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Trends in Tidal Levels and Mean Sea Level in the Gulf of Thailand

Nitinun Pongsiri[1,2], Rhysa McNeil[1,2]*, and Somporn Chuai-Aree[1,2]
[1]*Faculty of Science and Technology, Prince of Songkla University, Pattani 94000, Thailand*
[2]*Centre of Excellence in Mathematics, Bangkok 10400, Thailand*

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Abstract – Astronomical tides have a major impact on coastal sediment distribution, seawater levels, coastal navigation, and other coastal dynamics. Any significant change to tides could have impacts on coastal ecosystems. This study explored the hourly water level from 11 tidal gauge stations along the Gulf of Thailand over different periods using harmonic analysis. Secular trends of tidal levels, tidal range, mean sea level and tidal constituents were assessed using a linear regression model. We found changes in all the tidal levels assessed. Increasing trends were observed for almost all tidal levels and the mean sea level at all locations. At most of the locations, the trends in tidal levels were similar to the mean sea level. Widespread increasing trends were observed in relation to the tidal levels, and in most cases, the trends were consistent with the mean sea level. Analysis of the tidal harmonic constituents showed significant trends for the luni-solar diurnal constituent (K_1) at most stations. However, the magnitude of the trends in the harmonic constituents was less pronounced compared to the trends in water levels. Coastal management policies should take into account these widespread changes in tides.

Keywords – Gulf of Thailand, mean sea level, tidal constituent, tidal level, trend

1. Introduction

The water levels of coastal areas are very important as their dynamics have a large impact on fisheries, marine resource management, and coastal engineering projects (Kantha and Clayson 2000). In recent years, analysis of water levels has become vital due to the huge impact climate change is having on sea-level rise. However, such an analysis is quite complex because the water levels depend on the tides, mean sea level (MSL) and non-tidal residuals. A change in any of these components affects the variability of the water level (Rhein et al. 2013). While attempting to model the future dynamics of water levels, it is important to understand their historical trends and variability (Wahl and Chambers 2015, 2016).

There is evidence in the literature to suggest that the trends in global extreme water levels over the last century are consistent with those of the MSL. For example, Woodworth and Blackman (2004), using global tidal datasets from 141 stations, found that interannual variations of extreme water levels were consistent with those of the MSL. Similarly, increments in extreme high waters, dating back to the 1970s, were detected by Menéndez and Woodworth (2010) based on quasi-global datasets. These increments in the extreme high water levels were found to have been caused by a rise in the MSL. Also, the magnitude of tidal levels and tidal ranges have been observed to be consistent with that of the MSL at many locations around the world (Mawdsley et al. 2015). In the analysis of tidal water levels, different methods have been employed. Consistent among them are the classical harmonic analysis (Rasheed and Chua 2014; Mawdsley et al. 2015; Santamaria-Aguilar et al. 2017) and tidal percentile analysis (Woodworth and Blackman 2004; Mudersbach et al. 2013; Santamaria-Aguilar et al. 2017). Apart from the global water level and a handful of regional water level analyses that target isolated locations around Asia and Africa (Marcos et al. 2015; Mawdsley et al. 2015; Haigh et al. 2019; Devlin et al. 2018), these regions lack extensive research on extreme water levels, partly due to a lack of credible observational data (Menéndez and Woodworth 2010). One such place is Thailand, where trends and variability of long-term extreme water levels have been analyzed from a global perspective (Mawdsley et al. 2015).

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*Corresponding author. E-mail: rhysa.m@psu.ac.th

In terms of geographical location, in Thailand, the eastern region borders the Gulf of Thailand and the southern parts lie between the Andaman Sea and the Gulf of Thailand. Marine inhabitants and terrestrial ecosystems along the coastline are immediately affected by extreme events such as storms due to the northeast and southwest monsoon winds. The eastern and western coastlines of southern Thailand serve as a hub for the majority of tourist activities in Thailand. Although there have been local studies to characterize and explain the water level trends, these studies focused on the MSL, which represents just one component of the water level (Saramul and Ezer 2014; Sojisuporn et al. 2013; Trisirisatayawong et al. 2011). Time-series data on observed water levels are available for the majority of the tidal gauge stations along Thailand's coast. At these stations, the Marine Department of Thailand collects hourly water level data. The hourly time-series data from the Marine Department has not been extensively analyzed in any global or regional study.

This study explores the hourly tide-gauge datasets of 11 stations over different periods using harmonic analysis and takes into account the effects of the 18.6-year lunar-nodal cycle. We investigate the secular trends in tidal levels, tidal ranges and MSL, as well as the main tidal constituents, luni-solar declination diurnal tide (K_1), principal lunar declination diurnal tide (O_1), principal lunar semi-diurnal tide (M_2) and principal solar diurnal tide (S_2), at various stations along the Gulf of Thailand using a linear regression model. The water levels include two high water levels, two low water levels, and two tidal ranges per day.

