INVITED ARTICLE

Will sea-level really fall in the Gulf of Thailand?

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Abstract

Vongvisessomjai, S.
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Songklanakarin J. Sci. Technol., 2006, 28(2) : 227-248

Rate of sea-level changes due to climate changes vary according to latitudes: namely (i) in high and middle latitudes, successive glacial, interglacial and interstadial conditions occur with significant sea-level rises, and (ii) in low latitudes, successive humid and arid conditions occur with small sea-level rises or falls. Inter-governmental Panel on Climate Change's (IPCC) projection of future sea-level rise in the high and middle latitudes of 31, 66 and 110 centimeters in 100 years for low, middle and high scenarios respectively is wrongly accepted to be applicable to the Gulf of Thailand, which is in the low latitudes, where air and seawater temperatures are already high, and therefore, an insignificant increase of temperatures is found in several large cities. Analyses of 56 years data of tides recorded at Ko Lak, Prachuap Khirikhan province and Sattahip, Chonburi province revealed that sea levels are falling slowly, which is consistent with results of Gregory (1993) who reported sea-level falls in the low latitudes and the Gulf of Thailand of 0-50 milimeters, using U.K. Meteorological Offices Coupled Ocean-atmosphere General Circulation Model. In conclusion, the sea-level in the Gulf of Thailand is found preliminarily to be falling slightly or not changing, contradicting the belief that sea-level is rising in the Gulf of Thailand at the same rate as that in the high and middle latitudes. This should be investigated in more detail in the near future.

Key words : greenhouse, ocean-atmosphere, sea-level fall

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Received, 5 October 2005 Accepted, 31 January 2006

บทคัดย่อ

สุภัทท์ วงศ์วิเศษสมใจ

ระดับน้ำทะเลในอ่าวไทยลดลงจริงหรือ?

ว. สงขลานครินทร์ วทท. 2549 28(2) : 227-248

อัตราการเปลี่ยนแปลงระดับน้ำทะเลขึ้นกับการเปลี่ยนแปลงของภูมิอากาศ จึงมีค่าแตกต่างกันตามเส้นรุ้ง (latitude) คือ 1. ที่เส้นรุ้งสูงที่ขั้วโลกและระดับปานกลางในเขตอบอุ่น อิทธิพลของธารน้ำแข็งที่ขั้วโลกเป็นปัจจัยหลัก ทำให้ระดับน้ำทะเลเพิ่มขึ้นมาก และ 2. ที่เส้นรุ้งต่ำ ความร้อนชื้นและความแห้งแล้งเป็นปัจจัยหลัก ทำให้ระดับน้ำทะเลเพิ่มขึ้นน้อยหรือลดลง

Inter-governmental Panel on Climate Change (IPCC) ทำนายว่าในปี ค.ศ. 1990 ระดับน้ำทะเลจะเพิ่มขึ้นบริเวณเส้นรุ้งสูงและระดับปานกลาง 31, 66 และ 110 ซม. ในหนึ่งศตวรรษสำหรับค่าต่ำ ปานกลาง และสูง ตามลำดับ แต่เรากลับนำค่าเหล่านี้มาใช้กับประเทศไทยซึ่งอยู่ที่เส้นรุ้งต่ำ อุณหภูมิของอากาศและน้ำทะเลสูงอยู่แล้ว จึงมีการเพิ่มอุณหภูมิน้อยมากในเมืองใหญ่ ๆ การวิเคราะห์ระดับน้ำทะเล 56 ปีที่เกาะหลัก จังหวัดประจวบคีรีขันธ์ และสัตหีบ จังหวัดชลบุรี พบว่าระดับน้ำทะเลลดลงอย่างช้า ๆ ซึ่งสอดคล้องกับค่าที่รายงานโดย Gregory (1993) ว่าบริเวณเส้นรุ้งต่ำรวมทั้งอ่าวไทย ระดับน้ำทะเลลดลง 0-50 มม. จากการคำนวณโดยใช้แบบจำลองทางคณิตศาสตร์ของกรมอุตุนิยมวิทยา ประเทศอังกฤษ จึงสรุปในเบื้องต้นว่าระดับน้ำทะเลในอ่าวไทยลดลงอย่างช้า ๆ หรือไม่เปลี่ยนแปลง ตรงข้ามกับความเชื่อที่ว่าระดับน้ำทะเลในบ้านเราสูงขึ้นตามคำทำนายโดย IPCC (1990) ซึ่งควรจะได้ทำการศึกษาตรวจสอบกันอย่างละเอียดในอนาคตอันใกล้นี้

