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EXPLORING TIDAL CONSTITUENT TRENDS: UNVEILING THE IMPACT OF THE 18.6-YEAR LUNAR NODAL CYCLE THROUGH HARMONIC ANALYSIS AND LONG-TERM TIDE GAUGE RECORDS

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ABSTRACT: Understanding tidal constituent trends is becoming increasingly important in a world where climate change puts pressure on the tidal regime across the globe. Tidal constituents change constantly, but there is strong evidence that nodal modulation interferes with constituent amplitude values, thus hindering efforts to accurately measure their trends. Therefore, this paper proposes a practical approach to remove the influence of nodal modulation in constituent trend analysis. We collected multiple 18.6-year series of sea level data from tide gauges in Brest (France), Cananeia (Brazil), and Eastport (USA) and performed a harmonic analysis. Our main focus is to assess the interference of the nodal cycle on M2 tidal constituents. Although 19-year series are optimal to minimize this interference, they drastically reduce the number of data sets analyzed. To mitigate this problem, we employed a sliding window approach where each 19-year series starts one year after the previous one. The results of all three surveyed sites show that by employing this approach, the trends of the tidal constituents change significantly compared to what was previously seen with nodal interference. For instance, in Eastport, the analysis indicates that nodal modulation is partially responsible for the apparent reduction of the M2 amplitude tendency slope after 1980, a change that is softened when the effects of this modulation are removed. The reliability of the trends identified in this study suggests that this practical approach can also help future research predict the slope tendency of main tidal constituents.

Keywords: Tides; Nodal cycle; Harmonic analysis; Tidal Constituents; Tide gauge records.

RESUMO: *A compreensão das tendências das componentes de maré está se tornando uma pauta relevante, principalmente ao considerar que as mudanças climáticas podem afetar o comportamento das marés ao redor do mundo. As componentes de maré mudam constantemente, mas há fortes evidências de que a modulação nodal interfere nos valores de amplitude das componentes, dificultando assim os esforços para medir com precisão suas tendências. Portanto, o presente estudo propõe uma abordagem prática para remover a influência da modulação nodal na análise de tendências das componentes. Diversas séries de dados de nível do mar de longo período, ou seja, de 18.6 anos, foram coletadas de marégrafos em Brest (França), Cananéia (Brasil) e Eastport (EUA). Com base em tais dados, foram conduzidas diversas análises harmônicas. O principal foco deste estudo é avaliar a interferência do ciclo nodal nas componentes de maré M2. Embora as séries de 19 anos sejam ideais para minimizar essa interferência, elas reduzem drasticamente a quantidade de conjuntos de dados analisados. Para atenuar tal problema, foi empregada uma abordagem de janela móvel na qual cada série de 19 anos começa um ano após o início da série anterior. Os resultados dos três locais estudados mostram que, ao adotar essa abordagem, as tendências das componentes de maré mudam significativamente em comparação ao que foi visto anteriormente com a interferência nodal. Por exemplo, em Eastport, a análise indica que a modulação nodal é parcialmente responsável pela aparente redução da inclinação da tendência de amplitude da componente M2 após 1980, uma mudança que é suavizada quando os efeitos dessa modulação são removidos. A confiabilidade das tendências identificadas neste estudo sugere que essa abordagem prática também poderá ajudar pesquisas futuras na previsão de tendências das principais componentes de maré.*

Palavras-chave: *Marés; Ciclo nodal; Análise Harmônica; Componentes de Maré; Registros maregráficos.*

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1. INTRODUCTION

Global climate change has become one of the major global concerns of the 21st century because of the countless impacts it exerts on the environment. For instance, the change in sea level has been described as one of these major impacts (Nicholls, 2010) due to its far-reaching consequences. Presumably, the sea level rise (SLR) process is going to be accelerated throughout the 21st century (Meehl *et al*., 2007). Several studies show a trend toward a higher global relative SLR, which may pose a threat to coastal communities. Seaside areas host roughly 40% of the world's population and represent one of the most developed areas in the world (Vousdoukas *et al*., 2018).

Changes in the mean sea level (MSL) stand as the main factor in the evaluation of coastal vulnerability (IPCC, 2013). However, the natural variations in the sea level due to tidal phenomena combined with storm surges may cause extreme changes in sea level, leading to significant hazards to coastal zones, such as floods. Thus, according to Arns *et al*. (2017), the high tide period appears as the critical moment for coastal flooding, creating a demand to consider changes at both mean sea level and tidal range.

One of the traditional calculation methods for tidal variation is the classical harmonic analysis (HA), which divides the tide into several sinusoidal constituents. Each harmonic constituent, which is also called a harmonic constant, comprises a fixed frequency, usually associated with astronomical cycles, as well as a variable phase lag and a variable amplitude, depending on location (Godin, 1972). These constituents are usually used to predict the tidal variation, obtaining the predicted heights and time instants of high and low tides. Several studies showed that tidal constituents change over time (Haigh *et al*., 2020; Jay, 2009; Ray, 2009; Woodworth, 2010). These changes in the tidal constituents might affect the resulting tide, especially if they significantly alter the most energetic tidal components, such as the M_2 (principal semidiurnal lunar) and the S2 (principal semidiurnal solar). For example, Ray (2006) demonstrated an upward trend in M_2 amplitude in the Gulf of Maine, and concluded that part of the variations seemed to be related to local resonance and water depth changes. Nonetheless, the exact underlying mechanisms of these changes are not yet fully understood.

Moreover, annual samples of the harmonic constituents present a periodic variation when plotted together. The variation of harmonic constituents over 18.6 years is known as nodal modulation. This modulation usually equals the gravitational potential, and its estimation relies on lunar astronomical parameters. The nodal modulation occurs because the lunar plane of motion is inclined at a mean angle of 5°09' relative to the ecliptic. The lunar plane rotates over a period of 18.61 years, and this motion affects approximately 3.7% of the constituent amplitude (Pugh, 1996). However, studies suggest that some nodal modulations differ from their corresponding nodal equilibrium tidal constituents (Shaw & Tsimplis, 2010).

