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Report

Recent estimate of sea-level rise in the Gulf of Thailand

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Abstract: The annual local mean sea level (MSL) at 13 tide gauge stations bordering the Gulf of Thailand in Thai waters was used to investigate the apparent sea-level rise over the last 25 years (1985-2009). The annual local MSL was computed by averaging the hourly tidal data at each station for the whole year. The data at 11 stations showed a higher average annual local MSL than the mean Thailand MSL, which was set up over a century ago. The data from most stations showed rising trends of sea level, although at different rates depending on the station location. Averaging the annual local MSL by region into a single time series revealed a linear trend for the sea-level rise of about 5 mm/yr in the last 25-year time span. Land subsidence at the river mouths where the tide-gauge stations are usually located seems to play a major role in the observed higher annual local MSL. The findings are a warning that Thailand may face severe coastal recession in the near future if no measures are taken to halt the land subsidence near the coast.

Keywords: sea-level rise, land subsidence, local mean sea level, Gulf of Thailand

INTRODUCTION

The sea level fluctuates due to glacial–interglacial cycles. Globally, it has risen approximately 120 m since the last glacial maximum approximately 20,000 years ago [1]. It reached a near standstill 2,000-3,000 years ago when the rate of sea-level rise slowed to 0.1-0.2 mm/yr [2]. However, current research [3] shows that the world today is experiencing a rise in sea level due to global warming caused by human activities, which will lead to substantial sea-level rises along much of the world's coastline. The mean sea level (MSL) has increased in the recent past and will continue to rise in the future, possibly at an accelerated rate. The Intergovernmental Panel on Climate Change reported an increasing trend in the mean temperature in South-east Asia during the past several decades, with 0.1-0.3°C increase per decade recorded between 1951-2000. The region has also experienced a decreasing trend in rainfall and rising sea level, at 1-3 mm per year [4]. The projected precipitation during 2090-2099 also shows drier winter and wetter rainy season for the region.

Over the past three decades, there has been some debate on the sea-level rise in the Gulf of Thailand. Punpuk [5] low-pass filtered the hourly tidal data collected during 1960-1966 at two stations, namely KohLak and Sattahip, on the western and eastern coasts of the upper Gulf of Thailand and found that the annual sea level variation was about 0.5 m, and that this was in direct response to the Ekman transport due to the monsoonal wind regimes, while the response to the atmospheric pressure was found to be negligible. In 1992, the same author analysed the 50-year records (1940-1999) of the monthly tidal data at Koh Lak, Sattahip, Koh Sichang, Bangkok Bar and Chulachomkhlao Fort, and found a slightly decreasing trend in the MSL at Koh Lak and Sattahip, while the MSL at the other three stations showed an increasing trend. He hypothesised that the relative MSL rise at Bangkok Bar and Chulachomkhlao Fort was due to land subsidence [6].

Neelasri *et al*. [7] processed the hourly tidal data at Koh Lak and Sattahip by means of low-pass filters into monthly-mean tide levels, annual MSLs and the MSLs over the 1963-1987 period, and reported that the monthly-mean tide level during the north-east monsoon (November-December) was approximately 40 cm higher than the level during the south-west monsoon (June-July), which conformed to the yearly constituent (S_a) obtained from harmonic analysis [8]. The obtained 25-year MSLs for Koh Lak and Sattahip of 251.5 cm and 242.4 cm suggested a slightly declining level of 0.6 cm and 0.3 cm respectively.

In accord with Neelasri *et al*. [7], Vongvisessomjai [9] analysed continuous monthly MSLs over the 56-year span (1940-1996) at Koh Lak and Sattahip and found a declining rate of sea level at both places to be 0.36 mm/yr. These two tide stations are located on firm ground that is not likely to be affected by land subsidence. Vongvisessomjai concluded that the MSL in the Gulf of Thailand was falling slightly or not changing [9], which is in contrast to the belief that the sea level is rising in the Gulf of Thailand at the same rate as that in the high and middle latitudes.

Finally, Niemnil [10] analysed the sea level trend using the annual sea level data over a 63-year span (1940-2003) at Koh Lak, Koh Mattaphon, Koh Sichang and Sattahip, and found that the MSL at Sattahip, Koh Mattaphon and Koh Sichang had risen at a rate of 0.22, 0.51 and 0.81 mm/yr respectively, while that at Koh Lak had fallen at a rate of 0.52 mm/yr.

