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Behavior of Sea Level in the Period of 1980 to 2017 on the Port Area of Gulf of Maranhão, Brazil

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ABSTRACT: The Gulf of Maranhão, North Coast of Brazil, is one of the regions in the world with largest tidal ranges. The Port Area of Maranhão, in São Marcos Bay, represents the second most important in Brazil. The port facilities are naturally sheltered from swell, with nautical operations and maintenance dredging volumes directly conditioned by macro-tides, which exceed the 6.0 m tidal range, and associated tidal currents, which can reach 7.0 knots. In order to assess the behavior of sea levels in recent decades, in view of the influence of climate changes on tides in various ports around the world, a period of two lunar nodal tidal cycles of 18.61 years, from 1980 to 2017, was investigated using unpublished data recorded in tide gauges. The trend pattern obtained was analyzed statistically and, unlike many other port areas, a sensitive stability of the mean sea level was noted. An important conclusion is about the reduction in HHW and increasing in LLW, leading to a reduction in tidal ranges, in tidal currents and a significant reduction of the shear stress in the bottom, which may increase the dredging rates in the port areas in the next decades, due to an increasing siltation.

1 INTRODUCTION

Ports are a major component of the 21st century global economy. Therefore, in a context of climate change, assessing and predicting the sea level rise (SLR) have become paramount in Port Engineering. Back in 2005, there were 136 ports worldwide — thirteen of which were among the planet's twenty most important ones [13]. However, not every port is affected in the same way by SLR. Exposure to climate change effects increases more drastically in developing countries [13].

Continuous records of long tidal series on the Brazilian coast are scarce, given its 8,500 km length (Table 1) and Figure 1.

Table 1. Observed rates of sea level rise for several Brazilian locations.

Location	Rate ($mm{\cdot}yr^{-1}$)	Tidal Gage Period	Reference
Santos (SP)	3.3	1940–2014	[14]
Equatorial Atlantic	4.0	Altimetry	[8]
Belém (PA)	3.4	1948–1970	[4]
Fortaleza (CE)	0.3	1950–1970	[4]
Recife (PE)	5.6	1946–1988	[9]
Salvador (BA)	2.0	1950–2009	[11]
Canasvieiras (BA)	4.1	1950–1970	[4]
Rio de Janeiro (RJ)	3.6	1950–1970	[4]
Ubatuba (SP)	2.1	1954-1991	[2]
Santos (SP)	3.3	1940–2014	[2]
Cananeia (SP)	3.8	1957–1993	[2]
Imbituba (SC)	0.7	1950–1970	[4]

Figure 1. Site location of Brazilian main tidal stations network (adapted from GLOSS).

It has long been suggested that the use of a period of at least two lunar nodal tide cycles (encompassing 37.2 years) for proper sea level assessments is highly recommended [10, 15]. As there is usually a strong interest in extrapolating the trend detected with past data, it is also important that the records extend to dates as close to the present day. Only four tide stations located on the Brazilian coast meet these requirements, Gulf of Maranhão (MA), Ilha Fiscal (RJ), Santos (SP) and Cananeia (SP).

The city of São Luís is the capital of the state of Maranhão, in northeastern Brazil. It is in São Marcos Bay (in Gulf of Maranhão), the largest Brazilian bay, which is home to the second largest port complex in Latin America, and one of the world's largest in terms of cargo movement [3], therefore of great importance for Brazilian exports. With a 4 m average tidal amplitude, the region presents strong currents, which can reach 7.0 knots. This incurs complex port operations in São Marcos Bay [5], such as berth window management, approach channel navigation and overall vessel maneuverability, and ship loading. Due to the region's increasing urbanization, its economic importance for the Country and the safety of its port operations, the present article had the purpose to evaluate, with unpublished data, the future behavior of sea level to be faced in São Marcos Bay and surroundings. Lastly, such behavior was classified according to international benchmark on the subject and conclusions about possible consequences regarding the modification of tidal currents were drawn.