2. Data and Methods

Water level data, which are recorded hourly by the Marine Department of Thailand (https://www.md.go.th/md/), were obtained for 16 tidal gauge stations along the Gulf of Thailand. These stations cover the eastern coast of the country. The data for each station covered different periods. Standard criteria were used to select the records for each station. First, to ensure sufficient length and data quality, a calendar year of water level records was included if at least 75% of hourly

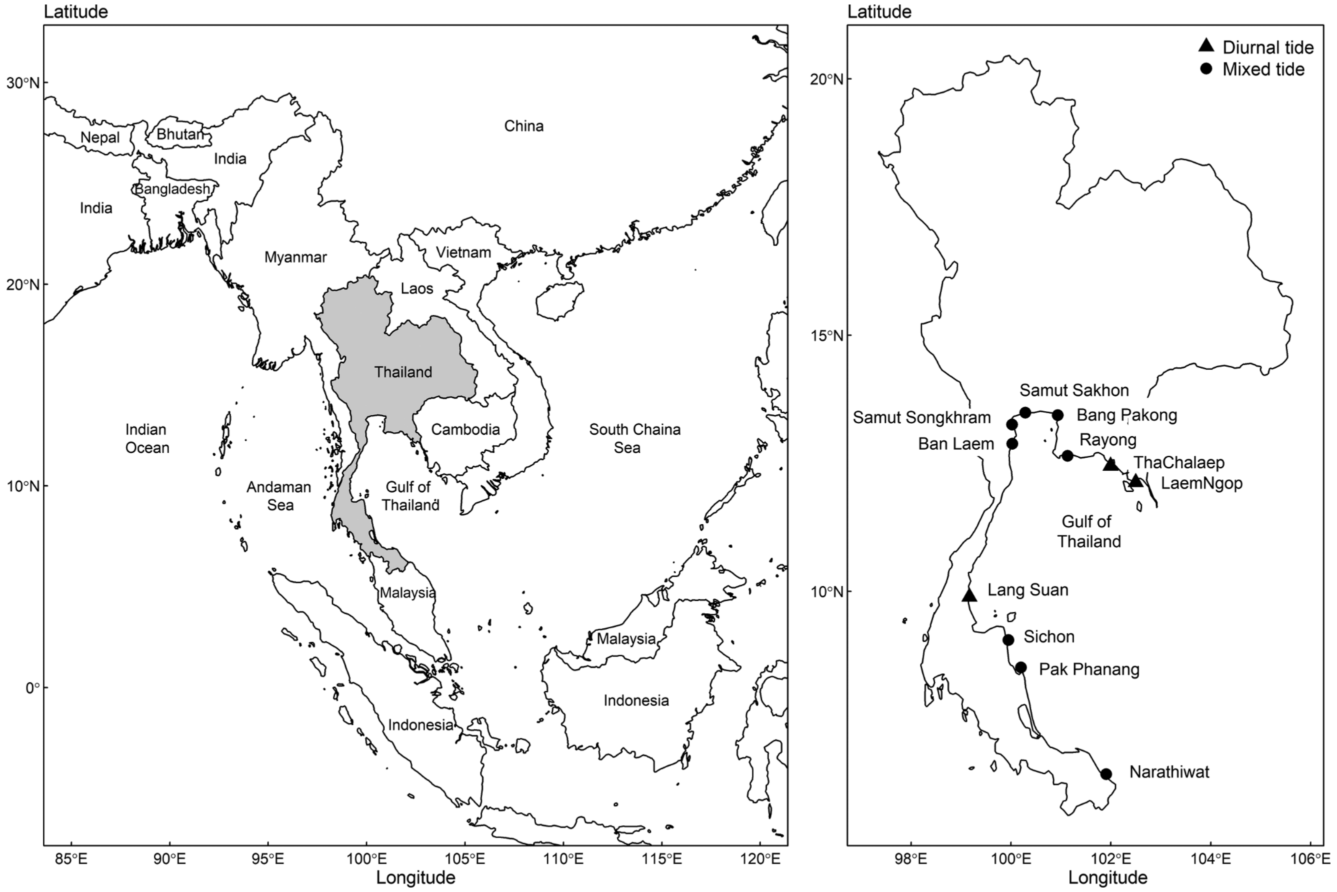

Fig. 1. Tidal gauge locations

values were present. Next, in order to account for the lunar-nodal cycle (18.61 years), the available data from each station was required to span at least 19 years. A 19-year span ensured that at least one lunar-nodal cycle is covered and the phase and amplitude of nodal modulations are appropriately approximated (Mawdsley et al. 2015; Woodworth et al. 1991). Of the 16 tidal gauge stations, 11 satisfied these inclusion criteria and were included in the analysis. The locations of these 11 stations are shown in Fig. 1. The data span for each station, as well as the length of available water level records, was different. The Samut Sakhon station had the highest data span of 40 years (1978–2017), with 35 years of the data available for analysis. The span and data availability (in years) for the 11 stations is shown in Fig. 2, with gaps representing years with less than 75% of data available. The hourly water levels for each of the 11 stations were detrended to remove the MSL effects. Instead of an annual mean, detrending was done by subtracting a 30-day centered moving average of each hourly record from the time-series (Carlberg 2015). The 30-day moving average is used to remove seasonal variations, time-scale signals related to land movement, and seasonal cycles caused