The relative sea level is affected by vertical land movements caused by tectonic movements, sedimentation, groundwater extraction and oil extraction [11]. From the inconclusive results summarised above, one wonders what happened to the tide-gauge data in Thailand. The main culprit is likely to be the vertical land movement that had been incorporated into the apparent sea level rise/fall in the tidal record. In fact, using geodetic data obtained from the Royal Thai Survey Department of the Royal Thai Army, Trisirisatayawong *et al*. [11] gave the following figures as the absolute long-term sea-level rises: 5.0± 1.3 mm/yr at Sattahip (1942-2004), 4.5± 1.3 mm/yr at Koh Sichang (1940-1999), 4.4± 1.1 mm/yr at Koh Mattaphon (1964-2004) and 3.0±1.5 mm/yr at Koh Lak (1940-2004). Analysis of altimetric data (1993-2009) [11] gave lower absolute sea-level rising rates at Sattahip (4.8± 0.7 mm/yr) and Koh Mattaphon (3.2± 0.7 mm/yr) but higher values at Koh Sichang (5.8±0.8 mm/yr) and Koh Lak (3.6± 0.7 mm/yr). Thus, the absolute long-term (1940-2004) sea-level rising rate for the Gulf of Thailand derived from the altimetric data and tide-gauge data at Koh Lak was 3.0 ± 1.5 mm/yr.

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There are throughout the Gulf of Thailand a number of tide gauges which are operated by the Marine Department. The present study is an attempt to investigate the local sea-level trend for the Gulf of Thailand using these available tidal data. The studies result should ascertain the rising/decreasing trend of the MSL in the gulf.

METHODS

The Gulf of Thailand is part of the continental shelf on the south-west frank of the South China Sea. The gulf is about 400 km wide and 720 km long and aligns itself in a NW-SE direction (Figure 1). The shallow (15 m deep on average) northernmost end is called the Upper Gulf of Thailand and is about 100 x 100 km in size, where micro- to meso-tides can be found, which can be classified as a semi-diurnal tide with inequalities, mixed tide and diurnal tide [12].

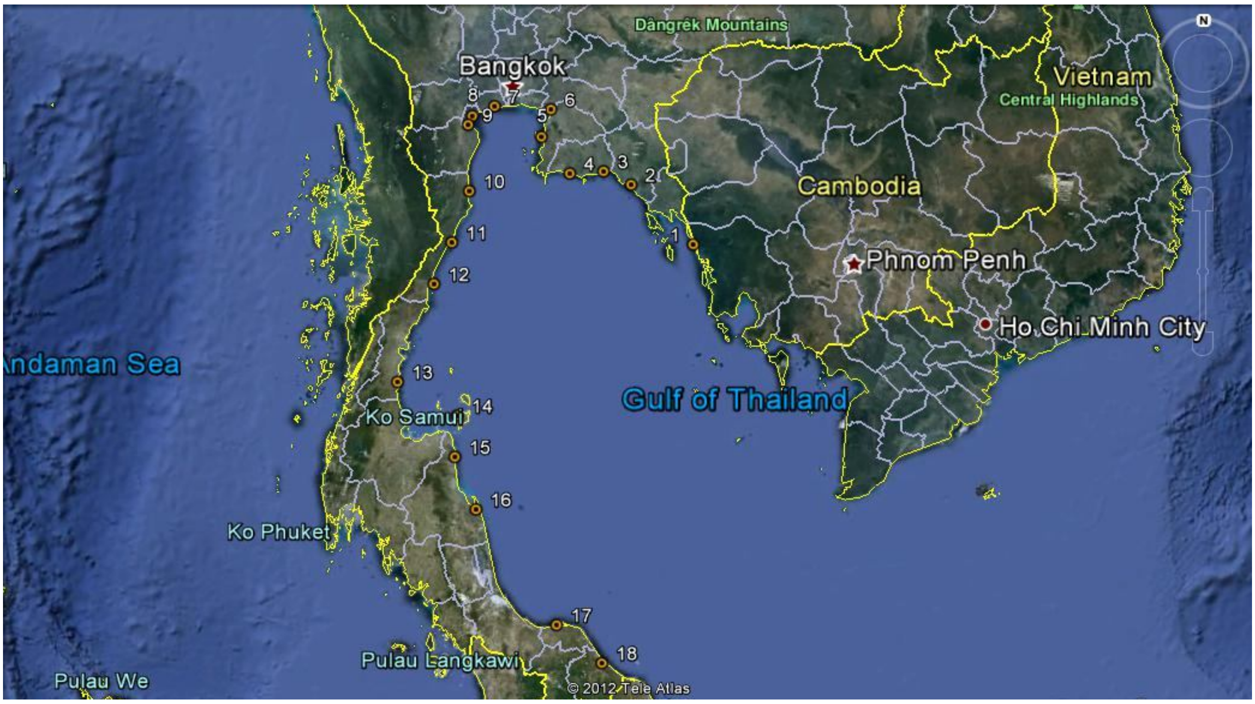

Figure 1. Map of the Gulf of Thailand showing tidal gauge stations along the coast. The station names and their locations are given in Table 1. (Base map is obtained from Google Earth.)

