The effect of Seasonal Variability in Mean Sea Level and Tidal Constituents: A case study in Sri Lanka

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Abstract- *The seasonal fluctuations cause water level variations in coastal regions. This research aims to investigate the seasonal variability of tidal constituents and Mean Sea Level (MSL). Seven years tidal data from the Colombo Port was used to investigate the seasonal variability of both Mean Sea Level (MSL) and tidal constituents. The processing of tidal data was performed using a harmonic analysis based tidal processing and analysis software TOTIS. The findings indicate that the MSL at Colombo exhibit a pattern with seasonal variations. MSL is high during the Southwest monsoon season than the Northeast monsoon season in generally. Then, the variability of amplitude and phase of diurnal (K1, M1, S1, O1), semi-diurnal (K2, M2, S2, T2), and long period (MF, MM, MSF, and SSA) tidal constituents were investigated for Colombo Port. The amplitude of all diurnal constituents exhibited a pattern with seasonal variations, with higher values during the Northeast monsoon season than the Southwest monsoon season. The amplitudes of all semidiurnal constituents exhibited a pattern opposite to that of the diurnal constituents in generally. However, it exhibited a complete opposite pattern during the years 2025 & 2020 where the MSL variation also altered. The long constituents were also exhibited a pattern with seasonal variations. The study found that the phase of each tidal constituent exhibited the same pattern in all years, although K1,M1,M2 and S2 changed the patterns during the same years in which the pattern of MSL was changed. Furthermore, unlike the amplitude variability patterns, the phase component patterns within the same category were not similar to each other. Finally, the study concluded that amplitudes and phases of tidal constituents exhibit a significance alterations with seasonal variations.*

Keywords - Harmonic Analysis, Mean Sea Level, Seasonal Variability, Tidal Constituents, Tide.

I. INTRODUCTION

Tides are the periodic rise and fall of sea level caused by the gravitational force of the moon and the sun and by the rotation of the earth. The moon exerts a greater influence on tides due to its proximity, but the sun also has a significant impact on tides. The position of the moon and sun relative to Earth and the shape of the ocean basin also influence tides, leading to complex tidal patterns. Tides can vary in their height, timing, and duration, depending on location and the influence of other factors such as winds, currents, and local geography. Tides can also vary with the seasons, due to changes in the position of the moon and sun relative to Earth, as well as changes in atmospheric conditions and ocean currents. The complex interplay of these factors makes it difficult to predict tides with certainty, leading to complex tidal patterns that can vary significantly from one location to another (Hargan, 2000).

Tidal constituents are the fundamental elements of the tidal wave used to describe and understand tidal behavior. They represent the periodic changes in water levels at a specific location, resulting from the gravitational interaction between the Earth, the Moon, and the Sun. The tidal wave is a complex phenomenon and cannot be described by a single frequency or a simple sinusoidal wave. It is composed of a number of different frequency components, each of which contributes to the overall tidal behavior at a particular location. Each tidal constituent possesses a unique period, as well as two harmonic constants: amplitude and phase. Tidal constituents can be categorized into three groups based on their periods: semi-diurnal constituents, diurnal constituents, and long-period (or mixed-frequency) constituents. The number of tidal constituents varies with the duration of the observational period, as each constituent corresponds to a distinct period. Consequently, longer observation periods yield a greater number of tidal constituents (Mousavian and Hossainali, 2012).

Harmonic analysis is a method used in the study of tides to decompose complex tidal data into individual tidal constituents or harmonics (Foreman & Henry, 1979). Each tidal constituent represents a specific frequency of the tidal oscillation, and the amplitude and phase of each constituent determine its contribution to the overall tidal signal (Foreman & Henry, 1989). Specialized software is used to perform harmonic analysis on tidal data which is capable of fitting a set of sinusoidal functions to the observed data. The output of the harmonic analysis will typically include the amplitude and phase of each constituent. The resulting amplitudes and phases can then be used to predict tidal heights at any time in the future.

Seasons are the regular changes in weather patterns that occur throughout the year. There are different kinds of changes in weather patterns during monsoon seasons. The winds, rainfall, ocean surface circulation, and water mass movement all undergo spatially variable and seasonal changes throughout the monsoon, which may all have an impact on the tides (Devlin et al., 2018). The effects of seasonal changes on tides can vary based on the location. Sri Lanka experiences two main monsoon seasons, which are the Southwest monsoon and the Northeast monsoon. The Southwest monsoon typically occurs from May to September, while the Northeast monsoon occurs from December to February. These monsoons can have a significant impact on the tides in Sri Lanka, causing variations in the height and timing of tides (Munasinghe and Gunasekara, 2017). Moreover, the tide is influenced by each of the tidal constituents, and changes in the characteristics of these constituents can lead to changes in sea level. Understanding the seasonal variability of tidal constituents is crucial for accurately predicting the behavior of the tides and sea level fluctuations. Therefore, it is necessary to perform an analysis to identify the seasonal variability of tidal constituents. This study was carried out to analyze, how the seasonal variations around Sri Lanka affect to tidal constituents and MSL.