ผู้เชี่ยวชาญด้านน้ำและสิ่งแวดล้อม บริษัททีม คอนซัลติ้ง เอนจิเนียริ่ง แอนด์ แมเนจเมนท์ จำกัด 151 อาคารทีม ถนนนวลจันทร์ แขวงคลองกุ่ม เขตบึงกุ่ม กรุงเทพฯ 10230

If the IPCC's projection of future sea-level rise of 31,66 and 110 centimeters in 100 years respectively for low, middle and high scenarios in 1990 would be applicable to the Gulf of Thailand, it would have major impacts on flooding and land loss of coastal areas and subsequent coastal erosion due to more exposure to wave attack. However, Thailand is located in the tropic, air and seawater temperatures are already high, and the increase heating due to global warming would be less. Coastal erosions in the Gulf of Thailand are not caused by sea-level rise but due to decrease of silt and sand supplies to the sea, which will be presented later (NRCT, 1989; JICA, 2001 and ONREPP, 2003).

It is important to find the actual rate of sea-level rise in the Gulf of Thailand through review and analysis of relevant data of sea-levels, land subsidence, coastal erosions, and temperatures of air and seawater, which will be described in the methodology.

Methodology

1. Greenhouse Effect

The Earth absorbs much radiation from the sun, including ultraviolet, visible, and other rays. After warming the atmosphere, the land and oceans, this energy is re-radiated to space at longer wavelengths (infrared rays). Normally the thermal budget of the Earth is balanced, with the radiation from the Sun equal to the thermal radiation from the Earth. However, when greenhouse gases (GHGs) exist in the atmosphere, some of the thermal radiation is absorbed by these gases. The absorbed energy is eventually radiated to space from higher, colder levels in the atmosphere, after repeated absorption and re-radiation by GHGs between the atmosphere and the surface of the earth (Figure 1). In brief, the atmosphere is easily penetrated by the radiation from the Sun but prevents some thermal radiation from the Earth from flowing out to space, and keeps the thermal energy near the surface. As a result of the greenhouse effect, the global mean surface temperature is already approximately 33ºC warmer than the Earth would be without GHGs. GHGs include water vapor (H_20), carbon dioxide (CO_2), methane (CH_4), chlorofluorocarbons (CFCs), and ozone (O_3), each of which has different Global Warming Potential (GWP) (Table 1).

2. Global Warming/Climate Change

The changes in the radiative balance of the Earth, including those due to an increase in GHGs, will tend to alter atmospheric and oceanic temperatures and circulation (the jet stream and ocean currents etc.), and weather patterns. Global warming and climate change are the general terms for these changes. Since the Industrial Revolution, the atmospheric concentrations of GHGs have been increasing dramatically, caused by accelerated consumption of fossil fuels, and land-use and land-cover change, etc. (Table 2). The Intergovernmental Panel on Climate Change (IPCC) reported that the best global estimate of annual average concentrations of CO_2 in 1991 was approximately 355 ppmv, given the recent observed rate of increase of 1.8 ppmv/yr, and that global mean surface temperature has increased by 0.3 to 0.6ºC over the last 100 years (IPCC, 1992).

3. Factors of Sea-level Rise

It is generally accepted that the mean sea level will gradually rise as a result of global warming, over a period of decades to a hundred years. There are four major factors related to global warming: **1) thermal expansion of the oceans:** The volume of seawater in the mixing layer of the oceans (from the surface to about 200 m in depth) expands, causing the sea-level to rise as a result of an increase in the temperature of seawater. The sea-level rise due to the thermal expansion has recently been examined by several types of models: Box-upwelling-diffusion Models; Subduction Models; and Coupled Ocean-atmosphere General Circulation Models, etc. 2) **mountain glaciers**

Table 1. Direct global warming potential (GWPs) for 100 years time horizon.

Gas	Carbon dioxide	Methane	Nitrous oxide	CFC-11	CFC-12	HCFC-22	HFC-134a
Direct Global Warming Potential (GWP)	1	11	270	3400	7100	1600	1200
Sign of the Indirect Component of the GWP	none	positive	uncertain	negative	negative	negative	none

*** Source: IPCC (1992)**

Table 2. Trace Gas Concentrations from 1765 to 1990.