The annual local MSLs from 18 tide-gauge stations (Table 1) along the coast of the gulf were obtained from the Marine Department (upon request). Owing to the limitation of record length and the fluctuation in the yearly data, the data from only 13 tide-gauge stations out of 18 were chosen for further analysis (Table 1). The longest record started from 1982 until present (2012). However, the data after 2004 were omitted because the 2004 Sumatra earthquake event caused the landmass to move continuously downward. Regression analysis was performed on the tide-gauge data to reveal the changing trends (if any).

RESULTS AND DISCUSSION

Figure 2 displays the rise in the average local MSL during 1985-2009 obtained from the combined data from 13 tide gauges operated by the Marine Department. The relative sea level rise in the gulf was about 5 mm/yr. When the data after 2004 were omitted, the relative rise was only 4 mm/yr. When the data from each tide-gauge station was analysed individually, three showed

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negative trends, viz. KlongYai (-0.2 mm/yr), Rayong (-2.6 mm/yr) and Langsuan (-11.2 mm/yr). The station at Langsuan coincided with GPS stations where land uplifting had been detected [11].

Table 1. Locations of the tide gauge stations maintained by the Marine Department [13] and the time periods of record. The stations in parenthesis were omitted from analysis due to short record length.

Region	Station name	Latitude (N)	Longitude (E)	Record length	No. of years
Eastern	1. KlongYai	11° 46’ 57.9”	102° 52’ 02.8”	1993-2004	14
	2. ThaChalab	12° 31’ 54”	102° 03’ 41”	1981-2009	29
	3. Prasae	12° 41’ 41”	101° 42’ 21”	1978-2009	32
	4. Rayong	12° 39’ 30”	101° 16’ 28”	1981-2009	28
Upper	(5. AoUdom)	13° 07’ 25”	100° 53’ 46”	2006-2007	2
	6. Bangpakong	13° 29’ 00”	101° 00’ 23”	1981-2007	27
	7. SamutSakhon	13° 30’ 36”	100° 16’ 40”	1977-2009	29
	8. SamutSongkram	13° 22’ 36”	99° 59’ 44”	1977-2007	31
	(9. Ban Laem)	13° 15’ 47”	99° 56’ 44”	1996-2007	12
Western	10. Pranburi	12° 24’ 17”	99° 59’ 41”	1992-2004	13
	(11. KlongWarl)	11° 44’ 27”	99° 47’ 38”	2006-2009	4
	(12. Bang Sapan)	11° 12’ 16”	99° 35’ 06”	1999-2004	5
	13. Langsuan	9° 56’ 38”	99° 09’ 38”	1982-2007	26
	(14. Samui)	9° 32’ 10”	99° 56’ 02”	2006-2009	4
	15. Sichol	9° 00’ 45”	99° 55’ 07”	1993-2007	15
	16. Pakpanang	8° 21’ 11”	100° 12’ 08”	1986-2009	24
	17. Pattani	6° 54’ 08”	101° 14’ 57”	1978-2009	32
	18. Naratiwat	6° 25’ 26”	101° 49’ 48”	1978-2009	32