II. METHODOLOGY

The obtained tidal data used in this study was collected from the tide gauge at Colombo. As well, the obtained data consist of hourly collected data. The collected data are often complex and require specialized methods for extracting meaningful information. Various methods for processing and analyzing tidal data exist, including harmonic analysis. In this study, a specialized software is used to perform harmonic analysis.

For the study, a dataset spanning seven years was selected. The period from October to the following year's September was considered as one year. The seven years of the dataset are as follows: 2013/102014/9, 2015/10-2016/9, 2016/10-2017/9, 2017/102018/9, 2018/10-2019/9, 2019/10-2020/9, 2020/102021/9. The data for each year was then separated into two sets, each covering one monsoon season.

The first set of data covers the period from October to March for the Northeast monsoon, and the second set of data covers the period from April to September for the Southwest monsoon. Subsequently, the TOTIS software was used to process each dataset.

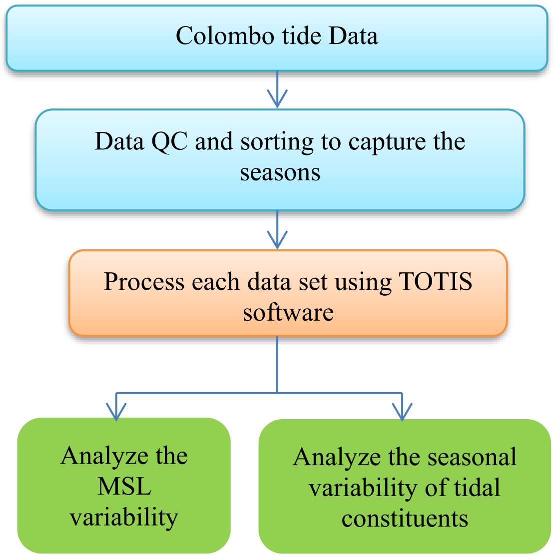

Fig 1. Methodology Flowchart

III. RESULTS AND DISCUSSION

The aim of the result analysis was to investigate the seasonal variability of tidal constituents and MSL and to identify any significant changes or patterns that were observed. Each analysis reports include MSL value and tidal constituents' amplitude and phase value. The necessary values were extracted from those reports to analyze the seasonal variability.

A.Analysis Mean Sea Level(MSL) variation with the seasonal variations

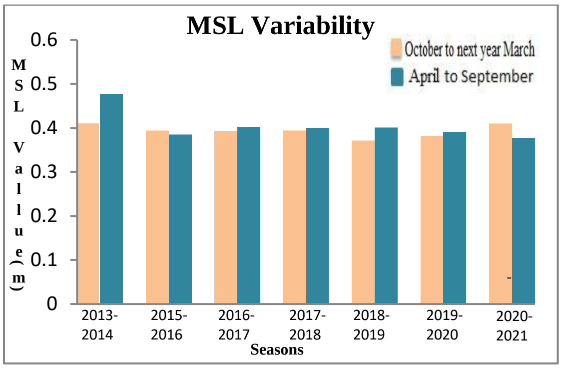

Fig 2. MSL Variability

The MSL values during the northeast monsoon were found to be lower than the values during the southwest monsoon in all years except in the 2015-2016 and 2020-2021 years, as shown in Fig. 2. However, the MSL value exhibited a similar pattern in the other five years except for the 2015-2016 and 2020-2021 years with seasonal variations.

The ONI Index values were considered over the seven-year period to identify if ENSO (El Nino Southern Oscillation) was responsible for deviations in MSL. According to the ONI Index values, a very strong El Nino event occurred during the northeast monsoon months of the 2015-2016 year. A moderate La Nina event occurred during the northeast monsoon months of the 2020-2021 year (Climate Prediction Center - ONI, 2023). El Nino and La Nina are two opposite phenomena; therefore, the results of these events should be opposite. However, the Mean Sea Level (MSL) rose during both events. This suggests that these events are not the reason for the MSL pattern changed.

To investigate the reasons for the change in the pattern of Mean Sea Level (MSL), tidal data was obtained from the PSMSL website for the Male tidal station in Maldives, covering the seven-year period that was used for the study. The data was processed using the same methodology as the Colombo tidal data processing.

