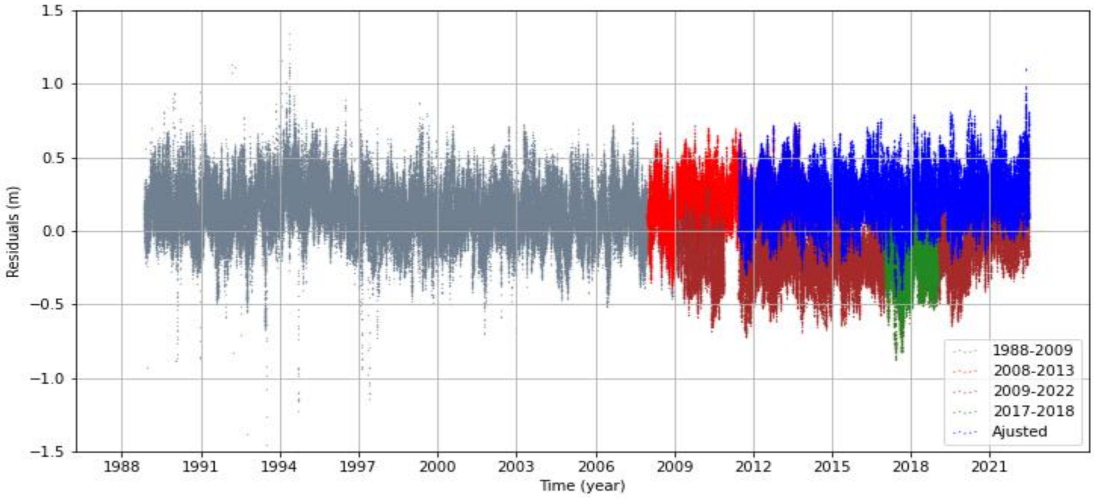
It is necessary to clarify that S_{xy} in Eq. (2) corresponds to the standard error of the regression, i.e., the standard deviation of the regression line. Meanwhile, n refers to the total number of months observed in the series. Eq. (3) provides the formulation for S_{xy}.

$$S_{xy} = \sqrt{\frac{\sum_i Y_i^2 - b(\sum_i X_i Y_i)}{n-2}} \tag{3}$$

The calculation of the mean sea level in this study did not include the correction for geodynamic effects, as the Ponta da Armação tide gauge in Niterói-RJ does not have an associated continuous Global Navigation Satellite System (GNSS) station. The nearest GNSS station, RJNI (code SAT 96361), is located approximately 3 km away and was only installed in 2019.

The absence of a GNSS station collocated with the tide gauge limits the possibility of monitoring local crustal movements, which would allow for distinguishing oceanic effects from geodynamic effects. Therefore, the mean sea level variations determined in this study should be interpreted as relative values, as they were not corrected for potential vertical displacements of the Earth's crust in the region.

Figure 1 – Composition of the series for jump correction. Series from 1988 to 2009 in the position of the stilling well sensor and platform 256 (gray); series from 2008 to 2013 in the position of the radar sensor and platform 400 (red); series from 2009 to 2022 in the position of the radar sensor and platform 415 (brown); series from 2017 to 2018 in the position of the stilling well sensor and platform 257 (green); and series from 2011 to 2021 with applied correction adjustments (blue).



Source: The Authors (2025).

2.3 Quantification of extreme events

From the filtered series of hourly sea level elevation values, the quantification of upper and lower events, i.e., ± 2 standard deviations (SD) and ± 3 standard deviations, was performed. The analysis periods were segmented according to the seasons of the year (Southern Hemisphere), as follows:

a) Summer – December, January, and February (DJF);
b) Autumn – March, April, and May (MAM);
c) Winter – June, July, and August (JJA);
d) Spring – September, October, and November (SON).

The segmentation of the periods according to the seasons of the year was adopted to enable a more detailed analysis of the seasonal variability of sea level and the occurrence of extreme events. This approach allows for the identification of specific patterns and behaviors associated with the different climatic conditions that characterize each season, making the interpretation of the results more accurate.

For the entire observation series, a reference standard deviation of 0.15 m was adopted. This value was determined based on the filtered sea level elevation data from the complete sample.