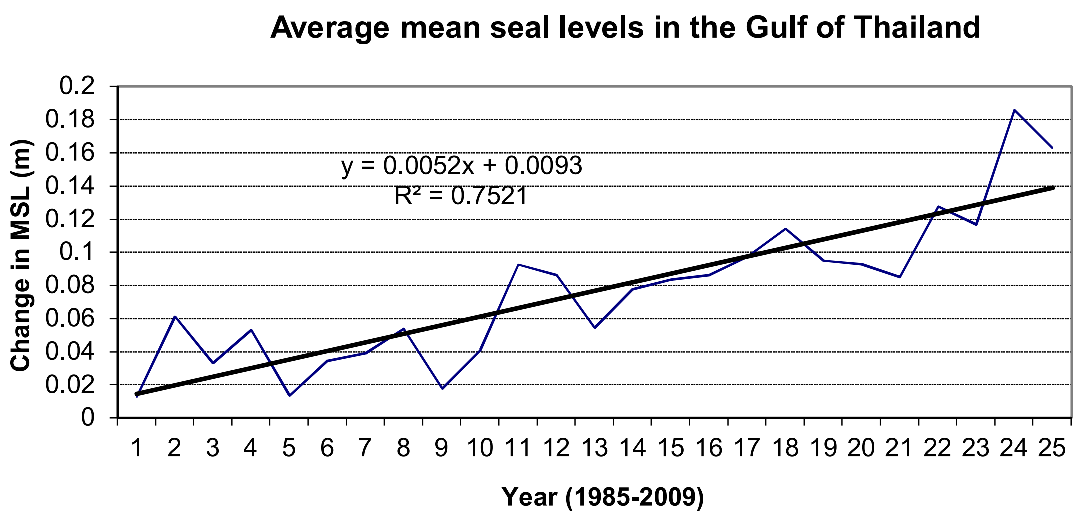

Figure 2. Average local MSLs from the combined tide-gauge data obtained from 13 stations with the regression line, regression equation and R^2 correlation coefficient

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As the MSL differed by location, we analysed the data by region. Figure 3 displays fluctuations in the annual MSL at three stations, i.e. Samut Songkram, Samut Sakhon and Bangpakong, in the upper gulf. These stations are located near the river mouths where land subsidence occurs. Regression analysis of the average annual data shows a relative rising trend of 12.7 mm/yr (R^2 = 0.90). Clearly the land subsidence problem has contributed to the apparent rising sea level for this area. A study by Thammasart University Research and Consultancy Institute in 2009 [14] reported a similar result.

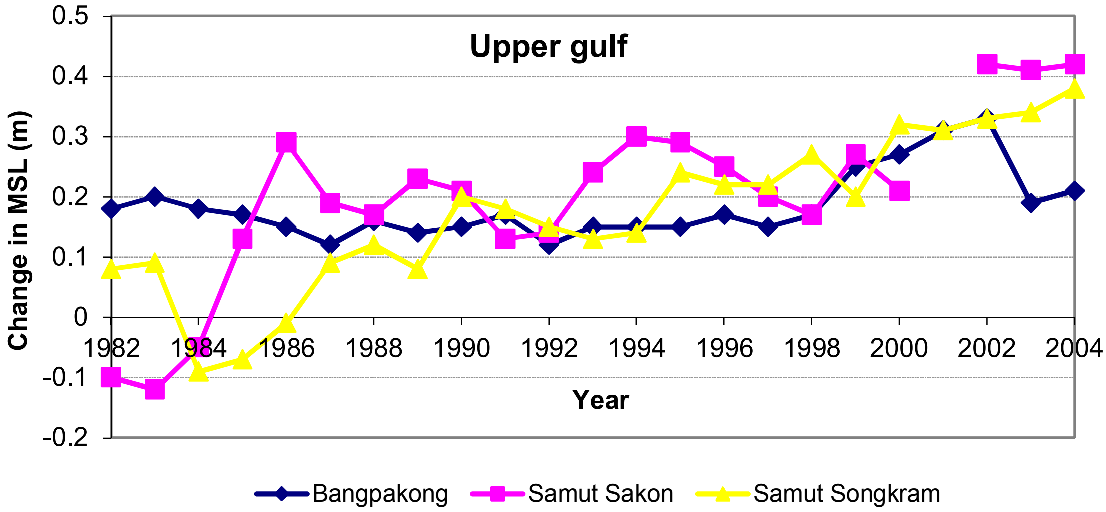

Figure 3. Fluctuations in the annual MSL during 1982-2004 at three tide-gauge stations in the upper Gulf of Thailand

Figure 4 shows fluctuations in the annual MSL at four stations, i.e. KlongYai, Tha Chalab, Prasae and Rayong, along the eastern side of the gulf. Only Tha Chalab station showed any significant increase in MSL, although with wild fluctuation, while the MSL at the other three stations varied only slightly from year to year. Regression analysis of the average annual data gave a relative rising trend of 4.5 mm/yr, although this was somewhat poorly supported (R^2 = 0.3). Excluding the erratic data from Tha Chalab station, the rising sea level was minimal at 0.7 mm/yr (R^2 = 0.03). In contrast to this, using six tide-gauge stations in this region, the study by Thammasart University Research and Consultancy Institute [14] reported a sea-level rise of 3.58-6.57 mm/yr.