mainly by oceanographic factors (Mawdsley et al. 2015). Although the 30-day signals could affect the solar monthly (MSm) and lunar monthly (Mm) constituents, these constituents reflect more meteorological aspects than tidal energy, and therefore, have minimal effects on the reconstructed tidal levels (Crawford 1982).

The detrended time series records for each station were separated into calendar years, and a harmonic analysis was done for each year of records to separate the astronomical tides and non-tidal residuals. The harmonic analysis was done using the *ftide* function from the TideHarmonics package in R (Stephenson 2016). The function estimates tidal harmonic constituents from observed water level records. Incorporated in the function are selectable tidal harmonics and other options which account for lunar-nodal cycles. The function also allows for gaps in the water level observation, but missing values in the date/time are not allowed. The harmonic analysis was performed using a standard set of 60 constituents. Amplitudes and phase lag obtained from the harmonic analysis were used to re-construct tidal contributions to the water levels for each calendar year.

Tidal levels and tide ranges were calculated based on the site classification (semi-diurnal, diurnal, or mixed). Four of

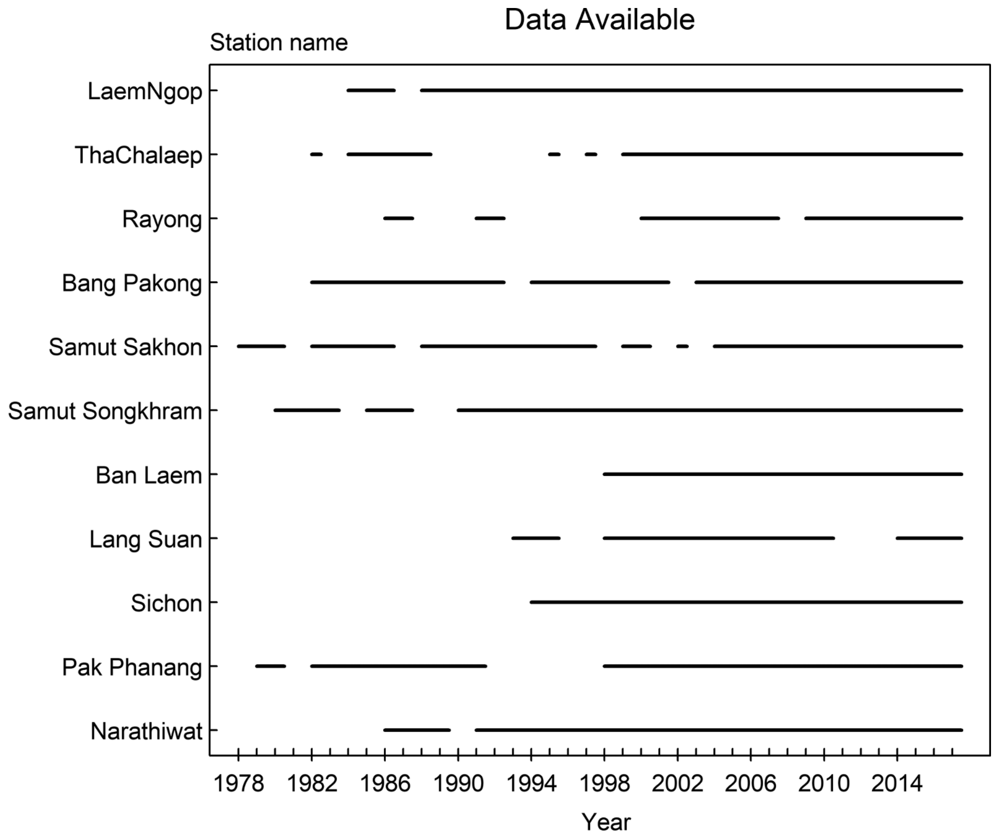

Fig. 2. Data span and data availability for each year of the 11 stations

the eleven stations (LaemNgop, ThaChalaep, Rayong, and Lang Suan) had predominantly diurnal tides, with one high and one low tide per day. The remaining stations had mixed tides, with two unequal high and two unequal low tides per day. Tidal levels were calculated based on the amplitudes of tidal constituents from the harmonic analysis (Stephenson 2016). For stations with diurnal and mixed tides, the standard tidal levels calculated include:

Mean Sea Level (MSL) = Z
Mean Higher High Water (MHHW) = $Z + (M_2 + K_1 + O_1)$
Mean Lower High Water (MLHW) = $Z + |M_2 - (K_1 + O_1)|$
Mean Higher Low Water (MHLW) = $Z - |M_2 - (K_1 + O_1)|$
Mean Lower Low Water (MLLW) = $Z - (M_2 + K_1 + O_1)$.

Z was estimated as the normal mean based on the number of observations available for each calendar year. Tidal ranges were estimated as shown below.

Greater Diurnal Tidal Range (GDTR) = MHHW – MLLW
Lesser Diurnal Tidal Range (LDTR) = MLHW – MHLW.

These tidal water levels were calculated for each year, and a linear regression model was used to assess the trends over the study period. Significant trends were identified based on the p-value from the linear model, assessing a null hypothesis that the slope of the fitted line was equal to zero, using a critical value (alpha) of 0.05. Trends with a p-value less than alpha were considered statistically significant. The changes in the main tidal constituents K_1, O_1, M_2 and S_2 were examined.

3. Results

Results from the tidal analysis reveal that there were changes in the tidal water levels at all 11 stations. While most of the observed changes in tidal levels and tidal ranges were significant, some of them were not. For example, the observed trends of MHHW were significant for all stations (p-value < 0.05) except at Lang Suan, and the trends of MLLW were significant for all stations except the Lang Suan, Pak Phanang and Narathiwat stations (p-value > 0.05) as shown in Table 1. The Rayong, Lang Suan, and Pak Phanang stations also had non-significant trends of MSL. The trends of six tidal levels and the MSL of selected stations are shown in Fig. 3. due to increases in annual MHHW and MLLW at most of the stations. The trends of GDTR were not significant for LaemNgop, Ban Laem, and Lang Suan stations. The increasing trend of GDTR was more pronounced at Narathiwat (11.36 mm/yr) and Rayong stations (10.23 mm/yr). In Narathiwat, high GDTR arises from the opposite trends of MHHW (10.74 mm/yr) and MLLW (-0.61 mm/yr). Similar to Narathiwat station, Rayong station also had increasing trends of MHHW (6.63 mm/yr) and decreasing trends of MLLW (-3.56 mm/yr). The stations with the lowest decreasing trends in GDTR were Lang Suan and Sichon. The trends of both MHHW and MLLW at Lang Suan were increasing, although non-significant, and these resulted in a non-significant increasing trend of 0.68 mm/yr for GDTR. However, the trend of GDTR (1.70 mm/yr) at Sichon was significantly positive, and the changes of MHHW and MLLW were also significant (6.64 mm/yr and 4.94 mm/yr, respectively). Although the highest increase of MHHW was observed at Samut Sakhon station, a corresponding trend of GDTR was relatively low compared to Narathiwat station. The trends of each tidal water level and MSL for each station are shown in Table 1. For all stations, trends in MSL and GDTR were similar, although the magnitude of the trends was different. The Samut Sakhon tidal gauge station recorded

Table 1. Trends in tidal levels and tide ranges (mm/yr) at 11 tidal gauge stations along the Gulf of Thailand