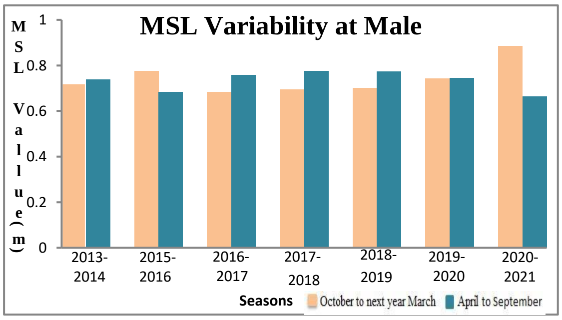

Fig 3.MSL Variability at Male

Fig. 3 shows the MSL variability graph for Male in the Maldives. The MSL values exhibit the same pattern as those exhibited in Colombo MSL variability, and this pattern also undergoes changes in the same years as Colombo. Thus, the results indicate that a common factor may have influenced the changes in MSL patterns at both locations.

B. Analysis of the seasonal variability of the tidal constituents.

In this study, 12 tidal constituents were selected to compare their amplitude and phase variability across different categories. The selected constituents were as follows:

Diurnal constituents: - K1,M1,O1,S1
Semidiurnal constituents: - K2,M2,S2,T2
Mixed-Frequency constituents:-MF,MM,MSF,SSA

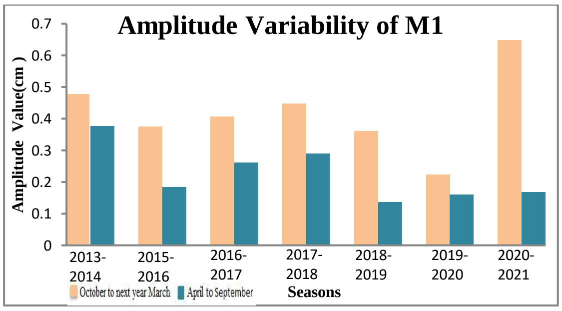

Fig 4.Amplitude variability of M1

The amplitude of M1 showed a consistent pattern with larger amplitudes during the northeast monsoon compared to the southwest monsoon in all years, as depicted in Fig 4.

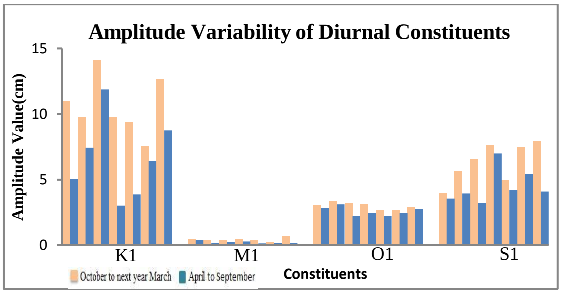

Fig 5.Amplitude variability of Diurnal constituents

The amplitude value of the northeast monsoon was greater than the amplitude value of the southwest monsoon for all constituents in all years, as shown in Fig 5. Therefore, it can be said that the amplitude of all diurnal constituents exhibited the same pattern with the seasonal variations.

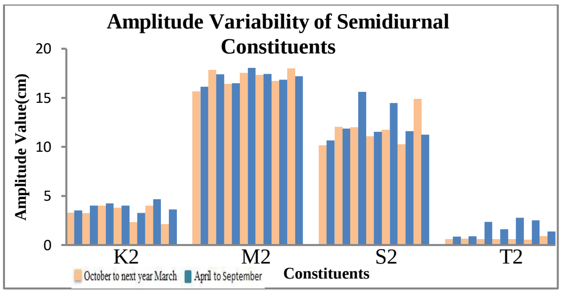

Fig 6.Amplitude variability of Semidiurnal constituents

Fig 6 shows the amplitude variability of all four semidiurnal constituents. The amplitude value of the northeast monsoon was less than the amplitude value of the southwest monsoon for all constituents in all years, except M2 and S2 in the 2015-2016 and 2020-2021 years. During the northeast of the years 2015-2016 and 2020-2021, the mean sea level was observed to have increased, as shown in Fig 2.Liang et al. (2022) demonstrated that sea level rise tends to enlarge the amplitude of semidiurnal tidal constituents rather than other constituents. The study also showed that the amplitudes of M2 and S2 tidal constituents are more sensitive to local depth changes. This could be the reason for the change in the amplitude variability pattern in the years 2015-2016 and 2020-2021.However, the amplitude of all semidiurnal constituents exhibits the same pattern with seasonal variations.

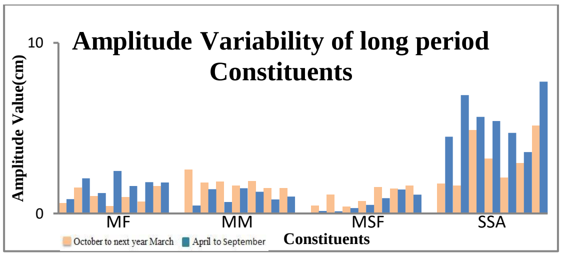

Fig 7.Amplitude variability of Mix-frequency constituents

The amplitude variability of all four long period tidal constituents considered in the study is shown in Fig 7. The figure shows that all four constituents exhibit a pattern in all years with seasonal variations but the patterns of all four constituents are not the same. Thus, the amplitudes of tidal constituents exhibited patterns with seasonal variations, as shown in Fig 5, Fig 6, and Fig 7. These patterns changed based on the category of the tidal constituents.