Gravitational forcing is commonly thought to be stationary on non-geological time scales and since humankind started instrumental measurements of the tides. In recent years, the most dramatic changes in tidal features have happened in estuaries and tidal rivers. Modifications in tides can be caused by a variety of motives, including turbulent mixing, channel and flat depth, surface area, width, convergence, resonance and reflection, river flow, and instrumentation modifications (Haigh *et al*., 2020). Consequently, the tidal constituents in these regions also suffer variations.

The long-term effects of the tidal constituents variation are still debated, especially regarding predicting extreme sea levels (Arns *et al*., 2017; Haigh *et al*., 2020). In tidal prediction, the values for short-term predictions should be updated to the forecast date (Guo *et al*., 2018). However, for long-term predictions, even updated values could generate misleading results due to the unstable attributes of the tidal constituents, especially in strong tidal regimes (Byun & Cho, 2009), and shallow-water environments. Notwithstanding, further research is still needed to fully understand the consequences of the variation in tidal constituent values (Church *et al*., 2011).

Tidal constituent changes are usually caused by local unknown phenomena, which may affect the amplitude of tidal constituents. The usual method to verify the trend of the tidal constituents in tide gauges consists of segmenting the data into 12-month periods (Pawlowicz *et al*., 2002). Despite this segmentation providing one set of tidal constituents per year, these constituents become affected by nodal modulation.

The nodal corrections are the common approach, although the 12-month period segmentation undergoes nodal modulation effect compared to the HA approach with more than 18.6 years of data (Foreman *et al*. 2009). Hence, one method to increase the precision of tidal constituents is to use a larger dataset. This method allows for the identification and isolation of "satellite" constituents, characterized by slight frequency deviations from the main tidal constituents. Such precision, as demonstrated by

Zetler *et al*. (2015), leads to enhanced accuracy in tidal trend analysis.

We can extract the nodal modulation signal from the main astronomical constituents by increasing the segmentation period to 19 years, once the series size exceeds the nodal cycle period (Cherniawsky *et al*., 2010). However, the number of constituent sets is severely reduced (i.e., one constituent set for every 19 years of data). Tide gauges that have been recently installed often lack a database extensive enough to adequately address nodal effects in the analysis, a limitation also observed in tide gauges with data gaps or collection failures. In these cases, nodal corrections are the most typical approach employed for trend analysis. Nonetheless, the Global Sea Level Observing System - GLOSS (IOC, 2012) database presents several tide gauge records with lengths that exceed the need for nodal corrections.

The harmonic analysis method on annual series is a widely used method for evaluating the constituents of a tide gauge (Foreman,1977; Godin, 1986). In these methods, nodal corrections are made to adjust the constituent values. However, even considering these corrections, changes in trend may be masked by remnants of the nodal effect. Therefore, our study proposed a method that uses long-period series, i.e. sets longer than 18.6 years, to conduct harmonic analysis to suppress nodal period modulation from the primary tidal constituent. The selected tide gauges to validate this approach were Brest (France), Cananeia (Brazil), and Eastport (USA). The proposed method eliminates nodal influence and facilitates seeing the trends of the tidal constituents. Hence, the identified changes provide relevant insights for future tide-dependent planning. Comprehending the potential coastal impacts resulting from tidal variations empowers us to implement optimal strategic planning measures.

2. DATA AND METHODOLOGY

2.1 Tide Gauge Data

This study used real tide gauge elevation data to evaluate the proposed approach. The tide gauge selection criteria included the following items: location across the globe, record length, data availability and discontinuities, and knowledge of local changes that might affect the tidal pattern.

We considered only tide gauges with more than 50 years of data. The selected tide gauges (Figure 1) comprised i) Brest, Bretagne, France (BRE) (Pouvreau *et al*., 2006; Wöppelmann *et al*., 2008); ii) Cananeia, São Paulo, Brazil (CAN) (Harari & Camargo, 2003; Prado *et al*., 2019); and iii) Eastport, Maine, United States (EAS) (Pan *et al*., 2019; Ray, 2006). The data from these tide gauges were provided by the University of Hawaii Sea Level Center (Caldwell *et al*., 2015). The following tide gauge records have met the length criterion: i) Brest from 1846 to 2021 (176 years); ii) Cananeia from 1954 to 2006 (53 years), and iii) Eastport from 1929 to 2019 (91 years).

We looked for errors and discontinuity in each selected tide gauge record. BRE retained several discontinuities before 1860, and in the stretch between 1938 and 1951; hence the data from these periods were disregarded in this study. We failed to find any discontinuity in CAN, such as missing or outlier values. The full dataset of EAS remained usable regardless of a minor discontinuity in 1976.

The BRE tide gauge datum remained stable over the 1890-1996 period, despite the bombing of Brest during the Second World War. After this event, a 19 mm offset in MSL was found in comparison with the nearby station of Newlyn (Wöppelmann *et al*., 2008).

The CAN tide gauge region underwent changes that impacted the tide data. The most important one was in the Valo Grande channel: the channel was closed in 1979 for the construction of a dyke in 1979 and then reopened in 1983. A significant geomorphological change also occurred in the same period, with a 1-kilometer dislocation of the Icapara inlet between 1962 and 2000 (Prado *et al*., 2019). Relatively large subsidence has been found in the location (Almeida *et al*., 2015) since the 1960s. Furthermore, Harari & Camargo (2003) observed that the sea level trends in Cananeia did not align with the patterns typically seen in Southeastern Brazil. In light of this discrepancy, Bouin & Woppelmann (2010) suggested the need for a comprehensive investigation into tide gauge motion, utilizing GNSS recording to gain a deeper understanding of the situation.

The EAS tide gauge presented a slightly negative vertical movement relative to the mean sea level (-0.21 ± 0.07 mm/yr) (Bouin and Woppelmann, 2010). However, GPS-derived vertical velocity data indicated a positive vertical movement (2.07 ± 0,89mm/yr), contrasting with those presented by the local tide gauge (Bouin & Woppelmann, 2010).

After the previous verifications about the data consistency, we conducted the Harmonic Analysis (HA) using the T_Tide package (Pawlowicz *et al*., 2002) for each tide gauge dataset.