The detection of exceedance events was conducted by considering the occurrence of hourly values that surpassed the reference standard deviation, regardless of the duration of the event over several days. This criterion allowed for a precise and objective analysis of the magnitude of the highlighted events relative to the normal variability of the observations. It is worth noting that, in the count of ± 2 SD events, ± 3 SD events are also included, aiming to improve the characterization of higher-intensity events.

For the evaluation of the seasonality of mean sea level, the series was segmented into two approaches:

(i) Calculation of monthly mean sea levels and their respective standard deviations; (ii) Determination of annual seasonal mean sea levels, their trends, and respective standard deviations.

Additionally, the minimum, mean, and maximum values of these averages were established for a more detailed understanding of seasonal variability.

2.4 Trend of harmonic components

The analysis of the evolution of harmonic components, considering amplitude and phase, was performed based on sea level time series with periods of one year and 19 years. The 19-year period corresponds to a complete lunar cycle, equivalent to 18.69 years (Torge & Müller, 2012). For the annual series, a period of 365 days was considered, totaling 33 periods. For the 19-year series, the initial reference was the year 1989, incremented by 18 years, resulting in a sequence of series covering the periods 1989–2007, 1990–2009, ..., 2002–2020, and 2003–2021, totaling 15 periods.

For determining the harmonic components of the annual series, the TIDEANL module of SLP64 was used. This procedure allowed generating 68 most significant components, which were also employed in prediction calculations.

In the case of the 19-year series, the extraction of harmonic components was performed using the PACMARÉ software, LONGSERIE module (Franco, 2009), with a 95% rejection probability for small components. In total, approximately 1014 components were generated for each analyzed period. However, this research focuses on the analysis of the eight main harmonic components: O1, K1, K2, M2, S2, M4, N2, and Q1.

3 RESULTS AND DISCUSSION

3.1 Determination of local sea level trend

The detection of discontinuities ("jumps") in the time series enabled the harmonization of the data into a single, consolidated reference frame. The most significant jumps were identified in February 2012 (0.428 m) and March 2020 (0.259 m). Additionally, to address the data gap from the radar sensor (platform 415), it was necessary to relocate the observations recorded between October 2017 and January 2018, originally collected by the stilling well sensor on platform 257, to the reference of the stilling well sensor on platform 256, ensuring the continuity and coherence of the time series.

After applying the corrections, the analysis of the residuals plot (Figure 2) indicated that the time series is positioned in the 2009 reference frame. However, more detailed corrections were not possible, as the BNDO does not provide information on geodetic control or Van de Casteele tests. These tests involve comparing sensor readings with tide staff measurements every 15 minutes during a complete tidal cycle (Miguez et al., 2008). Thus, the analysis developed in this study may present distortions associated with the replacement or movement of sensors over time. A more precise verification of these inconsistencies could be achieved by comparing the tide gauge time series with satellite altimetry data (Giehl, 2020). However, this approach is beyond the scope of this study.

The analysis of the residuals also allowed identifying deviations in observations from the astronomical standard, highlighting the influence of meteorological forcings on the ocean. As shown in Figure 2, the widest variations occurred during specific periods, notably between 1989 and 1998 and in the year 2022. However, overall, the series exhibited homogeneous behavior, with low presence of noise.

The mean sea level, calculated from monthly averages, was estimated at 2.28 m ± 0.07 m for the period from January 1989 to September 2022. However, it was not possible to link this value to a Benchmark of the Brazilian Geodetic System, due to the lack of information on the relationship between the radar sensor and the primary Benchmark, as well as the unavailability of the Van de Casteele test. Note that such corrections can be made as described in IBGE (2021, p. 32).

Figure 3 presents the series of monthly mean sea levels, reduced to the zero reference, along with the trend line over the analyzed period. The estimated trend for the series (1989-2021) was 2.66 ± 0.45 mm/year , a value consistent with trends observed in studies based on satellite altimetry series (Nerem et al., 2018).

However, when comparing this result with the tide gauge series from Macaé-RJ, which shows a sea level rise rate of 4.9 ± 1.2 mm/year for the period 2001–2015 (IBGE, 2021), the trend estimated in this study is observed to be almost twice as low. This discrepancy may be related to differences in the analyzed periods, the geographic location of the stations, and the methodological particularities of each dataset. Additionally, regional variations in sea level can be influenced by local oceanographic and geodynamic processes, such as subsidence or uplift of the Earth's crust, as well as atmospheric and hydrodynamic effects.