Station	MHHW	MLHW	MHLW	MLLW	GDTR	LDTR	MSL
Laem Ngop	4.037 ± 0.655*	3.289 ± 0.562*	3.182 ± 0.545*	2.434 ± 0.676*	1.604 ± 0.844	0.107 ± 0.407	3.236 ± 0.515*
Tha Chalaep	18.160 ± 2.389*	17.156 ± 2.281*	11.602 ± 2.177*	10.598 ± 2.215*	7.563 ± 2.059*	5.554 ± 1.702*	14.379 ± 2.06*
Rayong	6.632 ± 0.905*	3.897 ± 0.917*	-0.863 ± 1.22	-3.598 ± 1.409*	10.23 ± 1.227*	4.760 ± 0.746*	1.517 ± 1.013
Bang Pakong	6.732 ± 0.989*	4.921 ± 0.97*	4.770 ± 0.894*	2.958 ± 0.935*	3.774 ± 0.871*	0.151 ± 0.730	4.845 ± 0.858*
Samut Sakhon	21.832 ± 0.797*	18.194 ± 0.88*	19.140 ± 0.760*	15.502 ± 0.936*	6.330 ± 0.971*	-0.946 ± 0.790	18.667 ± 0.721*
Samut Songkhram	18.072 ± 1.036*	14.711 ± 0.856*	14.161 ± 0.963*	10.799 ± 0.823*	7.272 ± 0.807*	0.550 ± 0.685	14.436 ± 0.844*
Ban Laem	7.591 ± 2.006*	7.205 ± 1.608*	5.829 ± 1.682*	5.443 ± 1.283*	2.148 ± 1.580	1.376 ± 1.409	6.517 ± 1.487*
Lang Suan	3.520 ± 1.698	3.585 ± 1.753	2.770 ± 1.888	2.836 ± 2.031	0.684 ± 1.087	0.815 ± 0.666	3.178 ± 1.791
Sichon	6.644 ± 1.598*	5.937 ± 1.693*	5.651 ± 1.595*	4.944 ± 1.749*	1.701 ± 0.689*	0.286 ± 0.260	5.794 ± 1.640*
Pak Phanang	8.544 ± 2.327*	4.257 ± 2.418	4.362 ± 2.453	0.075 ± 2.610	8.469 ± 0.89*	-0.105 ± 0.268	4.309 ± 2.432
Narathiwat	10.744 ± 0.969*	5.550 ± 0.984*	4.582 ± 1.156*	-0.612 ± 1.857	11.356 ± 2.15*	0.968 ± 0.674	5.066 ± 1.019*

*Significance level of 0.05

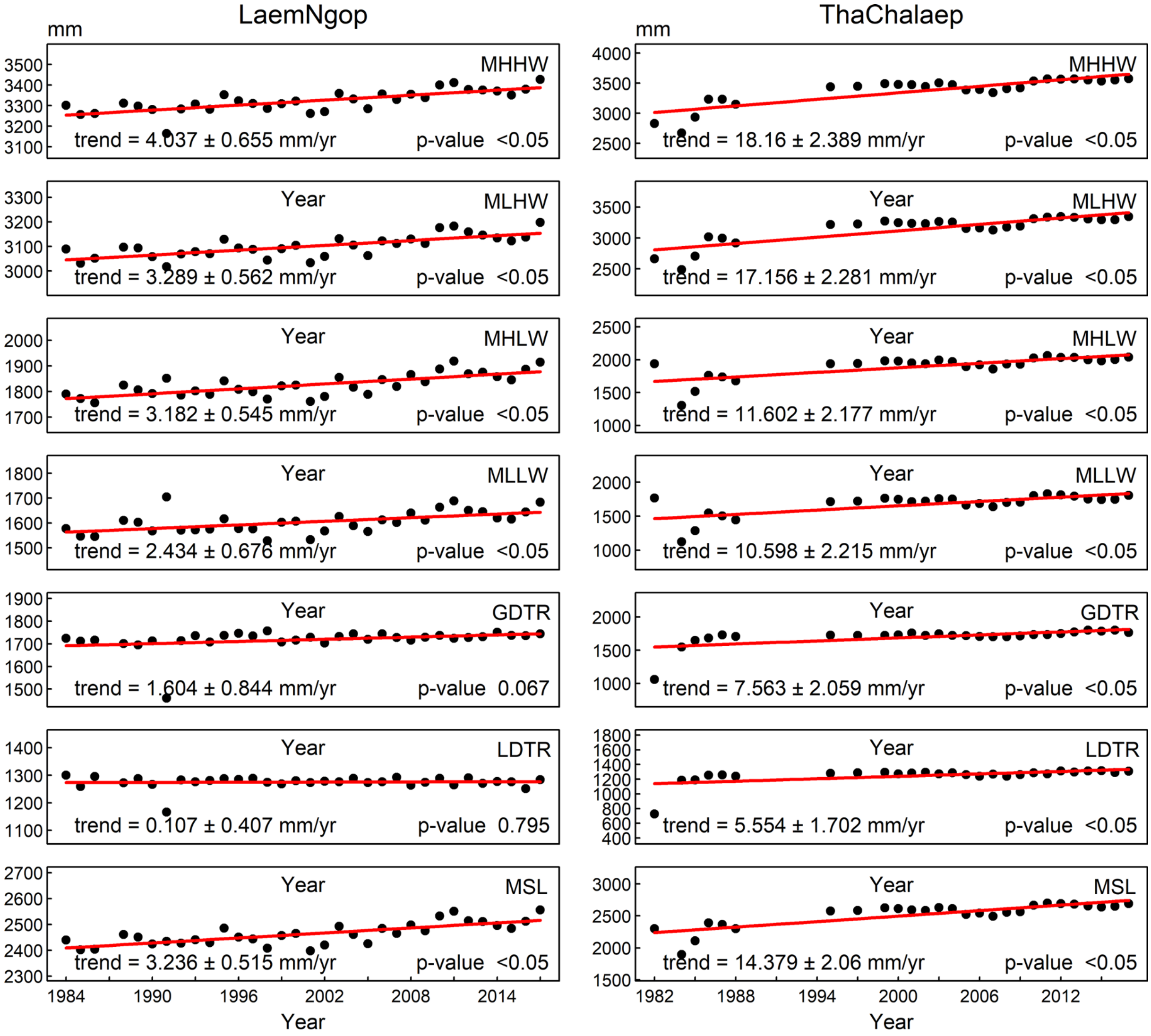

Fig. 3. Trends of six tidal levels and mean sea level for LaemNgop and ThaChalaep stations