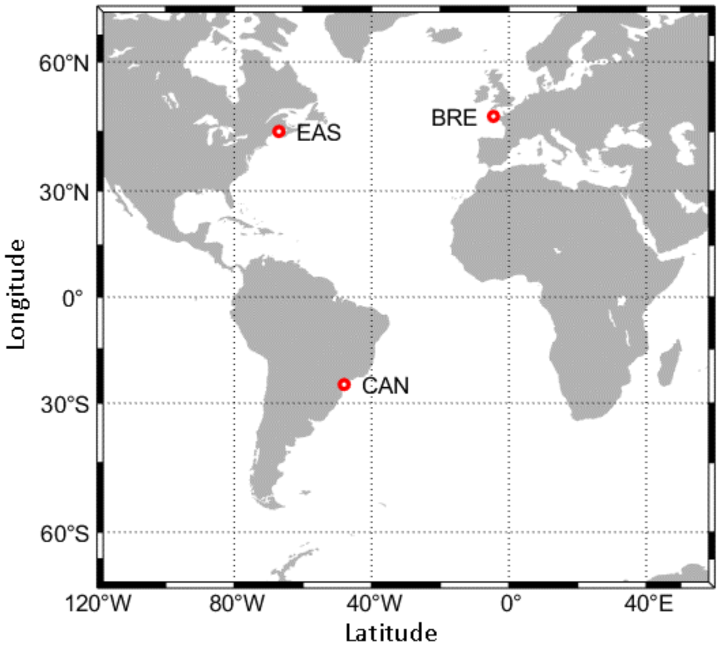

Figure 1. Tide gauge locations.

2.2 Harmonic Analysis

The tidal analysis method used in the T_Tide (Pawlowicz *et al*., 2002) assumes one-dimensional time series, expressed by Equation 1 (Foreman *et al*., 2009):

$$h(t_j) = Z_0 + \sum_{k=1}^{n} f_k(t_0) A_k \; COS \; [\omega_k \; (t_j - t_0) + V_k(t_0) + u_k(t_0) - g_k] + R(t_j) \tag{1}$$

where $h(t_j)$ is the measurement at time t_j; Z_0 is a constant background value (mean sea level); $f_k(t_0)$ and $u_k(t_0)$ are the nodal corrections to amplitude and phase lag, respectively, at some reference time t_0 for major constituent k with frequency v_k; A_k and g_k are the amplitude and the phase lag of constituent k, respectively; $V_k(t_0)$ is the astronomical argument for constituent k at time t_0; $R(t_j)$ is the non-tidal residual; n is the number of tidal constituents.

The approach of Godin (1986) for nodal corrections (applied in the T_Tide package) successfully stabilizes the amplitude and the phase lag variations with 18.6 years for most constituents. Nevertheless, the effectiveness of the nodal correction is subject to multiple factors, such as the location of the tidal record and the existence of nonlinear effects (Godin & Gutiérrez, 1986). Equation 1 also assumes that the amplitude and the phase of each constituent may remain stationary throughout the time series. This assumption might lead to an incorrect estimation of the amplitudes and phases of the tidal constituents (Codiga, 2011). Therefore, temporal changes in harmonic constituents should be evaluated using timely sequential tables of harmonic constituents. Thus, we checked only the M_2 constituent for this study, although the method may be applied to verify any major constituent stability and pattern changes.

2.3 Tendency analysis

During the analysis of the yearly HA constituents of the selected tide gauges, we identified the necessity for a method to suppress nodal modulation. All the significant components of the tide could be separated from 19 years of observations (Godin, 1986). The frequencies present in the diurnal and semidiurnal bands cluster in groups separated by a gap in frequency. Usually, in each group, one constituent dominates and is surrounded by others of lesser magnitude, which are called satellite constituents. Therefore, an analysis with more than 19 years of observations successfully separates these constituents and generates M_2 constituents with less variation.

Thus, we adopted a sliding window approach, in which each window has 19 years of data because HA suppresses the nodal variability when performed in datasets longer than 18.6 years. The central year of the 19-year series was presented as the reference year, for comparison purposes. We highlight that erroneous or missing values over long data series affect the HA results. Hence, we compared the yearly HA constituents and the 19-year HA constituents, which became a valuable source of information (Figure 2).

Additionally, in time-series analysis, the stability of a variable may be evaluated by performing statistical tests or verifying its adjustment to a previously fitted model. These evaluations consider mathematical approaches that identify pattern changes and structural breakpoints, although they fail to explain the cause of the change. However, the detection of tidal constituent changes in graphs depicting amplitude versus time was relatively straightforward. Thus, although a mathematical approach could be taken to confirm the quantitative changes (*e.g.*, a test with known break dates), the visual identification and historical study of local changes became a better approach.

In this study, breakpoint identification (Figure 2) took two steps: i) the detection of changes that may affect the tidal regime considering the local history; ii) the visual identification of pattern changes on generated graphs by the researcher.

Moreover, the tide gauge history knowledge facilitated the identification of vertical movements, changes in tide gauge location, or local changes near the tide gauge installation site. The M_2 amplitudes from tide gauges were compared with previously known pattern breaks presented in other studies.

We identified and considered a breakpoint for each tide gauge, which was used for the tendency analysis. We applied linear fitting to the values of M_2 amplitude. We also used the errors found in each HA to elaborate graphs and calculate tendencies. In summary, we followed the methodology described in Figure 2 to analyze the three tide gauges selected for this study.

We performed the yearly HA method and the 19-year HA method in BRE, CAN, and EAS tide gauges. In each tide gauge, we identified a breakpoint in the M_2 amplitude, by combining visual analysis of the amplitudes for both types of HA methods and considering local history. We disregarded the nodal correction method due to its higher variance. After removing the periods affected by the lack of information, we applied the 19-year sliding window approach. The obtained M_2 amplitudes before and after the breakpoints were submitted to linear fitting, considering the uncertainties in the amplitude values.