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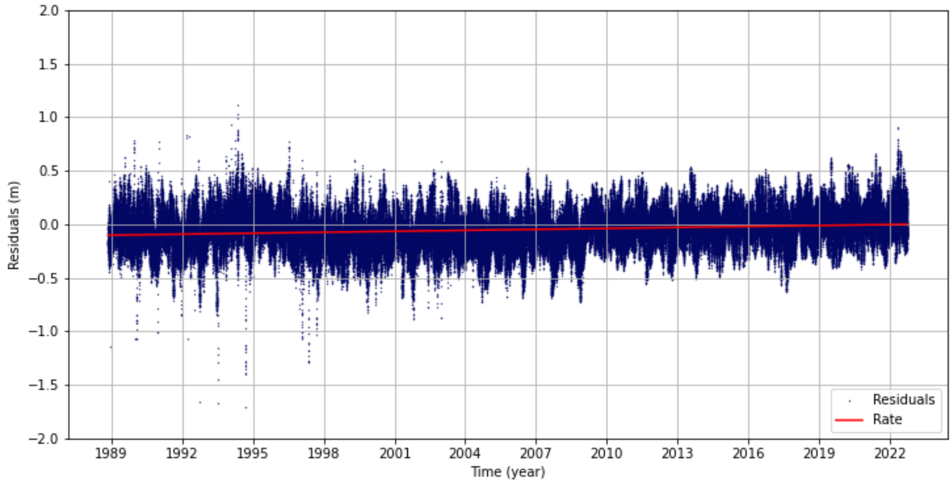
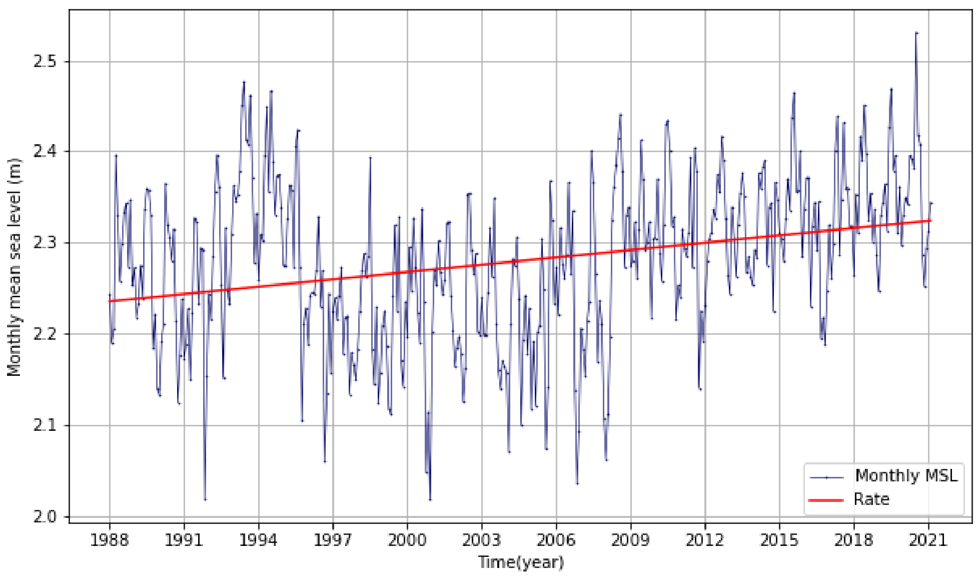
Figure 2 – Homogeneous residuals of the time series in the reference frame of the year 2009.



Source: The Authors (2025).

Figure 3 – Monthly mean sea levels and trend line.



Source: The Authors (2025).

The estimated values for the trend of mean sea level are sensitive to the period considered in the analysis, as short-term oscillations can introduce artificial trends in the time series. In this regard, Zervas (2009) highlights the influence of interannual variability, indicating that periods with a predominance of negative residuals reflect anomalous oceanic conditions. According to the author, these anomalies can be caused by variations in water temperature, salinity, winds, atmospheric pressure, currents, or river discharge.