Figure 5 shows the fluctuation in the annual MSL at six stations, i.e. Pranburi, Langsuan, Sichol, Pakpanang, Pattani and Naratiwat, along the western side of the gulf. The annual MSL at Sichol was below the country's MSL at all times, while that at Pakpanang rose from 0.2 m below it to about the same level as that of the country at present. Langsuan was the only site that clearly showed a falling trend in the local MSL. Regression analysis of the average annual data revealed a relative falling trend of -0.8 mm/yr (R^2 = 0.02). Thus, the MSL trend for the eastern and western coasts of the gulf is still debatable because of the contradictory trends among the tide-gauge data as well as the scarcity of available data in the past. Thammasart University Research and Consultancy Institute [14] reported that the upper and middle regions of the gulf's western side experienced a net sea-level fall while the lower region experienced a rise.

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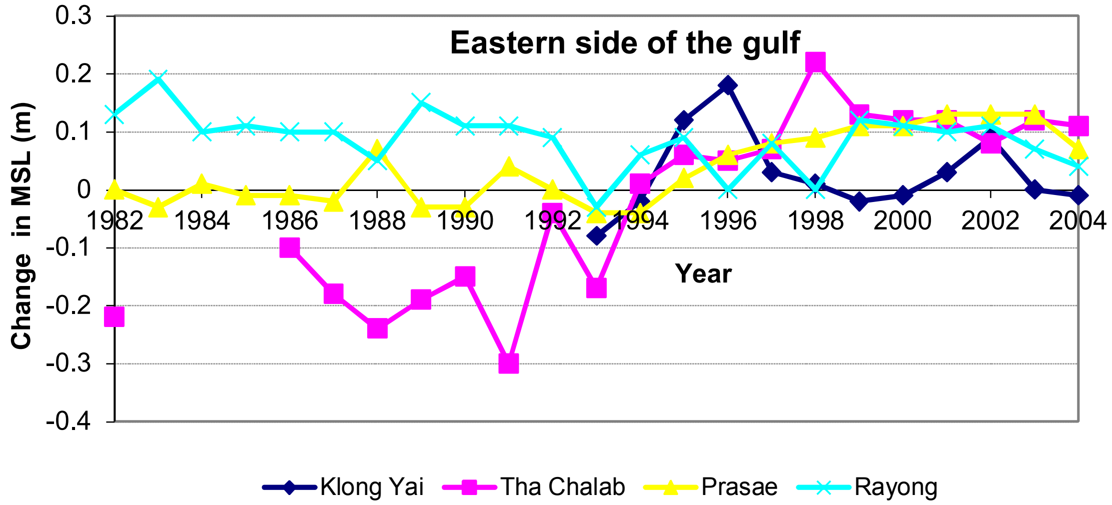

Figure 4. Fluctuations in the annual MSL during 1982-2004 at four tide-gauge stations along the eastern side of the Gulf of Thailand

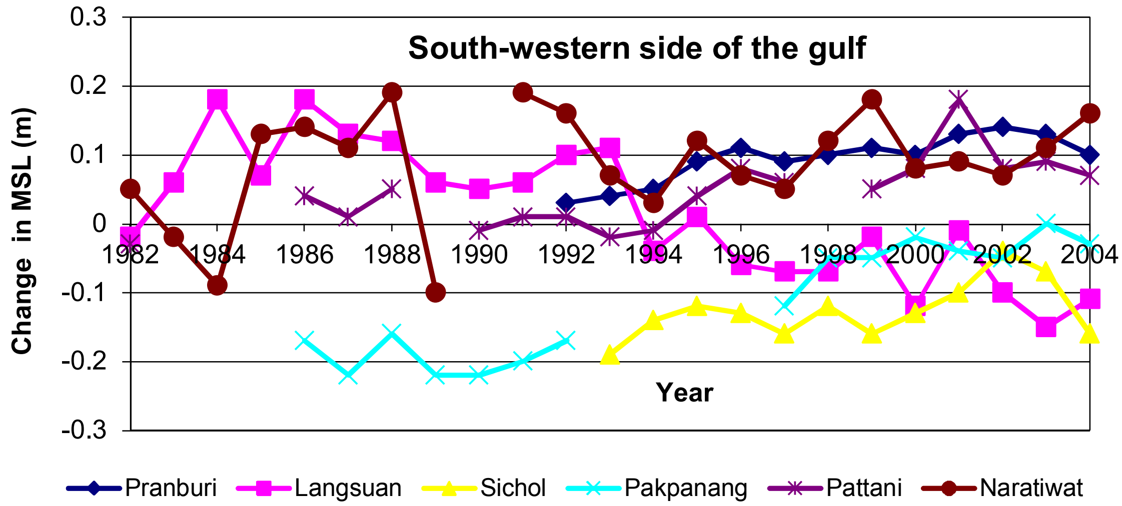

Figure 5. Fluctuations in the annual MSL during 1982-2004 at six tide-gauge stations along the western side of the Gulf of Thailand