2 STUDY AREA LOCATION

São Marcos Bay is the largest Brazilian bay. It is approximately 500 km long, 100 km wide and it is bordered by the mainland (to the west), the city of São Luís (east) and the mouth of the Mearim River (south). Due to its natural great depth (which allows receiving 23 m draft ships) and wave protection aspect, this region's port potential is known at least since 1612, when French invaders established the first port of São Luís. Nowadays, several important ports are set within São Marcos Bay area, among which are the Itaqui Port and the Ponta da Madeira Terminal. Figure 2 shows their location.

Figure 2. São Marcos Bay area in Gulf of Maranhão, State of Maranhão, Brazil.

Itaqui Port began operations in 1974. It currently handles general cargo, solid bulk, and liquid bulk in the order of 20 million tons per year [7]. Ponta da Madeira Terminal is a private port, and its operations began in 1986. This terminal, with depths up to 25.0 m (Chart Datum) allowing vessels up to 23.0 m of draft, is specialized mainly in the export of iron ore and, in the last decade, its throughput has increased from 96 million tons (2010) to 198 million tons (2018) – therefore being the Brazilian port with the largest cargo throughput [1].

3 MATERIAL AND METHODS

3.1 *Sea level, tides, and available data*

Despite its enormous propensity towards port development, São Marcos Bay is affected by astronomical, semi-diurnal tides usually ranging from 3.1 m (mean neap tidal range) to 5.4 m (mean spring tidal range) — typical of macro tidal regions. Such tidal amplitude results in strong currents, which pose a real challenge to maritime operations in the region [6]. Table 2 shows the main tidal aspects rendered from harmonic analyses of Itaqui Port and Ponta da Madeira Terminal tide gauges.

Table 2. Tide gauges, mean sea level, and mean tides in São Marcos Bay area.

	Ponta da Madeira Terminal	Itaqui Port
Location	02º 33,9' S 44º 22,7' W	02º 34,6' S 44º 22,2' W
Period	01/08/1991 – 31/07/1993	01/01/1985 – 31/03/1985
MSL, [Z_0] (cm)	328	343
MHWS / MHWN (cm)	597 / 482	625 / 502
MLWS / MLWN (cm)	59 / 172	61 / 184
Spring / Neap Tidal Range (cm)	538 / 310	564 / 318

Source: [17].

Highest High Water (HHW), Mean Sea Level (MSL) and Lowest Low Water (LLW) time series were obtained for both port locations. Ponta da Madeira Terminal data were promptly, digitally available and covered a 30-year span, ranging from 1988 to 2017 (but missing 1989–90). Older data, from Itaqui Port, were available for the years 1980 and 1984–86.

However, they were not recorded in digital format, which required a cumbersome transcription work.

Data generated from the Ponta da Madeira Terminal tide gauge covers 28 years over a 30-year span. Itaqui Port, on the other hand, has available data for older years. Its tide gauge lies within only 1.2 NM of the Ponta da Madeira Terminal tide gauge. Together, these gauges begotten data for 32 years over a 38-year span. This makes up for 84% data completion over a period of two lunar nodal tidal cycles.

Sea level behavior in São Marcos Bay will be compared with British recommendations [18] (see in Table 3).

Table 3. British recommended contingency allowances for sea level rise rates (mm·yr^{-1}) and cumulative SLR (m).

Time Period	Low-Rate [Cum. SLR]	Moderate Rate [Cum. SLR]	High Rate [Cum. SLR]
1900–2025	2.5 [0.09]	3.5 [0.12]	4.0 [0.14]
2025–2055	7.0 [0.30]	8.0 [0.36]	8.5 [0.40]
2055–2085	10.0 [0.60]	11.5 [0.71]	12.0 [0.75]
2085–2115	13.0 [0.99]	14.5 [1.14]	15.0 [1.21]

According to [6], the maximum tidal currents (flood or ebb) in São Marcos Bay are proportional to the tidal range elevated to exponent 0.67, based on measurements made for the Ponta da Madeira Terminal project.