To investigate this issue, tests were conducted considering different time intervals to assess the variability in trend estimation. The results demonstrate that the configuration of the observation set can result in different trend values, depending on the analyzed period. Thus, when inferring a trend for a specific location, it becomes essential to correlate the data with other sources or measurement platforms. Additionally, as previously mentioned, trend estimates should not be considered absolute, as they may be influenced by non-oceanic processes, such as vertical crustal movements, including uplift and subsidence.

Table 1 presents the results of the tests conducted, highlighting the variation in trend estimation based on the observation set used. Between 2000–2021 and 2000–2022, a sharp increase in the trend is observed. However, when compared to the complete series (1989–2022), this increase is not as evident, suggesting a smoothing of values at the extremes of the series. The analysis of the period from 2009 to 2022 reveals a trend consistent with the complete series, albeit still influenced by the decline recorded between 2000 and 2009 (Figure 3).

Additional factors, such as small fictitious variations or more intense meteorological signals over time, can also significantly impact this estimation. Therefore, it is essential that institutions responsible for tide gauge data document the interferences experienced by sensors over time, ensuring quality control as recommended by the IOC (2020). Another important measure is the availability of consolidated series, properly cleaned and controlled. Thus, the importance of complementary investigations using alternative series, such as those derived from satellite altimetry, is reinforced to enhance the interpretation of observed trends.

Table 1 – Tests of trend calculations according to the considered period.

Period (year)	Number of Observations (months)	Mean Sea Level (m)	Trend (mm/year)
1989 - 2022	405	2.28 ±0.07	3.01 ±0.43
1989 - 2021	396	2.28 ±0.07	2.66 ±0.45
2000 - 2022	262	2.29 ±0.07	7.89 ±0.67
2000 - 2021	253	2.28 ±0.07	7.67 ± 0.39
2009 - 2022	165	2.33 ±0.05	4.45 ± 1.22
2009 - 2021	156	2.33 ±0.05	3.28 ± 1.35

Source: The Authors (2025).

3.2 Analysis and quantification of extreme events

The quantification of exceedance events by season is detailed in Table 2, while Figure 4 presents the thresholds and values that exceed the standards in the time series between 1989 and 2021. The analysis of these data allows identifying significant seasonal patterns in sea level variation, highlighting periods more prone to extreme events.

Table 2 evidences that autumn concentrates most of the sea level rise events, representing 54.62% of the total, followed by winter, with 34.63%. Additionally, these episodes occurred predominantly between 2018 and 2021, suggesting a recent intensification of these phenomena. In contrast, sea level lowering events are predominant in winter (49.09%), followed by spring (34.08%), with the most extreme events occurring between 1990 and 1995.

When refining the analysis and considering only events that exceed ±3 SD, the contrast between the seasons becomes even more evident: 66.20% of extreme elevations occurred in autumn, while 44.33% of intense lowerings were recorded in winter. Both cases reflect meteorological tide events exceeding ±0.45 m, demonstrating the significant impact of atmospheric forcings during these periods.

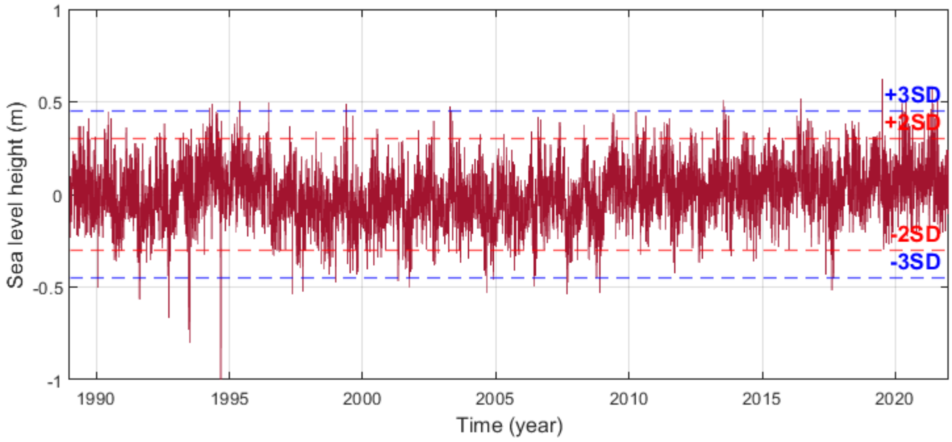
Summer, on the other hand, showed a low incidence of extreme events, with only 7.38% of elevations and 5.85% of lowerings for ±2 SD. In the more rigorous analysis, considering ±3 SD, no elevation events were recorded, while lowering cases represented only 5.22%. This result reinforces the trend of lower sea level variability in this season, possibly due to the lower frequency of intense meteorological systems during this period.