Year	GAS				
	CO_2 (ppmv)	CH_4 (ppbv)	N_2O (ppbv)	CFC-11 (ppbv)	CFC-12 (ppbv)
1765	179.00	790.0	285.00	0	0
1900	295.72	974.1	292.02	0	0
1960	316.24	1272.0	296.62	0.0175	0.0303
1970	324.76	1420.9	298.82	0.0700	0.1211
1980	337.32	1569.0	302.62	0.1575	0.2725
1990	353.93	1717.0	309.68	0.2800	0.4844

*** Source: IPCC (1992)**

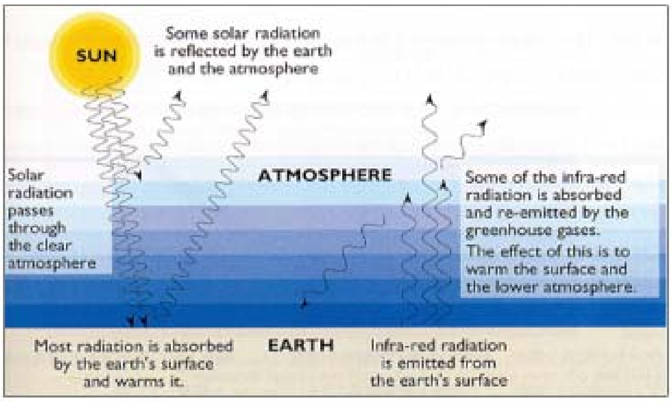
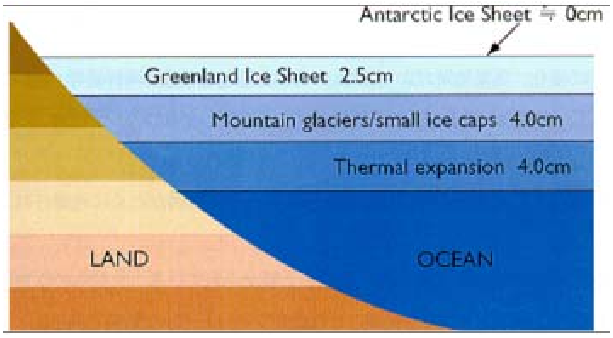


Figure 1. A simplified diagram illustrating the greenhouse effect (IPCC, 1990).



* Indicated figures are from the best estimate over the last 100 years in Table 3

Figure 2. Mechanisms of sea-level rise. (IPCC, 1990).

and small ice caps: The amount of ice stored in mountain glaciers and small ice caps is only a fraction of the total amount of land ice. However because they have shorter response times than the large ice sheets of Greenland and Antarctica, they are thought to be important for sea-level rise on a time scale of 10 to 100 years. Oerlemans and Fortuin (1992) reported that the rate of rise in sea level due to the melting of mountain glaciers and small ice caps would be 0.58 mm/yr for a temperature increase of 1 ºK. **3) the Greenland ice sheet:** A significant summer melting of the Greenland ice sheet, induced by the warmer climate of Greenland, is likely to contribute to a rise in sea level. IPCC (1990) reported that the rate of rise in sea level due to melting of the Greenland ice sheet was 0.3±0.2 mm/yr/ºC. **4) the Antarctic ice sheet:** IPCC (1990) assumed that global warming would not diminish the size of the Antarctic ice sheet. The IPCC (1990) reported that snowfall and accumulation rates in Antarctica would increase because of increasing atmospheric moisture caused by global warming, and that at least for the next half century, the most likely contribution of Antarctica to the impacts of global warming would be an effective decrease in sea level. The IPCC (1990) reported on the best estimated values of sea level rise due to the above major factors (Figure 2) of 4, 4, 2.5 and 0 cm respectively over the last century for a sum of 10.5 cm while observed value is 15 cm as listed in Table 3.

Clark *et al*. (1978) proposed a number of numerical models based on a spherical viscoelastic earth with varying layered structures and on different assumptions of the rate of northern hemisphere ice melt. They incorporated into their

Table 3. Estimated contributions to sea-level rise over the last 100 years (in cm).

	Thermal expansion	Glaciers/ small ice caps	Greenland Ice Sheet	Antarctic Ice Sheet	Total	Observed
LOW	2	1.5	1	-5	-0.5	10
BEST ESTIMATE	4	4	2.5	0	10.5	15
HIGH	6	7	4	5	22	20

***Source: IPCC (1992)**

models some of the known 'facts' of relative sea level change. They were careful to point out that so little is known of the elastic and viscous behaviour of the earth; that the rates of ice melt are also little known, particularly in a regional context; and that the effects of Antarctic ice movements had been ignored, so that their predictive models owed much to these 'known facts'. Despite the in-built drawbacks which this circular reasoning involved, they were able to extend Walcott's arguments on regional responses to deglaciation. Figure 3 illustrates their six sea-level zones for the 'realistic melting case' together with examples of predicted curves in the Pacific for zones where submerged (Zone IV) and emerged beaches (Zones III and V) are predicted. Differences between prediction and observation indicated that assumptions on ice melt and on the rheology of the lithosphere needed refinement. They suggested that as much is to be learned of glacial history and the earth's rheology from observations on sea level change as of the history of sea level change from studies of the earth's rheology.