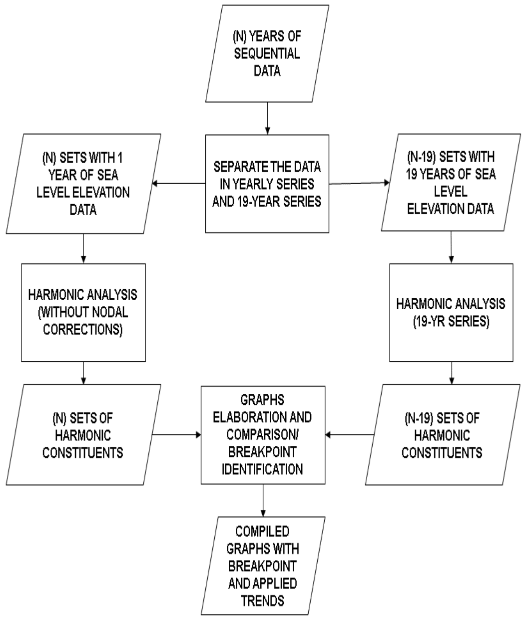

Figure 2. Flowchart for the methodology steps.

3. RESULTS AND DISCUSSION

Breakpoints were identified in different periods: 1945 to 1951 in BRE, 1983 in CAN, and 1980 in EAS. Table 1 provides a summary of the slopes, intercepts (with their respective standard deviations), and root mean square errors (RMSE) of the fitted lines.

The root-mean-square error was considerably smaller in the 19-year HA than its yearly counterpart, as expected by the smoothing characteristics of the 19-year analysis. The standard deviation was also smaller in the 19-year analysis, accounting for the suppression of the nodal effect. Usually, the slopes and intersections found were maintained, except in BRE general slope, CAN 1983-2007 intersect, and EAS 1929-1979 intersect. The specific results for each tide gauge are presented in the following sections.

3.1 Local Analysis

3.1.1 Brest

In the BRE case, the missing data near the 1940s is well known (Wöppelmann *et al.*, 2008). The lack of tidal constituents between 1945 and 1952 highlighted a slight upward change in the previous downward trend. However, this change became de-emphasized by the clear nodal modulation in the M_2 constituent.

Table 1. Linear fit of tide gauge M2 amplitude data for yearly HA, and 19-year HA

		YEARLY HA			19-YR HA		
		SLOPE (mm/yr)	**INTERSECT (mm/yr)**	**RMSE (mm)**	**SLOPE (mm/yr)**	**INTERSECT (mm/yr)**	**RMSE (mm)**
BREST	1860-2020	0.02±0.01	2019.76±25.41	55.3	0.12±0.01	2276.28±12.20	7.8
	1860-1937	0.39±0.03	2789.85±65.67	53.9	0.46±0.02	2928.96±35.10	2.7
	1953-2020	0.60±0.05	867.44±106.34	54.0	0.22±0.04	1619.86±78.43	2.4
CANANEIA	1954-2007	0.27±0.04	164.51±82.45	11.6	0.40±0.03	436.52±56.16	1.1
	1954-1982	0.45±0.09	515.30±186.03	10.9	0.56±0.07	735.20±130.05	0.2
	1983-2007	0.38±0.16	389.72±325.38	12.1	0.19±0.09	117.94±187.66	0.4
EASTPORT	1929-2019	1.00±0.04	676.63±88.65	65.8	0.80±0.02	1064.44±49.66	8.6
	1929-1979	1.80±0.18	882.42±344.81	47.9	0.83±0.08	1000.11±147.93	10.9
	1980-2019	1.04±0.15	584.71±303.53	52.6	0.98±0.10	689.59±203.51	3.0

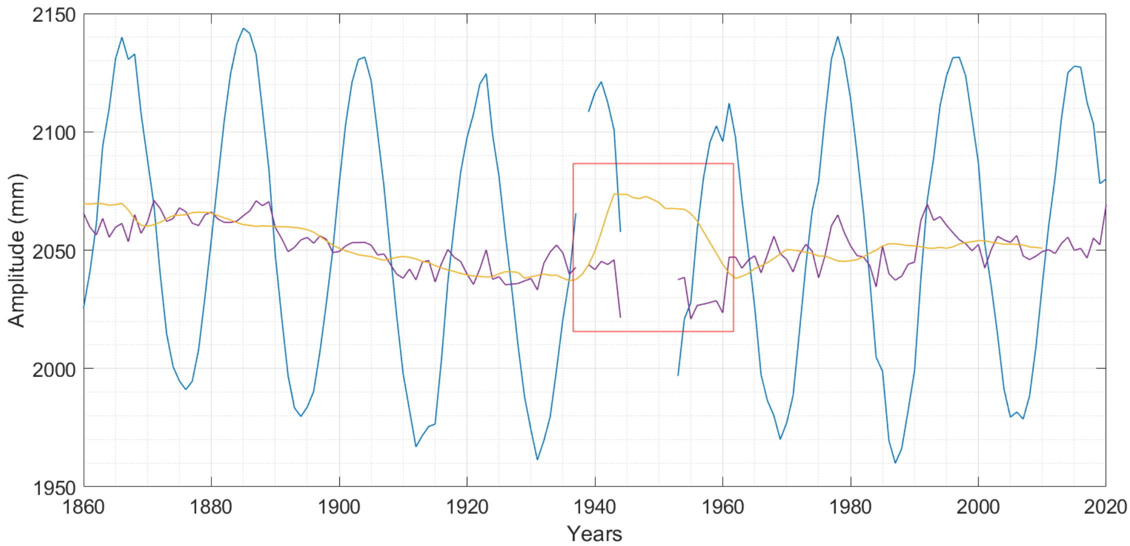

Figure 3. (BRE) M2 amplitudes (mm): without nodal corrections in blue; with nodal corrections in purple; the 19-year analysis in yellow. The red box highlights the large discrepancies found where the 19-year analysis was affected by the missing data.

The data gap (1945-1952) affected the 19-year HA results, masking the amplitude of unidentified constituents in the M_2 amplitude. The lack of information created a seemingly larger M_2 amplitude, with no physical causes (Figure 3). Therefore, this extra value in the amplitude of the M_2 constituent must come from the adjacent constituents, misidentified as M_2 due to the smaller volume of data available for HA.