3.2 *Quality of the time series*

Ponta da Madeira Sea Level Station is registered with number 200 in GLOSS – Global Sea Level Observing System of the Intergovernmental Oceanographic Commission of UNESCO - to provide final quality assessed high frequency data in near-real time and metadata to the GLOSS Sea level station Monitoring Facility (see Figure 1). It is also registered with number 1736 in PSMSL – Permanent Service for Mean Sea Level of The Global Sea Level Observing System. In the Quality Assessment of Sea Level Data by the University of Hawaii Sea Level Center/National Oceanographic Data Center Joint Archive for Sea Level, is registered as Contributor DHN – Diretoria de Hidrografia e Navegação Banco de Dados Oceanográficos of Brazilian Navy. Therefore, data quality is audited by the Brazilian Maritime Authority.

Data are analog, with instrument type float and stilling well and digitalized interval spot hourly from 01 Jan 1988. The gaps over than 1 month occurred: 10 Feb 1988 - 21 May 1988; 09 Jun 1988 - 18 Nov 1989; 11 Dec 1989 - 05 Jan 1991;27 Feb 1991 - 01 Jul 1991.

4 RESULTS AND DISCUSSION

Figure 3 shows the historical series, the linear trend lines, and the confidence intervals (95%) for MSL, HHW and LLW for São Marcos Bay region. Itaqui Port vertical datum was employed.

Albeit LLW level increased with a rate of 4.8 mm·yr^{-1} throughout the period, both HHW and MSL decreased with rates of -6.4 and -0.7 mm·yr^{-1}, respectively. According to the British criterion depicted in Table 3, São Marcos Bay MSL fall within the low-rate contingency allowance for SLR, while HHW decrease rate and LLW increase rate lie in the high-rate contingency allowance for SLR. Still, considering the confidence intervals calculated for each data series, no significant change in sea level in São Marcos Bay region can be stated. Mean sea level remains statistically constant between 1980 and 2017. However, the mean tidal range decreased 1.116 cm·yr^{-1}, corresponding in a linear trend reduction of 1.12 m from 1980 to 2080, which is equivalent to a reduction of the maximum tidal currents of 11.55% (proportional to the tidal range elevated to exponent 0.67) and of the shear stress in the bottom of the bay of 21.77% (shear stress is proportional to the square of the velocity).

These are highly unanticipated results. From Table 1, it follows that for Belém (650 km westward from Ponta da Madeira) and Fortaleza (700 km eastward from Ponta da Madeira), the most nearby port cities from São Luís (see Figure 1) with long tide series, with SLR rates of 3.4 mm·yr^{-1} and 0.3 mm·yr^{-1}, respectively. However, since these figures were calculated from tide gauge data over a 20-years period (i.e., comprising only one lunar nodal tide cycle), such SLR rates may be overestimated [10, 15] and are from old series ended in 1970. It should be mentioned that the region is tectonically stable, as well as there are no subsidence effects due to the extraction of underground fluids (water, natural gas or oil).

A similar process, but of increasing tidal ranges, off the coasts of the North Sea from Belgium to Germany, was attributed [12, 19] to a shift of the amphidromic points of harmonic constituent M2 (lunar semidiurnal) tide wave of North Atlantic (see Figure 4). From 1950 to 2005 (three lunar nodal tide cycle), the trend corresponded to 30.5 cm·century^{-1}. Just as there is a system of amphidromic points in the North Sea, there is also one of them in the Caribbean Sea (see Figure 4), and its shift may be causing the trend, that is, the reduction of tidal ranges in Gulf of Maranhão. There are a lot of consequences of an accelerated reduction of the mean tidal range, e.g., changes in coastal morphology and sedimentation problems, causing siltation of port nautical depths in access channels, basins, and berths.