Table 2 – Quantification of exceedance events of ±2 SD and ±3 SD.

Exceedance	Quantity by Season				Total
	Spring	Summer	Autumn	Winter	
Above +2SD	233	510	3773	2392	6908
Below – 2SD	2462	423	793	3547	7225
Above +3SD	0	0	378	193	571
Below -3SD	289	47	165	399	900

Source: The Authors (2025).

Figure 4 – Exceedance of ±2 standard deviations (red line) and ±3 standard deviations (blue line).



Source: The Authors (2025).

The analysis of meteorological tide exceedance events can be visualized through histograms, allowing for the identification of both the frequency and magnitude of extreme values in each season. Figure 5, which presents the values for ±2 SD and ±3 SD, highlights the predominance of meteorological tide events below -0.30 m during spring and winter. In contrast, elevations above +0.30 m occur mainly in autumn. These results are corroborated by the study of Tecchio et al. (2024), who analyzed the time series of Ilha Fiscal, located in the Guanabara Bay, Rio de Janeiro-RJ, and found a similar distribution of these events, reinforcing the need for closer monitoring of these oscillations within the bay.

Additionally, it is essential to highlight events that exceed ±3 SD, as they represent the most pronounced variations in the historical series. A significant number of lowering events below -0.45 m are observed in spring and winter, while elevations above +0.45 m are more frequent in autumn.

The impacts of these elevations in autumn are particularly relevant for the Niterói shoreline, where episodes of sea level rise have caused significant damage. The comparison between the bad weather warnings from the Directorate of Hydrography and Navigation (DHN, 2022) and the record of extreme events in the last decade confirms the recurrence of these phenomena. Notable examples include the storms between April and June of 2011, 2016, and 2021, which caused the destruction of coastal infrastructure, flooding, and urban disruptions.

The highest sea level elevations in the region are associated with the presence of a low-pressure center over the ocean and a high-pressure center over the continent, typically characterized by a post-frontal high. This configuration, combined with an extensive wind fetch, which can extend from the Uruguayan coast to the southeastern Brazilian coast, and the action of winds parallel to the coast, favors the occurrence of extreme elevations of meteorological tide in the Guanabara Bay (Tecchio et al, 2024).

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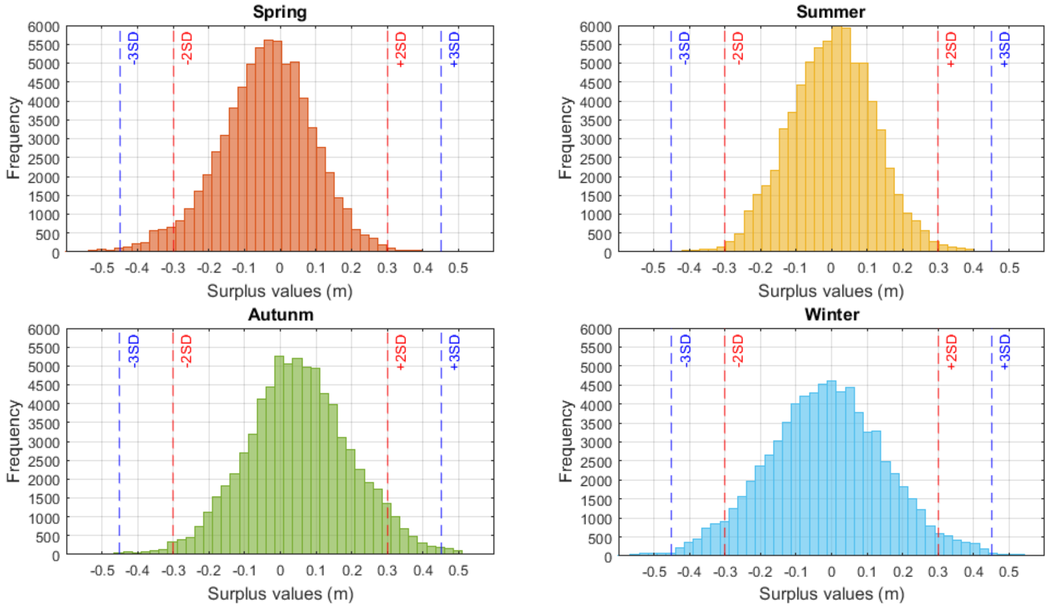
Figure 5 – Histogram of exceedance beyond ±2 SD (red line) and ±3 SD (blue line).