Notwithstanding the identified minimum vertical motion of the tide gauge, there was no apparent correlation with the amplitude fluctuations in the M_2 tidal constituent. The BRE yearly HA presented an apparent nodal modulation effect in the M_2 amplitudes (Figure 4), as expected by the absence of nodal corrections. The remaining modulation effect was still identifiable in the 19-year M_2 amplitudes (Figure 5). The small oscillatory pattern noticed in Figure 5 and the original nodal oscillation noticed in Figure 4 present differences between phases. This result suggests that some long-period amplitude could be misidentified as a nodal influence. Thus, other long-period effects, such as the 8.85-year perigean cycle, still affect the M_2 amplitude in the 19-year HA. The change in the slope found in the yearly HA (-0.39±0.03 mm to 0.60±0.05 mm) also exists in the 19-year HA (-0.46±0.02 mm to 0.22±0.04 mm).

Our results align with the findings of Pouvreau *et al*. (2006), which suggested a long-period oscillation in the M_2 amplitudes, but no tidal constituent or combination of constituents could cause this oscillation tendency. However, the downward trend in the amplitude of the M_2 constituent noted in Brest between 1880 and 1920 might be attributed to harbor development or dredging activities as pointed out by Pouvreau *et al*. (2006)

Furthermore, Pineau-Guillou *et al*. (2021) found that several tide gauges in the North-East Atlantic exhibit a consistent break pattern, indicating that the observed change was unlikely to be attributed to local factors such as dredging or instrumentation errors.

The upward trend found post-break was expressively smaller in the 19-yr HA (0.60±0.05 mm vs 0.22±0.04 mm). On the other hand, a general downward trend (-0.12 ±0.01 mm) would not be adequate to represent the current pattern of these tide gauge constituents, due to the change near the 1940s. This downward trend was also questioned by Pouvreau *et al*. (2006), since their results, from 1960 on, pointed to an increase in the M_2 amplitude tendency.

3.1.2 Cananeia

The CAN analysis remained unaffected by the presence of identified missing values. The apparent sea level rise at a high rate, combined with a negative vertical movement in the region still needs a careful investigation, as stated by Bouin & Woppelman (2010). In CAN, both subsidence reported by Almeida *et al*. (2015) and the estuary changes pointed out by Prado *et al*. (2019) could potentially exert some influence on the upward trend observed after 1983.

For CAN, both the yearly HA (Figure 6) and the 19-year HA (Figure 7) exhibit an upward trend in the M_2 amplitude. However, the breakpoint observed in 1983, which appeared as a vertical offset in the yearly HA, was not evident in the 19-year HA. In the 19-year HA, a potential oscillatory pattern becomes visible in the later years (1983-1998) of the analysis. Interestingly, this pattern also existed in the early years (1963-1983) of the analysis, but it was obscured by the steep slope of the amplitude tendency.

The yearly HA revealed an upward trend in the amplitude of the M_2 constituent (0.45±0.09 mm to 0.38±0.16 mm). In the

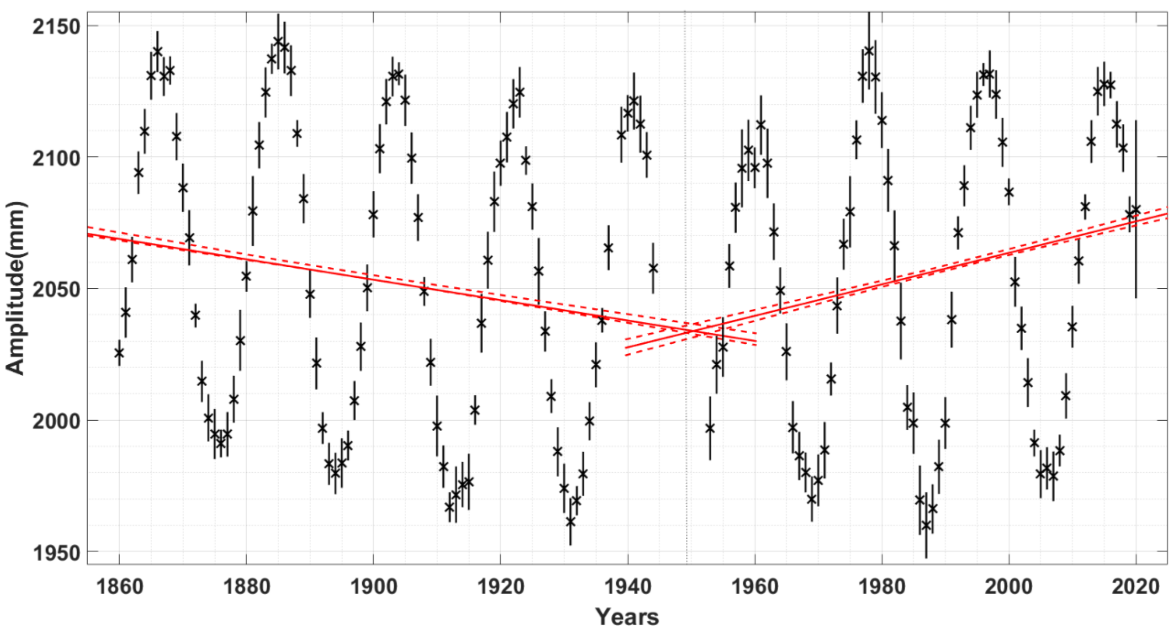

Figure 4. (BRE) Yearly HA M_2 amplitudes in mm, M_2 amplitude standard deviation in mm, and linear fits pre-1940s and post-1950s (red lines) considering the imprecision of the data (red dashed).