4. Additional Processes Affecting Sea-level Changes

A global sea-level rise as described earlier in 1., 2. and 3. would mainly result from thermal expansion of seawater and from melting of land ice such as mountain glaciers, and at the same time changes in ocean currents and atmospheric pressure patterns could alter the mean sea level topography at the regional level. Gregory (1993) calculated the regional distribution of changes of mean sea-level with a version of the U.K. Meteorological Office's Coupled Ocean-atmosphere General Circulation Model (CGCMs) in which the CO_2 concentration increases at 1% per year over 75 years. This study shows that there is considerable regional variation in the changes of mean sea-level, showing that the global figure by itself gives only a rough idea of the local rise in sea-level. Figure 4 shows relative changes in sea surface topography and that the Gulf of Thailand is in the zone of sea-level fall of 0-50 mm and between latitudes 30^{o}S and 60^{o}S sea-levels fall 50-100 mm.

Relative sea-level is affected by vertical land movements caused by tectonic movement, sedimentation, groundwater and oil extraction. Warrick *et al.* (1993) summarized four main processes affecting sea level changes: (A) glacio-eustasy, (B) emergence/subsidence of land, (C) manmade activity, and (D) ocean-atmosphere effects (Table 4). These factors vary widely in their effects on relative changes in sea-level.

Regarding the process (B), vertical land movements, Yanagi and Akaki (1993) studied sea-level variation rates from 1950 to 1991 in the East Asian region. Figure 5, in which the shaded area denotes where the sea-level falls due to the plate tectonics, shows that the sea-level has fallen for the past 40 years in an area including the southern part of the Sea of Japan, the Korean Peninsula, Indochina, and the Malay Peninsula. Figure 6 shows the tectonic map of the East Asian region, which is presently the most active area along Java Trench that generated 2004 Sumatra tsunami resulting in highest damage and casualties (Vongvisessomjai and Suppataratarn, 2005). However, Michel *et al.* (2000) reported on crustal motion in east and southeast-asia from GPS measurements that Sundaland i.e. Indonesia as well as the west-