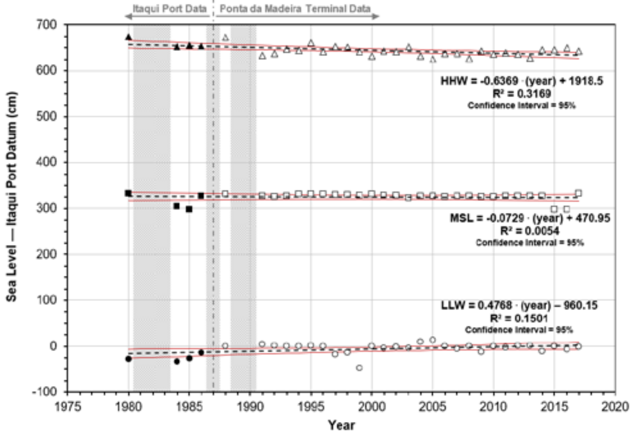

Figure 3. Historical series (1980–2017) and analyses for annual tidal level variability in São Marcos Bay.

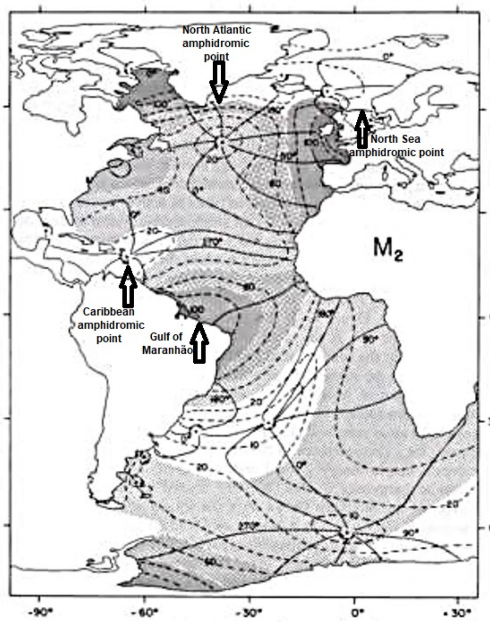

Figure 4. Cotidal and coamplitude (in cm) charts of semidiurnal (M2) tide of the Atlantic Ocean, adapted from [16].

5 CONCLUSION

In this article was evaluated the sea level behavior (HHW, MSL and LLW) in São Marcos Bay from 1980 to 2017. Data covering two lunar nodal tide cycles, and unpublished till now, were employed. Even so, it cannot be stated that there is a statistically significant SLR trend. This is an unexpected result, given what is being observed in other port locations in Brazil and around the world. It is suggested that this could be due to a shift of the amphidromic point of harmonic constituent M2 (lunar semidiurnal) tide wave since there is one in the Caribbean Sea.

Otherwise, an important conclusion is that mean tidal range decreased 1.116 $cm \cdot yr^{-1}$, corresponding in a linear trend reduction of 1.12 m from 1980 to 2080, which is equivalent to a reduction in the maximum tidal currents of 11.55% and the shear stress in the bottom of 21.77%. A lot of consequences from this accelerated reduction in the mean tidal range can be expected, e.g., changes in coastal morphology and sedimentation problems, causing siltation of port nautical depths in access channels, basins, and berths, increasing the necessity of maintenance dredging.