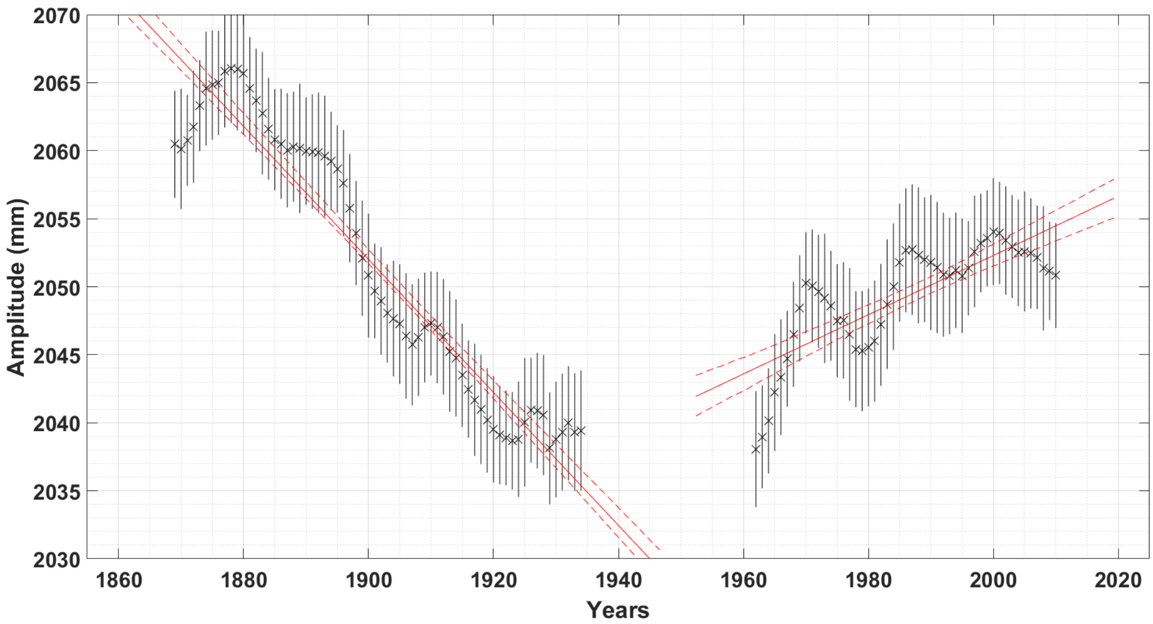

Figure 5. (BRE) 19-year HA M_2 amplitude in mm, amplitude standard deviation in mm, and linear fits pre-1940s and post-1950s (red lines) considering the imprecision of the data (red dashed).

19-year HA, the M_2 amplitude also presents an upward trend, but the trend found post-break was not as significant (0.56±0.07 mm to 0.13±0.09 mm) as the yearly trend. The milder slope observed in the 19-year HA suggests that a portion of the M_2 amplitude calculated in the yearly HA may have been influenced by nodal effects, indicating a significant nodal modulation in the yearly HA analysis values.

3.1.3 Eastport

The data unavailability affected the EAS results, which could explain some of the high deviation observed in the yearly HA (Figure 8). The 19-year HA (Figure 9) solved the deviation effect. However, even in the 19-year analysis, a smaller period modulation was still noticeable, suggesting that a portion of the effect initially attributed to nodal modulation comprised modulations with other periods. The yearly HA of EAS was consistent with the results of Ray (2006) and Pan *et al*. (2019). The inconclusive 1972 M_2 yearly amplitude (Figure 8) also correlates with the observation made by Pineau-Guillou *et al*. (2021). In both yearly and 19-year HA, the M_2 amplitude trend continued to show an upward direction, albeit with a minor vertical offset. The reduction in the trend slope is more visible in the yearly HA (1.80±0.18 mm to 1.04±0.15 mm). Conversely, the slope of the 19-year HA trend increased after 1980, suggesting that the drop in the M_2 amplitude during the 1980s could be attributed to changes in nodal modulation. Figure 9 depicts that the M_2 amplitude without nodal modulation maintains a relatively consistent slope as before (0.83 ±0.08 mm to 0.98 ±0.1 mm)

The upward trend identified here contradicts the results of Greenberg *et al*., (2012), which suggested that trends in M_2 amplitude after 1982 at Portland, Eastport, and Saint John were approximately half of those observed earlier due to an apparent regime shift, evident in both M_2 amplitude and MSL trend changes. Moreover, according to Pan *et al*. (2019), the North Atlantic Oscillation might also be a contributing factor to this effect, and the apparent reduction in M_2 amplitude could be attributed to nodal modulation. The 19-year HA effectively filters the interference caused by the nodal modulation. As a result, the residual modulation becomes minimal in comparison to the yearly HA. In the case of EAS, the 19-year HA does not exhibit a decrease (0.83 ±0.08 mm to 0.98 ±0.10 mm) in slope following the breakpoint. Therefore, the decrease reported by Greenberg *et al*. (2012) and also observed in our yearly HA analysis (1.8±0.18 mm to 1.04±0.15 mm) is closely associated with the nodal modulation effect on the M_2 constituent. The 19-year HA results in EAS showed that the trend slope increased after 1980. This outcome implies a potential correlation between the reduction in M_2 slope noted in other studies and the influence of nodal modulation.