the highest increasing trend of MSL (18.67 mm/yr), while the lowest increasing trend was observed at LaemNgop station (3.24 mm/yr). Although the trends of MSL were lowest for Rayong and Lang Suan stations, they were not significant.

The trends of LDTR found were similar to the trends of GDTR, except at Samut Sakhon and Pak Phanang stations where the trends of LDTR were negative. However, unlike GDTR, the magnitude of LDTR trends was generally lower. The only station where the LDTR trend was higher than the GDTR trend was Lang Suan. Apart from ThaChalaep and Rayong stations, the LDTR trends were not significant for the remaining nine stations. The magnitude of the increasing trends of LDTR was 5.55 mm/yr for ThaChalaep station and 4.76 mm/yr for Rayong station. The MHLW and MLHW in Rayong station revealed opposite trends, with the former decreasing (-0.86 mm/yr) and the latter increasing at a magnitude of 3.90 mm/yr. The maps shown in Fig. 4 indicate the summary of the trends of tidal levels, tidal ranges and MSL at all stations. The K_1 constituent showed significant trends in amplitude at seven of the eleven stations. The trends in the amplitude of the K_1 constituent were not statistically significant at LaemNgop, Lang Suan, Sichon and Pak Phanang stations. At ThaChaleap and Rayong the amplitudes exceeded 2 mm/yr, while that of Narathiwat was -1.84 mm/yr. The trends of O_2 and M_2 amplitudes revealed significant increases at Rayong, Bang Pakong, and Samut Songkhram stations. No significant decreases were found in the amplitudes of O_2 and M_2 at any of the stations. For the amplitude of the S_2