REFERENCES

1. Agência Nacional de Transportes Aquaviários (ANTAQ): Anuário Estatístico Aquaviário 2018 – Movimentação de Cargas. (2018).
2. Alfredini, P., Arasaki, E.: Estimation of Sea Level Rise in Santos Port (Brazil). TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation. 13, 2, 453–458 (2019). https://doi.org/10.12716/1001.13.02.25.
3. Amaral, R., Alfredin, P.: Modelação Hidrossedimentológica no Canal de Acesso do Complexo Portuário do Maranhão. RBRH. 15, 2, 5–14 (2010). https://doi.org/10.21168/rbrh.v15n2.p5-14.
4. Aubrey, D.G., Emery, K.O., Uchupi, E.: Changing coastal levels of South America and the Caribbean region from tide-gauge records. Tectonophysics. 154, 3, 269–284 (1988). https://doi.org/10.1016/0040-1951(88)90108-4.
5. Bernardino, J.C., Pion, L.M., Esferra, R., de Oliveira Bezerra, R.: Definition of Mooring Plans for Vessels at Port Terminals Using Physical Models. TransNav, the International Journal on Marine Navigation and Safety of Sea Transportation. 13, 1, 107–114 (2019). https://doi.org/10.12716/1001.13.01.10.
6. Carvalho, J.J.R., Souza, O.J., Alfredini, P.: Rubble mound groins design in area submitted to strong tidal currents. In: International Symposium on Design of Hydraulic Structures. Balkema (1989).
7. EMAP – Porto do Itaqui: Relatório de Movimentação de Cargas (2001 a 2018). , São Luís (2018).
8. França, C.A.S.: Contribuição ao estudo da variabilidade do nível do mar na região tropical do Atlântico por altimetria do sa-télite TOPEX/POSEIDON e modelagem numérica. Universidade de São Paulo (2000).
9. Harari, J., Camargo, R.: Tides and mean sea level in Recife (PE): 8o3.3'S 34o51.9'W: 1946 to 1988. , São Paulo (1994).
10. Hicks, S.D.: Sea level - A changing reference in surveying and mapping. Surveying and Mapping. 28, 285–289 (1968).
11. Losada, I.J., Reguero, B.G., Méndez, F.J., Castanedo, S., Abascal, A.J., Mínguez, R.: Long-term changes in sea-level components in Latin America and the Caribbean. Global and Planetary Change. 104, 34–50 (2013). https://doi.org/10.1016/j.gloplacha.2013.02.006.
12. Mudersbach, C., Jensen, J.: Recent Sea Level Variations at the North Sea and Baltic Sea Coastlines. In: Coastal Engineering 2006. pp. 1764–1774 World Scientific Publishing Company (2007). https://doi.org/10.1142/9789812709554_0149.
13. Nicholls, R.J., Hanson, S., Herweijer, C., Patmore, N., Hallegatte, S., Corfee-Morlot, J., Château, J., Muir-Wood, R.: Ranking Port Cities with High Exposure and Vulnerability to Climate Extremes. OECD Environment Working Papers. 1, (2008). https://doi.org/10.1787/011766488208.
14. Painel Brasileiro de Mudanças Climáticas (PBMC): Impacto, vulnerabilidade e adaptação das cidades costeiras brasileiras às mudanças climáticas: Relatório Es-pecial do Painel Brasileiro de Mudanças Climáticas (PBMC). , Rio de Janeiro (2016).
15. Penland, S., Ramsey, K.E.: Relative Sea-Level Rise in Louisiana and the Gulf of Mexico: 1908-1988. Journal of Coastal Research. 6, 2, (1990).
16. Pugh, D.T.: Tides, Surges and Mean Sea-level: A Handbook for Engineers and Scientists. John Wiley & Sons Ltd (1987).
17. Salles, F.J.P., Bentes, F.C.M., Santos, J.A.: Catálogo de Estações Maregráficas Brasileiras. FEMAR, Rio de Janeiro (2000).
18. UK Department for Environment Food and Rural Affairs: Flood and Coastal Defence Appraisal — Guidance FCDPAG3 Economic Appraisal (Supplementary Note to Operating Authorities – Climate Change Impacts. , London (2006).
19. US National Research Council: Responding to Changes in Sea Level, Engineering Implications, Committee on Engineering Implications of Changes in Relative Mean Sea Level. Marine Board, Commission on Engineering and Technical Systems, National Research Council. National Academy Press, Washington DC (1987).