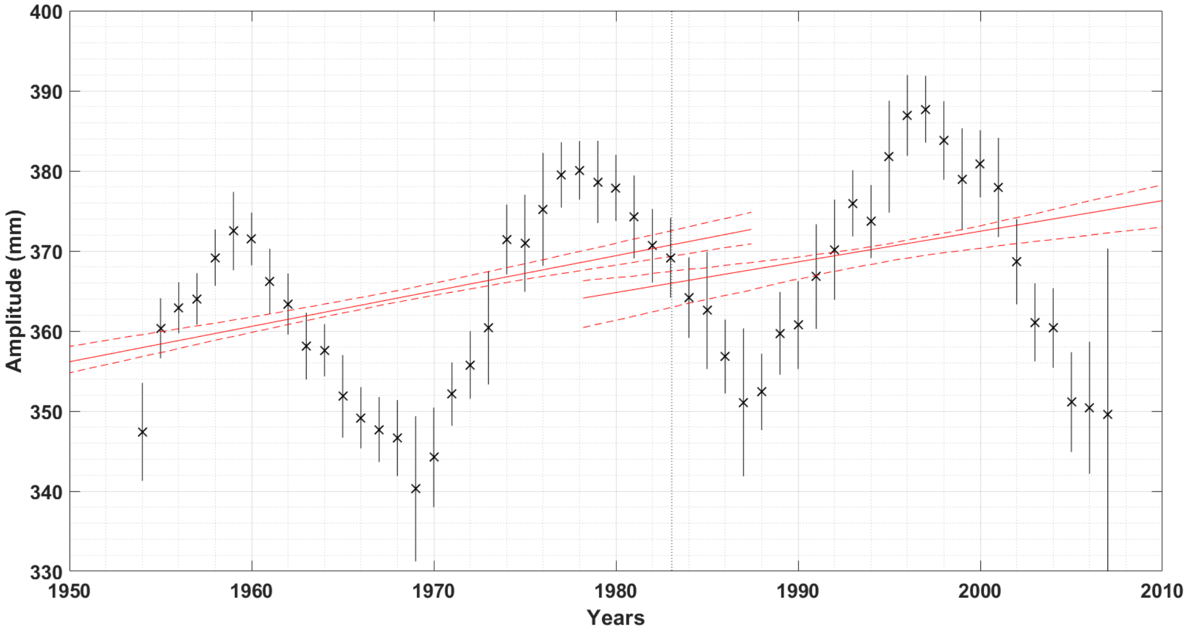

Figure 6. (CAN) Yearly HA M2 amplitude in mm, amplitude standard deviation in mm, and linear fits pre-1983 and post-1983 (red lines) considering the imprecision of the data (red dashed).

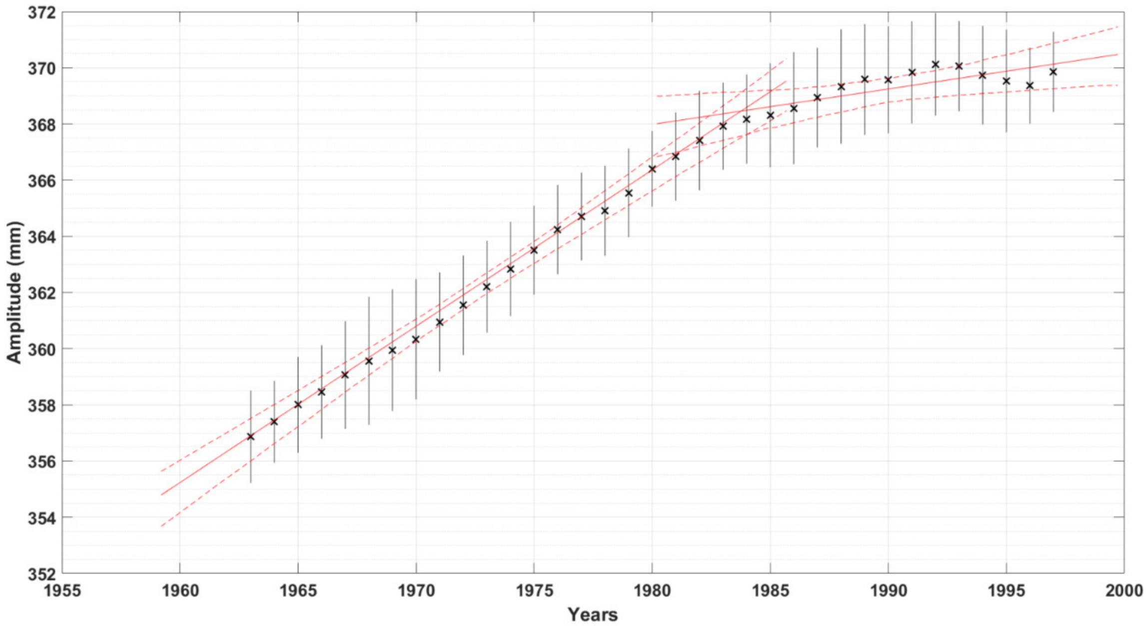

Figure 7. (CAN) 19-year HA M2 amplitude in mm, amplitude standard deviation in mm, and linear fits pre-1983 and post-1983 (red lines) considering the imprecision of the data (red dashed).

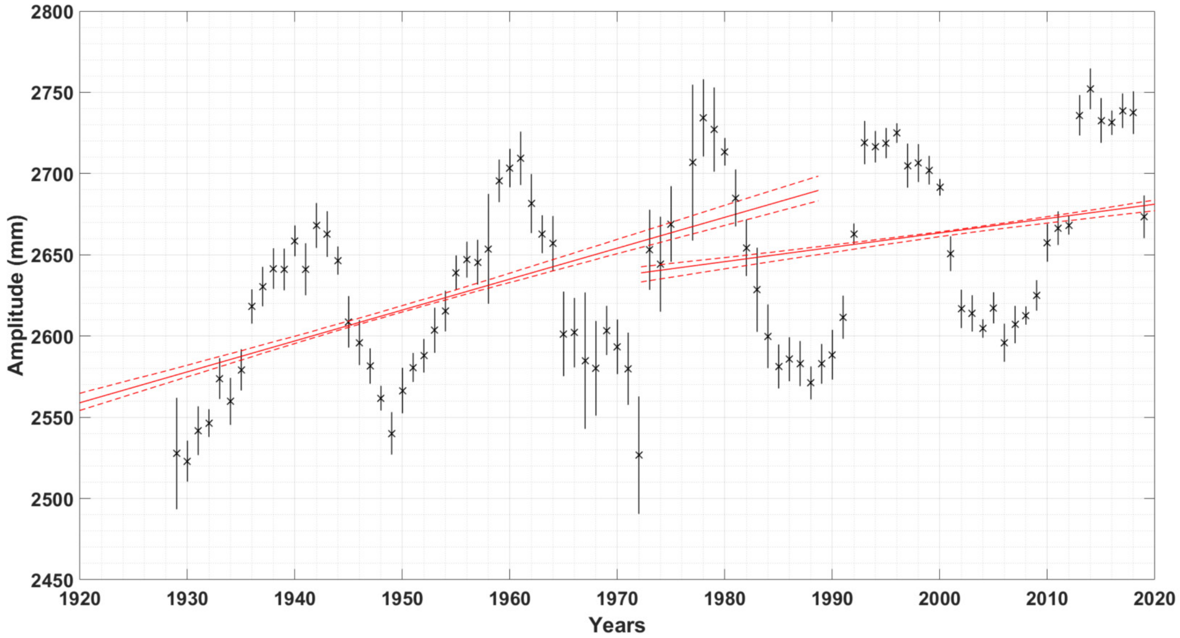

Figure 8: (EAS) Yearly HA M2 amplitude in mm, amplitude standard deviation in mm, and linear fits pre-1980s and post-1980s (red lines), considering the imprecision of the data (red dashed).