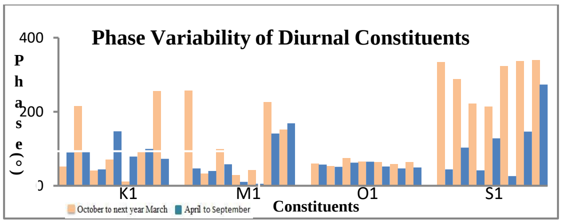

Fig 8.Phase variability of diurnal constituents

Fig 8 shows the phase variability of all four diurnal constituents considered in the study. The phase of all four diurnal constituents exhibited a pattern with seasonal variations, although K1 and M1 exhibited different patterns in the years 2015-2016 and 2020-2021. However, the patterns of all four constituents were not the same. Furthermore, the MSL pattern changed in the 2015-2016 and 2020-2021 years according to Fig 2. This suggests a possible relationship between the change in the MSL pattern and the change in the phase patterns of K1 and M1. Fig.9 shows the phase variability of semidiurnal constituents.

The phase of all four semidiurnal constituents exhibited a pattern with seasonal variations, although M2 and S2 changed patterns in the years 2015-2016 and 2020-2021, and the patterns of all four constituents were not the same as each other. Furthermore, the Mean Sea Level (MSL) exhibited pattern changes in the same years as the phase patterns were altered, as depicted in Fig 2.This could be a possible reason for the change in the phase patterns of M2 and S2.

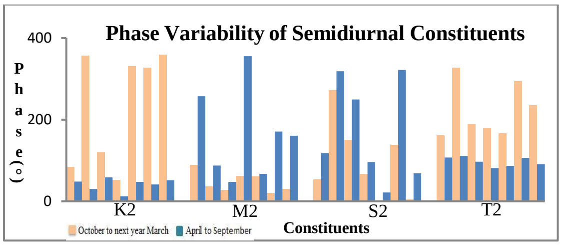

Fig 9.Phase variability of Semidiurnal constituents

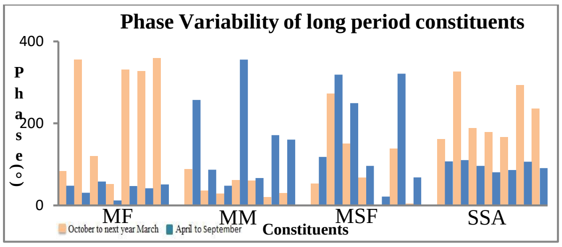

Figure 10.Phase variability of Mix-frequency constituents

Fig 10 shows the phase variability of all four long period constituents considered in the study. In all years, all four mixed-frequency constituents exhibited a pattern with seasonal variations; however, the patterns of these constituents were not the same.

IV.CONCLUSION

The MSL value for Colombo during the northeast monsoon was found to be lower than the values during the southwest monsoon in all years, except for the years 2015-2016 and 2020-2021. The MSL pattern of Male changed in the same years as the MSL pattern of Colombo. Thus, it can be concluded that a common reason may have influenced the changes in MSL patterns at both locations. Further research is needed to identify the causes for the variations observed in the abovementioned two years, along with other factors that may affect tidal variability. However, it can be concluded the MSL value exhibits the same pattern with seasonal variations by showing a high value during the southwest monsoon. The amplitude of all diurnal constituents was higher during the northeast monsoon compared to the southwest monsoon, indicating this pattern in all years for Colombo. Additionally, the amplitude of all semidiurnal constituents exhibited the opposite pattern of the diurnal constituents, while M2 and S2 changed patterns during the years 2015-2016 and 2020-2021. A previous study has proven that the amplitude pattern of M2 and S2 can be changed due to the MSL pattern change. Moreover, the amplitude of long-period constituents exhibited a similar pattern in all years, although patterns differed among each constituent. Therefore, it can be concluded that the amplitude of tidal constituents exhibits patterns with seasonal variations based on their respective categories. The phase of all tidal constituents exhibited a similar pattern with seasonal variations in all years, although K1, M1, M2, and S2 exhibited different patterns in the years 2015-2016 and 2020-2021. However, there is no relationship between these patterns, unlike the patterns of amplitude variability. The pattern of mean sea level (MSL) changes in the same years as the phase patterns of K1, M1, M2, and S2 constituents, indicating a possible relationship between the pattern changes. Finally, it can be concluded that amplitude and phase of tidal constituents' exhibit patterns with seasonal variations.

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