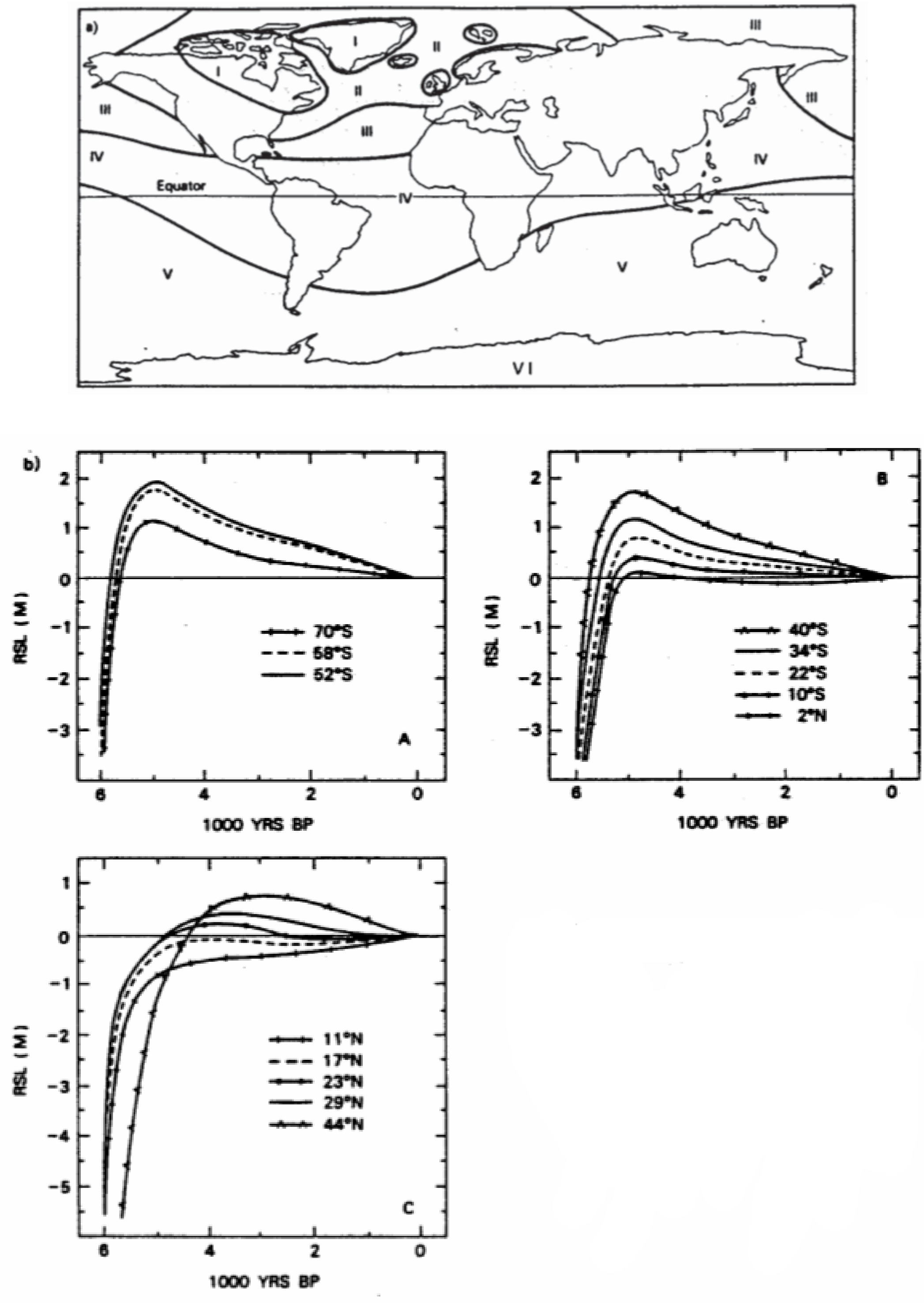
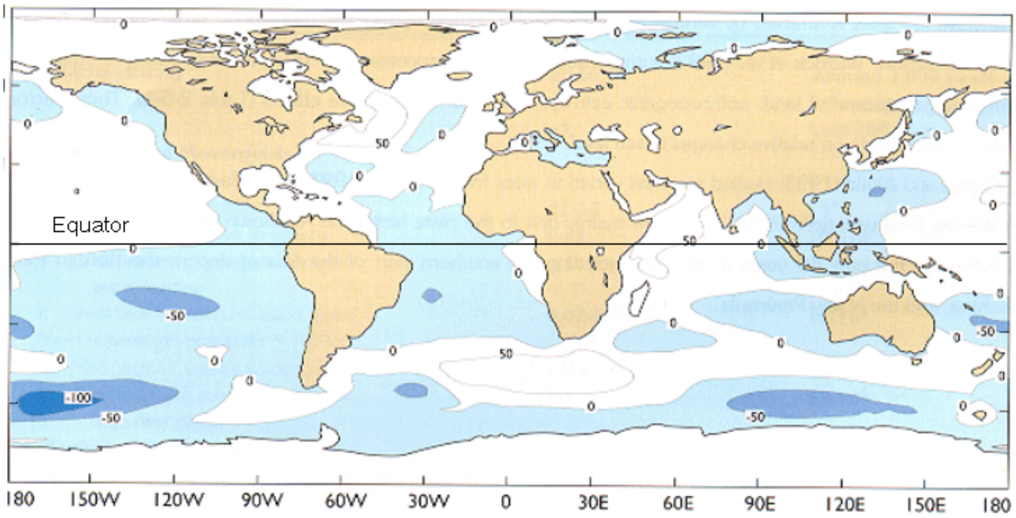


Figure 3. **(a) Illustration of the six sea-level zones for the realistic melting case.**
(b) Predicted relative sea-level curves for a transect from north to south of the Pacific along the meridian 165W (Clark *et al.*, 1978).



*Contours at 50 mm intervals, shaded where negative

Figure 4. Relative changes Δh in sea surface topography, years 66-75 (Gregory, 1993).