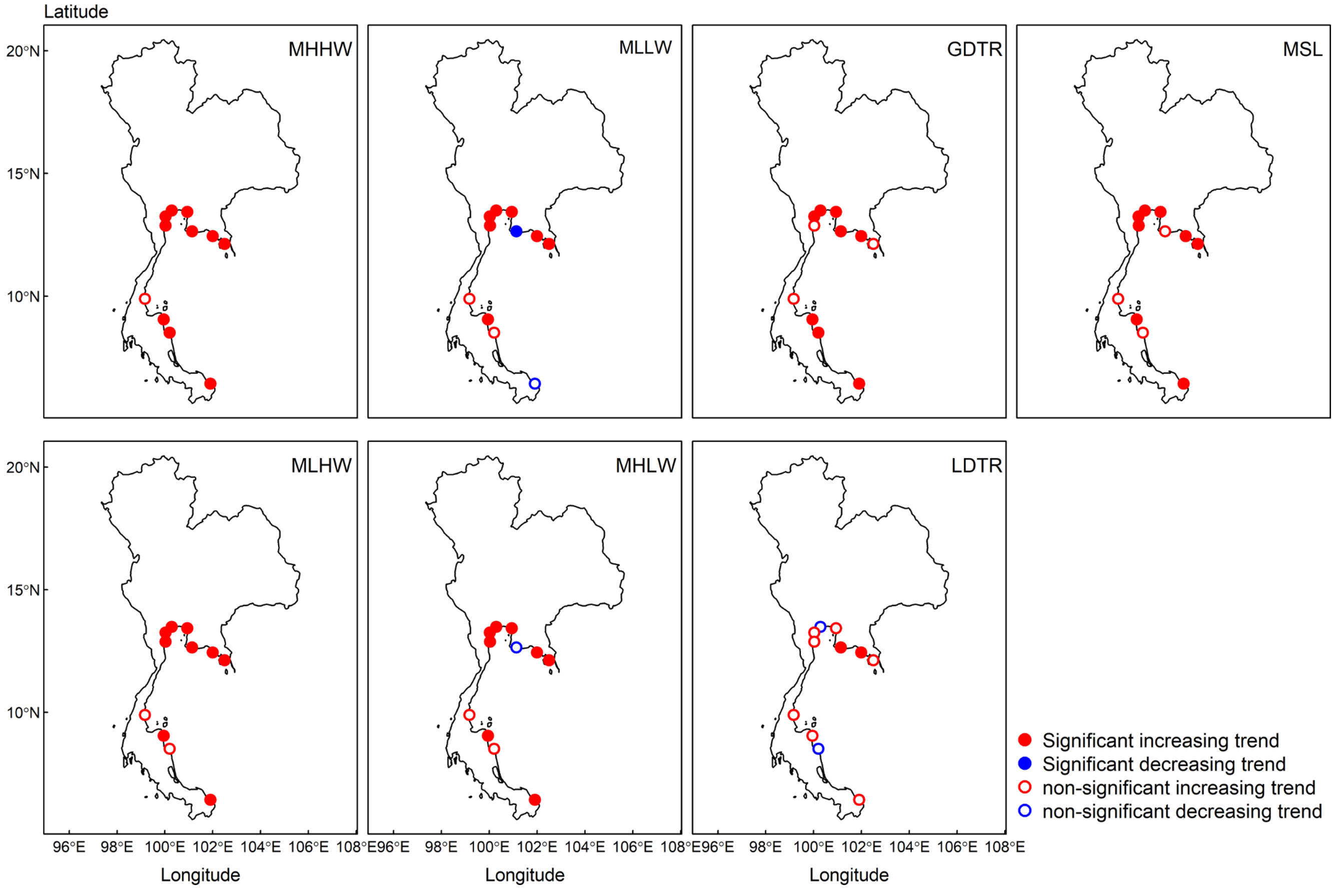

Fig. 4. Trends of tidal levels, tidal ranges and mean sea level

constituent, three stations (ThaChalaep, Samut Sakhon and Samut Songkhram) had significantly decreasing trends between 0.84 mm/yr and 0.30 mm/yr while an increasing trend in magnitude of 1.44 mm/yr was observed at the Lang Suan station. The trends in amplitudes of tidal constituents are shown in the table below. For the diurnal constituents, a significantly increasing trend was found for the O_1 constituent at Narathiwat station and an opposite trend was found for the K_1 constituent at