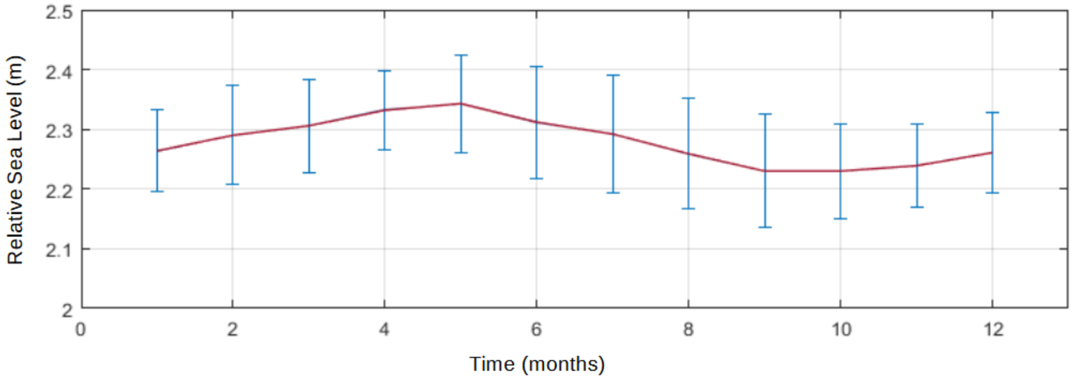
Source: The Authors (2025).

The results of the monthly mean sea levels and their respective standard deviations, presented in Figure 6, indicate a well-defined annual cycle. The months from March to June, corresponding to autumn, are observed to record the highest averages, while the months from August to November, predominantly in spring, show the lowest values. These seasonal variations are evidenced in the histogram for autumn, presented in Figure 5, where the mean value is centered around approximately 5 cm. Similarly, the histogram for spring indicates that the mean values are centered around approximately -5 cm, reinforcing the trend observed throughout the annual cycle.

The analysis of seasonality on a broader temporal scale, represented in Figure 7, reveals that, in addition to annual oscillations, there are periods of significant sea level rise and fall over the decades. In particular, the intervals from 1993 to 1996 and from 2019 to 2021 were characterized by more pronounced elevations, suggesting the influence of climatic and oceanographic phenomena during these periods. In contrast, significant reductions were recorded in the winter and autumn of 1997 to 1998, as well as in the spring and summer between 2007 and 2009, indicating the existence of long-term cyclical oscillations superimposed on the previously identified seasonal pattern.

Regarding trends, the data point to a consistent rise in mean sea level, with a positive rate of approximately 3 mm/year in all analyzed seasons. This homogeneous behavior suggests that, despite seasonal and interannual oscillations, there is a persistent trend of rising mean sea level over time.

Figure 6 – Monthly means and standard deviation of the series.



Source: The Authors (2025).