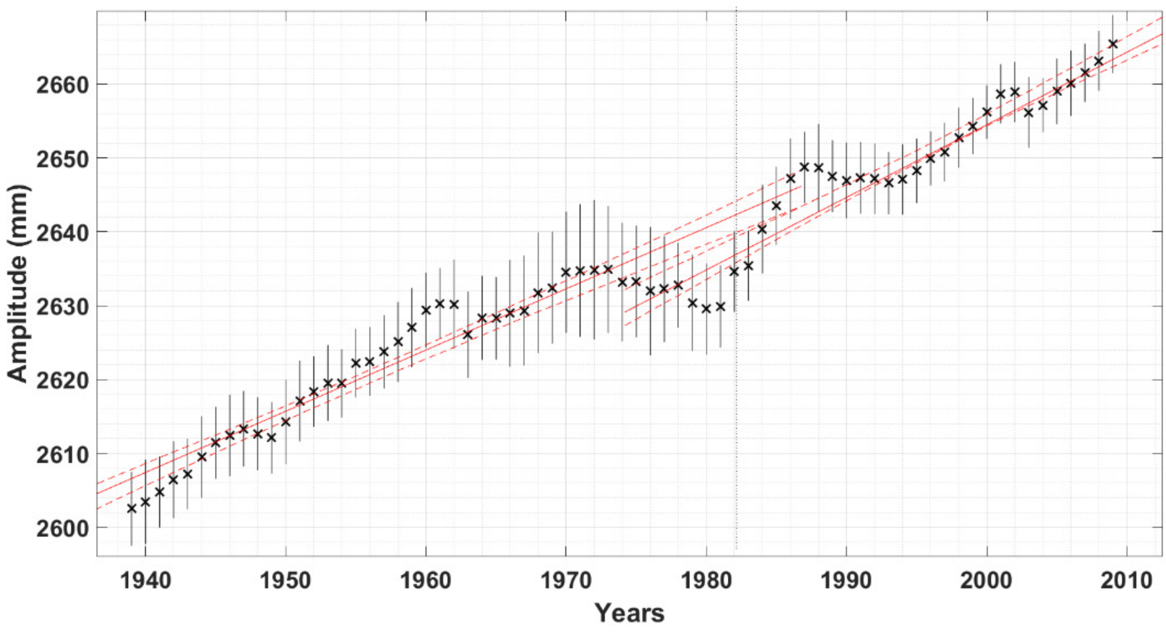

Figure 9: (EAS) 19-year HA M2 amplitude in mm, amplitude standard deviation in mm, and linear fits pre-1980 and post-1980 (red lines), considering the imprecision of the data (red dashed).

3.2 General Analysis

The results of each tide gauge reinforced the significance of conducting local research prior to data interpretation. During this phase, researchers play a crucial role, as they are required to engage in visual analysis with a discerning perspective. For instance, the observed shift in trend at the CAN tide gauge is linked to alterations in the estuary. Lacking awareness of the local context, the cause of this trend shift might erroneously be attributed to tide gauge movement. Likewise, a similar misinterpretation could arise at BRE if the researcher overlooks the 8-year data gap (indicated by the red square in Figure 3). In the case of EAS, we observed a high deviation in the yearly HA, which was solved by using the 19-year HA approach.

Nonetheless, local factors present challenges to breakpoint identification. Without a deeper understanding of local tidal circulation and hydrodynamics, the researcher might find multiple incorrect breakpoints without a physical basis. Each location must be thoroughly studied to gather information on potential causes of tidal trend changes. The availability of data can also invalidate the proposed approach, as it needs multiple consecutive 19-year series.

The 19-year HA results in EAS showed that the trend slope increased after 1980. This outcome implies a potential correlation between the reduction in M_2 slope noted in other studies Greenberg *et al*. (2012), Pan *et al*. (2019) and the influence of nodal modulation. Furthermore, the relationship between vertical movement and the 19-year HA results was opposite in EAS compared to CAN. EAS showed an upward slope, while CAN exhibited a downward slope. Despite this dissimilarity, there is no apparent direct association between vertical movement and fluctuations in M_2 amplitude tendencies.

Our proposed approach of 19-year HA method effectively eliminated the nodal impact on the M_2 amplitudes. The smoothing of variations led to diminished errors and improved the clarity of linear trend visualization. The comparison of yearly and 19-year HA allowed the identification of nodal influence in the M_2 amplitudes for each tide gauge.

Moreover, the variations observed in the three examined sites may potentially stem from shifts in mean sea level (MSL), alterations in coastal structures, and occurrences linked to climatic events.

4. CONCLUSIONS

The investigation of tidal nodal modulation has become a prominent subject of numerous studies in the present day. Researchers have been actively discussing the nodal modulation local influence and proposing several approaches to either eliminate or assess its impact. The nodal modulation might interfere with the value of the harmonic constituents, causing changes in the results of trend analyses. We recommend additional localized studies to gain a deeper understanding of how regional changes exert influence over M_2 amplitude and the overall tidal fluctuation. Our approach has demonstrated that nodal modulation can affect the tendencies in constituent amplitudes. Moreover, our approach facilitates the pinpointing of potential breakpoints. Therefore, our proposed approach of 19-year HA poses a relevant approach to verify these tidal constituent trends in locations affected by the nodal modulation variability. Subsequent research will be dedicated to investigating how these alterations impact tidal predictions and relative sea levels. Understanding the behavior of tides enables us to differentiate expected patterns from an astronomical tide perspective and identify potential effects attributed to climate change. Additionally, this comprehension empowers us to develop more effective coastal management plans tailored to tide-related factors.

CONTRIBUTIONS

André de Lima Coelho: Study conception, data collection, analysis and interpretation of results, manuscript writing and revision. Tiago Zenker Gireli: Study conception, analysis and interpretation of results, manuscript revision. Kelly Kawai Venancio: Analysis and interpretation of results, manuscript writing and revision. Patrícia Dalsoglio Garcia: Study conception, manuscript revision.

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