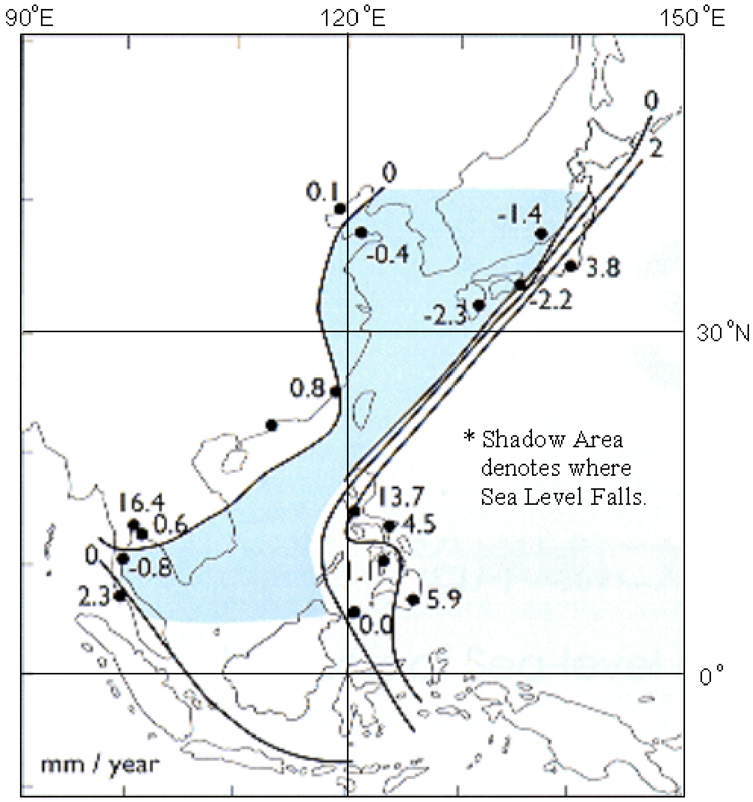


Figure 5. Sea-level variation rate (mm/yr) in 1950-1991 in the East Asian region (Yanagi and Akaki, 1993)

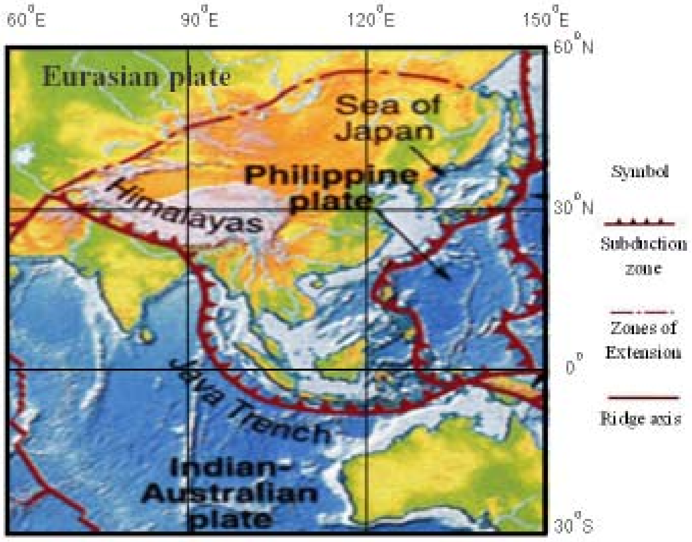


Figure 6. Tectonic map of East Asian region.