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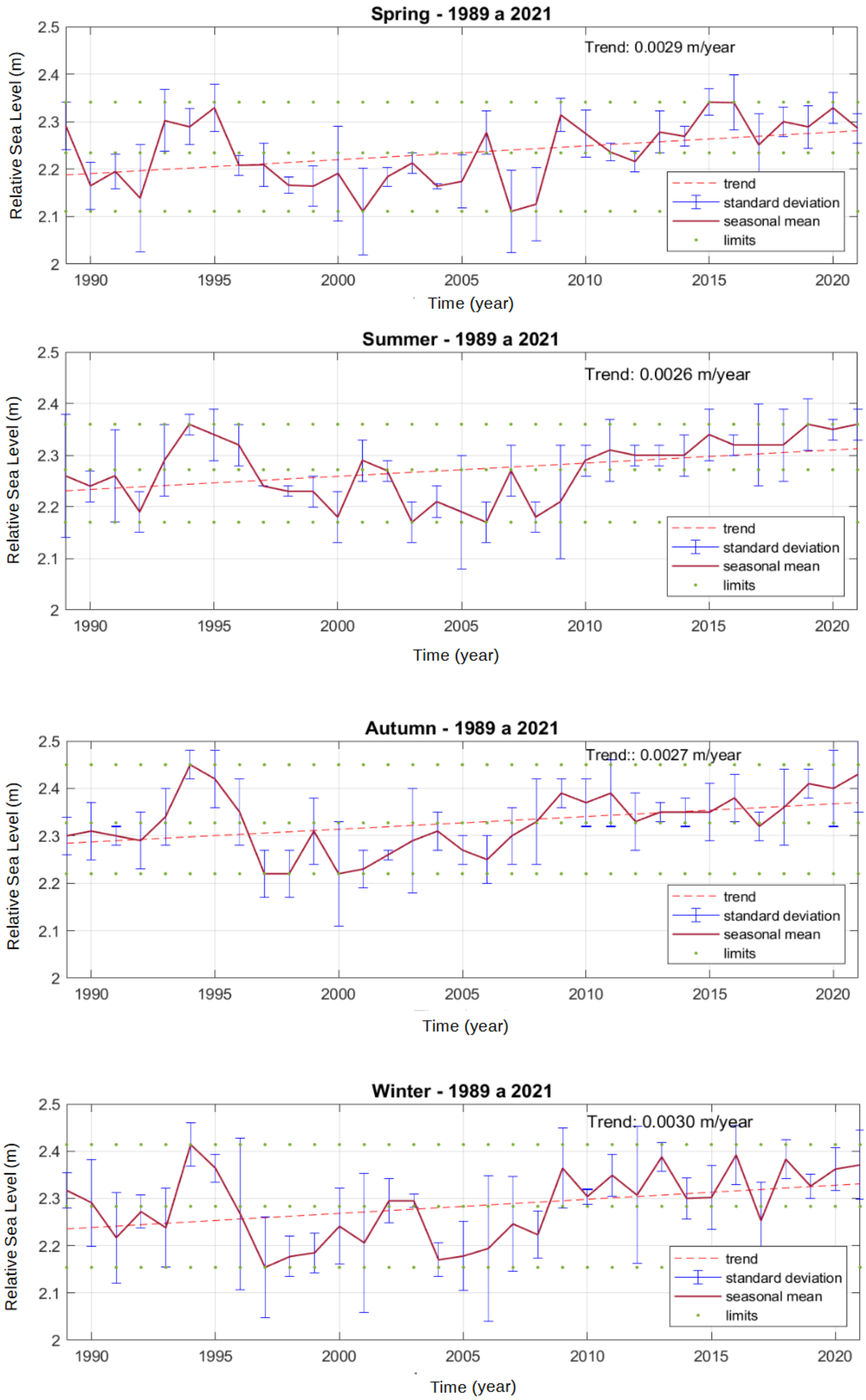
Figure 7 – Seasonal mean sea level for the spring, summer, autumn, and winter periods.



Source: The Authors (2025).

3.3 Harmonic analysis of the time series

Table 3 presents the evolutionary values of amplitude and phase for the constants O1, K1, K2, M2, S2, M4, N2, and Q1, considering both the annual series and the 19-year period series.

In the annual series, note that, except for the N2 component, all show a positive trend in amplitude, particularly M2 and S2, which exhibit the highest growth values. Regarding phase, only K2, N2, and Q1 show a positive trend.

In the 19-year series, the highest positive amplitude trend is identified in the M2 component (+0.090 cm/year), followed by S2 (+0.049 cm/year). Unlike the annual analysis, the 19-year series reveals, for the most part, amplitude trends slightly higher magnitudes. In the case of phase, more significant trends are also observed, albeit predominantly negative.

The comparison between the two series shows that the trend values for each component present little discrepancy. The highest amplitudes were observed in M2 and S2, with values of +0.050 cm/year and +0.042 cm/year in the annual series and +0.090 cm/year and +0.049 cm/year in the 19-year series. These results are consistent with those from Tecchio (2024) for the Ilha Fiscal site in Rio de Janeiro-RJ, reinforcing the consistency of the estimates. In turn, the phase showed more discrepant variations, mostly negative, with the highest value identified in the M4 component (-0.089 degrees/year for the annual series and -0.193 degrees/year for the 19-year series).