The above-mentioned results were the apparent (relative) sea-level rise obtained from the tide-gauge data. In order to get the absolute MSL rise, one must consider the vertical crustal motion. Recently, the vertical crustal motion in Thailand has been monitored by the Royal Thai Survey Department of the Royal Thai Army. Trisirisatayawong *et al.* [11] used the vertical crustal motion at Chon station (in Chon Buri province), Koh Lak station (in Prachuab Kirikhan province) and Banh station (in Chumporn province) to come up with the absolute sea-level rise at Sattahip, Koh Lak and Mattaphon tide-gauge stations. Here, the vertical land movement data at Chon and Bahn were used to evaluate the absolute sea-level rises for sites located along the eastern and south-wesstern coasts of the gulf respectively (Table 2). Since the land subsidence rate (caused by human activities) along the inner part of the upper gulf was quite high, we opted to use the relative sea-level rise as the absolute one. The absolute sea-level rise appeared to vary with region, ranging from 1.4 to 12.7 mm/yr (Table 2). The rate of sea-level rise in the inner part of the upper gulf was quite high and this will likely lead to frequent coastal flooding in the future.

Table 2. Relative sea-level rise and absolute sea-level rise (after correction with vertical crustal motion) for three regions of the Gulf of Thailand

Location	Relative sea-level rise (mm/yr)	Vertical crustal motion (mm/yr) [9]	Absolute sea-level rise (mm/yr)
Upper gulf	12.7	-	-
Eastern side	0.7	3.8 ± 1.3	4.5
South-western side	-0.8	2.2 ± 0.8	1.4

The Sumatra earthquake in 2004 changed the vertical crustal motion in Thailand. According to an analysis by Trisirisatayawong *et al*. [11], the land mass moved upwards at a varying rate but around a few millimetres per year before the earthquake event (pre-2004). After that the land mass moved downwards at a faster pace and currently there is no sign of levelling out. Thus, this should lead to a higher absolute rate of sea-level rise in the Gulf of Thailand in the future.

As mentioned by Punpuk [5] and Neelasri [7], the change in the intra-annual MSL was due to the Ekman transport set up by the monsoonal wind. Therefore, we tried to relate the fluctuation in the annual MSL with the strength of the monsoonal wind. The monthly wind data covering latitude 5-10^{o}N and longitude 100-105^{o}E during the year 2000-2007 were obtained from the National Aeronautics and Space Administration (NASA) database [15]. A regression analysis was performed between wind strength at each degree and average MSL for each year. The regression and correlation results showed similar trends. The fluctuation in the annual MSL at Naratiwat, Samut Songkram and Samut Sakhon correlated moderately well with the strength of the south-southeastern (SSE) wind (148°-163°) (R^2 ~ 0.6), while that at Rayong correlated with the north-northwestern wind (NNW, 342°). Thus, the strength of the NE monsoonal wind and SE wind (inter-monsoon period) would give rise to annual MSL changes along the western side of the gulf as well as the inner part of the upper gulf, whilst the NNW wind during the SW monsoon would give rise to changes in the sea level in the eastern side of the gulf.

As for the future sea level in the next century (year 2100), the database for impact and vulnerability analysis [16] was used to simulate the sea-level rise under different greenhouse gas emission scenarios with reference to the base condition in the year 1995. The model predicted a rise in the MSL between 0.28-0.65 m, which falls within the range of the absolute sea-level rise rate found in this study, i.e. a total rise of 0.14-1.27 m.

CONCLUSIONS

Tide-gauge data from the Marine Department has revealed that the MSL in the Gulf of Thailand rises at different rates depending on the station location. The impact of the sea-level rise varies by location and depends on a range of environmental characteristics as well as human activities. Land subsidence along the inner Gulf of Thailand makes the area likely to experience great harm under the impact of the rise in sea level. Attention with regard to coastal management plans and preparation for disaster is therefore vital.

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