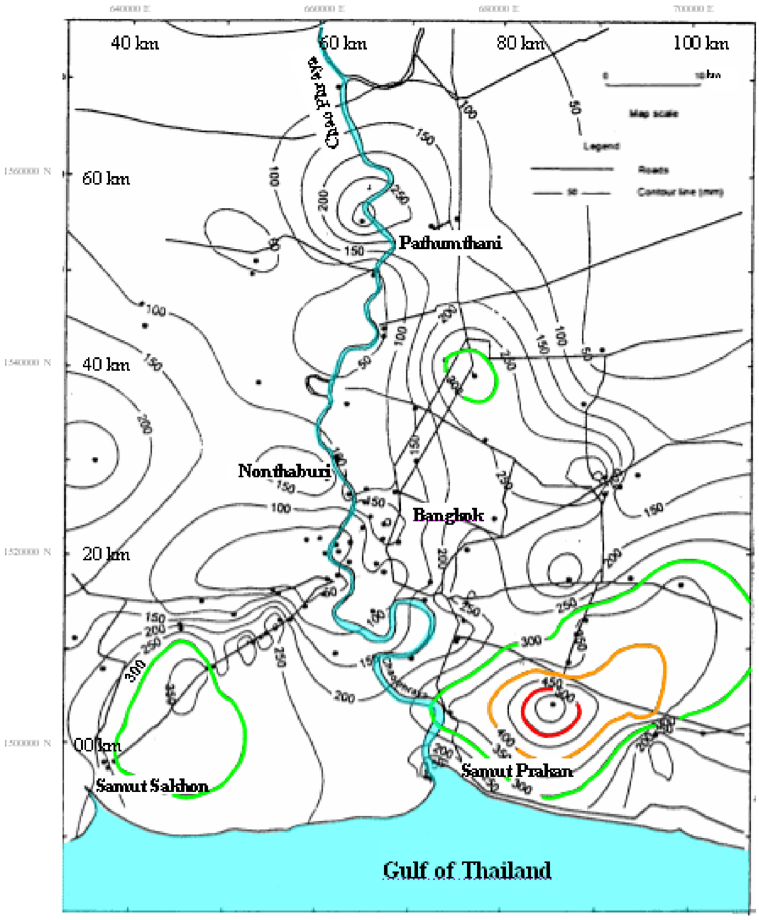


Figure 7. Land subsidence in Bangkok and nearby areas from 1986 to 1997 (DMR, 1998).

Table 4. Summary of processes affecting sea-level changes.

	Process	Rate (mm/yr)	Period (yr)
A	**Glacio-eustasy**	up to 10 ~1 Last 100	Around 7,000 years following deglaciation
B	**Vertical Land Movements**		
1	Long-wavelength processes 100-1000 km		
	a Glacio-isostatic changes	±1-10	10^4
	b Shelf subsidence due to oceanic lithosphere cooling and sediment/ water loading	0.03	10^7-10^8
	c Shelf sediment accumulation, global	0.02-0.05	10-10^6
2	Short-wavelength processes <100 km		
	a Neo-tectonic uplift/subsidence	±1-5	10^2-10^4
	b Shelf sediment accumulation, local-large river deltas	1-5	10-10^4
C	**Anthropogenic activity**		
	a Water impoundment in dams, reservoirs	-0.75	<100
	b Groundwater mining (to river runoff)	0.7(?)	<100
	c Subsidence due groundwater/oil/gas withdrawal (local)	3-5	<100
		Amplitude (cm)	Period (yr)
D	**Ocean-atmosphere effects**		
	Geostrophic currents	1-100	1-10
	Low-frequency atmospheric forcing	1-4	1-10
	El Nino	10-50	1-3

*** Source: Warrick *et al.* (1993)**

ern and central part of Indonesia, together with South-China, constitute an apparently stable tectonic block that was decoupled from Eurasia, and this block moved to the south horizontally not vertically.

Neelasri *et al.* (1998) investigated the mean sea-level change in the Upper Gulf of Thailand using hourly time series of tidal heights at two stations on the west and east coasts of the Upper Gulf of Thailand, Ko Lak and Sattahip, for the year 1963 to 1987 by harmonic analysis for defining the major tidal constituents that characterized the tide in the Upper Gulf of Thailand. Tidal data were processed by mean of low pass filters into monthly mean tide levels, annual mean sea levels and the mean sea-level in 25 years period of those two stations. The monthly mean tide level in the northeast monsoon, during November and December was approximately 40 cm higher than the mean tide level in the southwest monsoon, during June and July, which conformed with the yearly constituent obtained from harmonic analysis. The annual mean sea levels of all the series varied stochastically and the magnitude of the variations were considerably wide. The 25 years mean sea-level for Ko Lak and Sattahip of 251.5 cm and 242.4 cm being compared with the recent 8.6 years mean sea level of 250.9 cm and 242.1 cm inferred a slightly declining level at both stations of 0.6 cm and 0.3 cm; thus it did not give a tendency of the mean sea level change in this area.

Regarding the process (C), manmade activity, the land subsidence due to groundwater abstraction in Bangkok and nearby areas was investigated by the Asian Institute of Technology (AIT) jointly with the Department of Mineral Resources (DMR) for a project entitled "Groundwater resources in Bangkok Area: Development and Management Study" for the National Environment Board of Thailand (NEB) in different phases, i.e. Phase I in October 1978 and Phase IV in April 1982 while subsequent monitoring has been made by DMR (1998). Examples of land subsidence from 1986 to 1997 are shown in Figure 7, while Figure 8 shows the areas identified by DMR (1998) as being at greatest risk of future subsidence and where ground water abstraction is being actively discouraged in Bangkok, Samut Prakan and Samut Sakhon. Critical zone 1 is where land subsidence is more than 3 cm/yr and groundwater drop more than 3 m/yr; Critical zone 2 where land subsidence is 1-3 cm/yr and groundwater drop 2-3 m/yr; and Critical zone 3 where land subsidence is less than 1 cm/yr and groundwater drop less than 2 m/yr.