The differences observed in the series can be explained by factors such as dredging processes, common in ports, climatic events, and long-term meteorological effects, as pointed out by Harari and Camargo (1995). Additionally, Harari et al. (2013) emphasize that the M2 and S2 components should be analyzed over extensive time series, with resolutions spanning decades, to more accurately highlight trends in relative sea level along the Brazilian coast. These results underscore the importance of long-term analysis for understanding tidal variations and their impacts on the coastal environment.

Table 3 – Tests of trend calculations according to the period.

Component	Trend			
	Amplitude (H) (cm/year)		Phase (G) (degrees/year)	
	Annual	19 year	Annual	19 year
O1	0.015	0.022	-0.088	-0.032
K1	0.002	0.011	-0.013	-0.027
K2	0.012	0.004	0.006	0.029
M2	0.050	0.090	-0.050	-0.053
S2	0.042	0.049	-0.009	-0.038
M4	0.010	0.028	-0.089	-0.193
N2	-0.011	0.008	0.046	0.141
Q1	0.001	0.004	0.014	0.110

Source: The Authors (2025).

4 CONCLUSIONS

This study analyzed sea level variability in the Guanabara Bay, highlighting the presence of extreme events and trends over the time series. The use of the tide gauge located at Ponta da Armação (Niterói-RJ) as a reference allowed for a detailed evaluation of oceanographic data, revealing the need for stricter control and in-depth documentary analysis to ensure greater reliability in the results. Data quality, essential for correctly interpreting oceanic dynamics, depends directly on the calibration and correlation of the different components of the tide gauge.

Despite limitations in data control, the trend of rising mean sea level, estimated at 2.66 r ±0.45 mm/year , proved consistent with measurements obtained by satellite altimetry, as shown in previous studies, such as those by Nerem et al. (2018). This finding reinforces the relevance of the analyzed series for monitoring sea level changes, despite needing methodological improvements.

The investigation into residuals proved fundamental for identifying anomalies in the time series, allowing for a more precise distinction of extreme events. These residuals played an essential role in separating events that exceed the limits of ±2 and ±3 standard deviations, significantly contributing to the robustness of the investigation and improving data interpretation.

The analysis of extreme events indicated that sea level rise occurs predominantly in autumn (54.62%), with a second peak in winter (34.63%). Lowering events were more frequent in winter (49.09%) and spring (34.08%). The period between 2018 and 2021 showed a higher incidence of sea level rise, while the most intense events were recorded between 1990 and 1995. When analyzing the most severe events, exceeding ±3 standard deviations, a strong seasonality was evident, with positive peaks in autumn (66.20%) and negative peaks in winter (44.33%), with variations exceeding ±0.4 m. The results corroborate the conclusions of Campos et al. (2009), who relate the most significant sea level rise events to the action of low-pressure systems during specific periods, accompanied by intense southwest winds. This agreement reinforces the influence of atmospheric factors on sea level variability and highlights the importance of continuous monitoring for understanding the processes impacting coastal regions.

The examination of harmonic components revealed positive trends in the amplitudes of the annual series, particularly for the M2 and S2 components, as well as variations in the phases of the M4, N2, and Q1 components. These results indicated the existence of structural changes in local sea level oscillations over the analyzed period.

The inability to properly link sensor observations to the Brazilian Geodetic System represents a significant challenge for improving sea level analysis in the country. Therefore, it is recommended that the institutions responsible for sea level data collection perform the necessary controls, as established by the IBGE at their tide gauge stations.

It is therefore recommended that future research includes the application of the Van de Casteele test for series refinement, as well as correlation analyses with satellite altimetry data, as in Giehl et al. (2022). Comparison with the tide gauge series from Ilha Fiscal-RJ is also necessary for a more comprehensive understanding of variations in the Guanabara Bay. Additionally, the installation of a GNSS station near the Ponta da Armação tide gauge would be essential to distinguish the contributions of oceanic and crustal movements, to improve the monitoring of processes influencing sea level rise in the region.

Authors' Contributions

The author E.G.S.. contributed with Conceptualization, Data Curation, Formal Analysis, Research, Methodology, Validation, Visualization, and Writing –initial draft and in Writing –review and editing of the work. The author R.T.contributed to Conceptualization, Formal Analysis, Validation, and Writing –review and editing.

Conflicts of Interest

There is no conflict of interest.

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