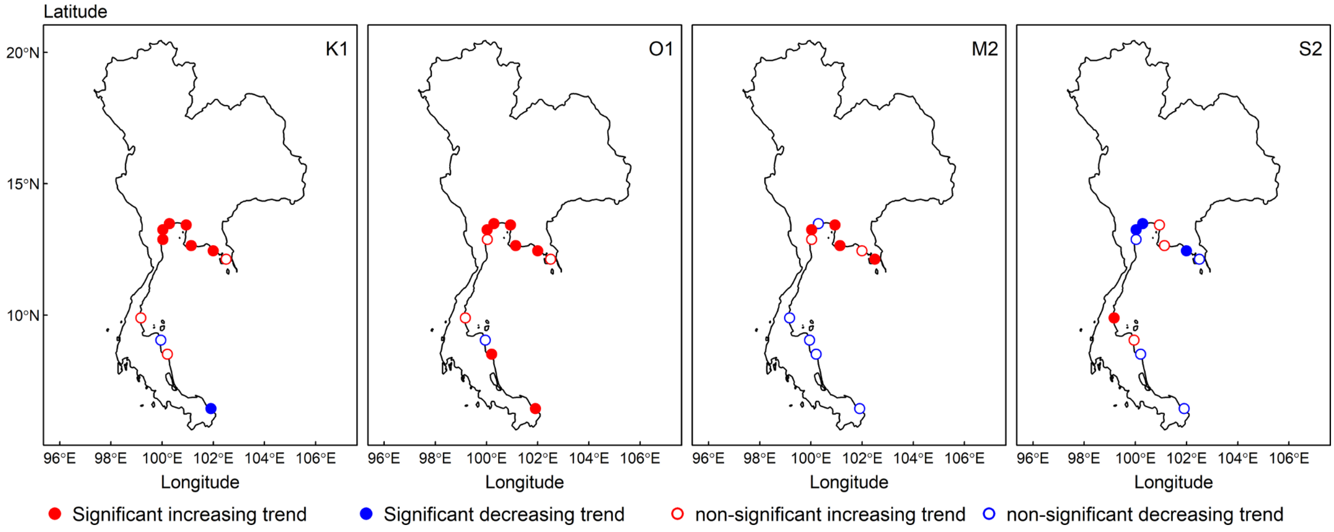

Fig. 5. Trends of amplitude

Table 2. Amplitudes of the tidal constituents

Station	Amplitude			
	K_1	O_1	M_2	S_2
LaemNgop	0.021 ± 0.073	0.395 ± 0.280	0.374 ± 0.130*	-0.188 ± 0.094
ThaChalaep	2.004 ± 0.739*	0.948 ± 0.302*	0.210 ± 0.165	-0.836 ± 0.229*
Rayong	2.106 ± 0.249*	1.641 ± 0.254*	1.364 ± 0.165*	0.132 ± 0.147
Bang Pakong	0.592 ± 0.097*	0.906 ± 0.378*	1.228 ± 0.323*	0.007 ± 0.099
Samut Sakhon	0.638 ± 0.119*	1.819 ± 0.391*	-0.314 ± 0.253	-0.394 ± 0.143*
Samut Songkhram	1.047 ± 0.097*	1.681 ± 0.340*	0.878 ± 0.256*	-0.301 ± 0.105*
Ban Laem	0.494 ± 0.222*	0.193 ± 0.676	0.905 ± 0.778	-0.940 ± 0.488
Lang Suan	0.222 ± 0.203	0.330 ± 0.613	-0.141 ± 0.158	1.447 ± 0.439*
Sichon	-0.112 ± 0.375	-0.063 ± 0.821	-0.042 ± 0.133	0.469 ± 0.498
Pak Phanang	0.295 ± 0.783	1.151 ± 0.162*	-0.436 ± 0.315	-0.099 ± 0.112
Narathiwat	-1.838 ± 0.626*	2.239 ± 0.412*	-0.287 ± 0.220	-0.151 ± 0.178

*Significance level of 0.05

Samut Sakhon station. The summary of trends of amplitudes of the four main tidal constituents are shown in Fig. 5.

4. Discussion and Conclusion

Changes in the MSL, astronomical tides, and non-tidal residuals can cause significant long-term changes in water level. This study has presented long-term trends of astronomical tides and MSL along the Gulf of Thailand, based on trends of tidal levels, tidal ranges and tidal constituents at 11 tidal gauge stations. Although local studies have been conducted on the water level trends in Thailand, most of them focused on either harmonic constituents or MSL; none of them went beyond the MSL to emphasize the changes in the mean levels of astronomical tides origin. The harmonic and linear regression analyses from this study show that long-term changes have occurred not just in the MSL but also in the tidal levels and tidal ranges, as well as the underlying harmonic constituents at each station.

Generally, long-term increasing trends were observed in the tidal levels, mainly due to increases found in the amplitudes of the main diurnal constituents K_1 and O_1. The MHHW, MLHW, GDTR and MSL present general increasing trends at all stations along the coast. These patterns are consistent with the trends observed throughout South-east Asia (Mawsdley et al. 2015). Three stations in the upper Gulf of Thailand (ThaChalaep, Samut Sakhon and Samut Songkhram) illustrate the highest trends in all tidal levels and the MSL. At the same stations, the amplitudes of K_1 and O_1 show trends consistent with the tidal levels and MSL. Another study by Saramul and Ezer (2014) also found higher increasing trends of MSL at stations in the upper Gulf of Thailand compared to other locations, which was attributed to land subsidence. An analysis from Sojisuporn et al. (2013) also showed that the inter-annual deviations of MSL were higher at the upper Gulf of Thailand. A major source of water in the upper Gulf of Thailand is the South China continental shelf. Hence, water heights and sea levels are likely to be higher and more varied than at other parts of the Gulf of Thailand (Aungsakul et al. 2007).

The MSL trends observed in this study with tidal gauge data could be different if compared the estimate with satellite altimetry data. Such differences can be explained by annual and decadal variations such as the El Nino Southern Oscillation (ENSO) and regional vertical co-seismic displacements (Trisirisatayawong et al. 2011). The changes in tidal levels and ranges could have been caused by other factors as well. For instance, on a global scale, changes in tidal levels and tidal ranges have been observed at different locations, and these changes are caused by underlying large scale location-specific oceanic processes (Mawdsley et al. 2015). While changes in MSL and ocean stratification have helped explain tidal changes on a global scale, tidal changes on a local scale are caused by land reclamation, dredging, river flow, surface area and other local morphological factors (Woodworth 2010; Hill 2016; Haigh et al. 2019).

Although this study did not attempt to establish a relationship between tidal levels and MSL, the presence of any relationship between them could be positive or negative (Haigh et al. 2019). The correlation between MSL and tidal levels are determined by several mechanisms, including the movement of constituent amphidromic points (Mawdsley et al. 2015;

Jay 2009). Coherent increases were found in the K_1 and M_2 amplitudes, which could be due to shifts in diurnal and semi-diurnal amphidromic regions (Qi-Zhou et al. 1994; Yanagi and Takao 1998; Jay 2009). The present analysis suggests that there could be a significant increase/decrease in water levels at the coastal basin within the next century as a response to changes in both tidal levels and MSL. These significant changes could be catastrophic for coastal inhabitants and coastal ecosystems along the Gulf of Thailand. Consequently, future coastal management policies should take into account these tidal changes and include impact assessments caused by sea-level change.

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