Coastal erosion in the Upper Gulf of Thailand had been extensively investigated by the follow-

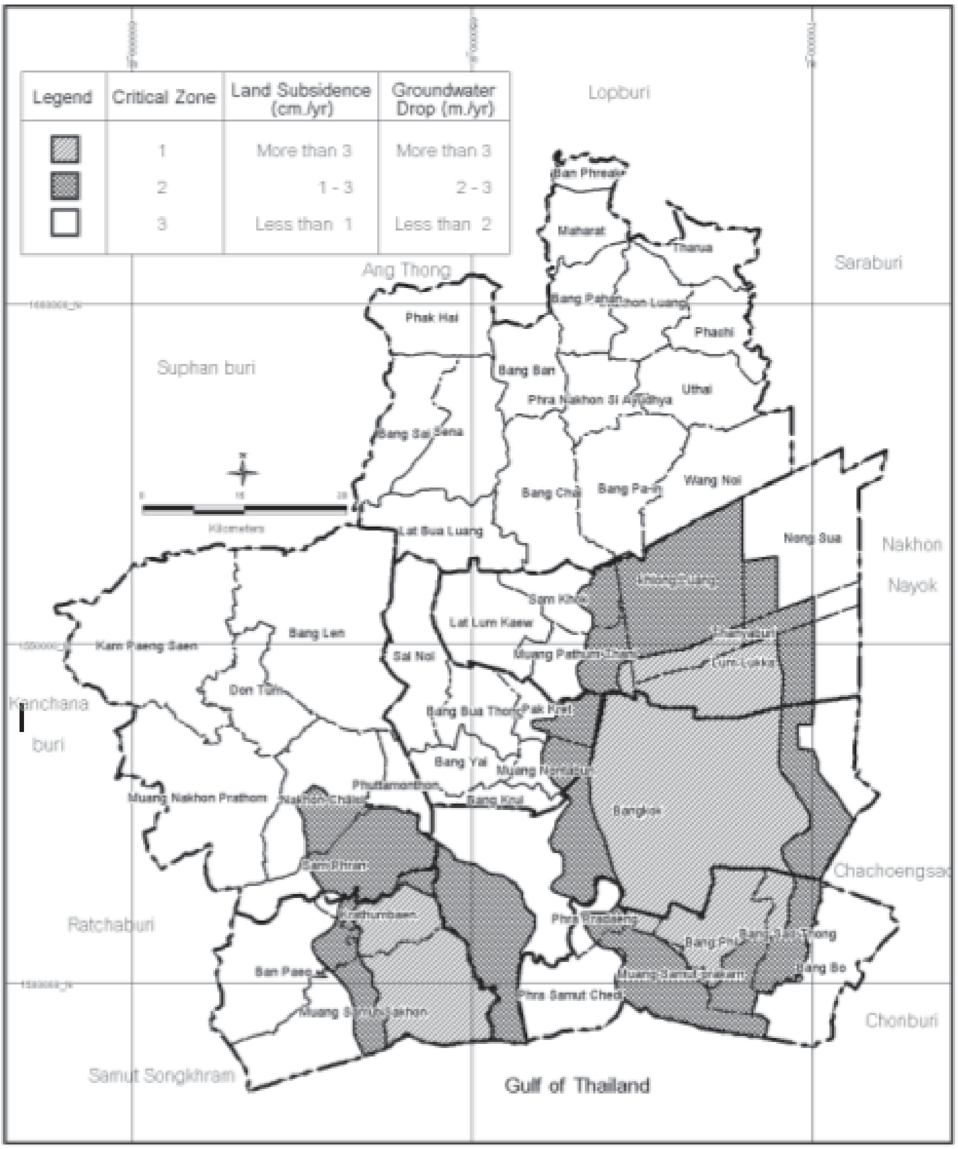


Figure 8. Groundwater action zones in Bangkok and nearby areas showing critical zones 1,2 and 3 (DMR, 1998).

ing investigators (i) National Research Council of Thailand (NRCT, 1989), (ii) Japan International Cooperation Agency (JICA, 2001) and (iii) Office of Natural Resources and Environment Policy and Planning (ONREPP, 2003) as follows: NRCT (1989) reported on coastal erosion/accretion of coastlines in the Gulf of Thailand with dominant changes, such as the Chao Phraya river mouth and the east coast of the peninsula by analysis of available satellite images (Landsat 1-5) together with topographic maps and aerial photographs. Severe coastal erosion with eroded distance in the bracket can be found on the west of the Chao Phraya river mouth at area A (-500 m), and in Phetchburi at area 2 (-200m) and Hua Hin at areas 5 and 6 (-100 m). The locations of shorelines selected for the study are shown in Figure 9, the head of the Upper Gulf of Thailand and the east coast of the

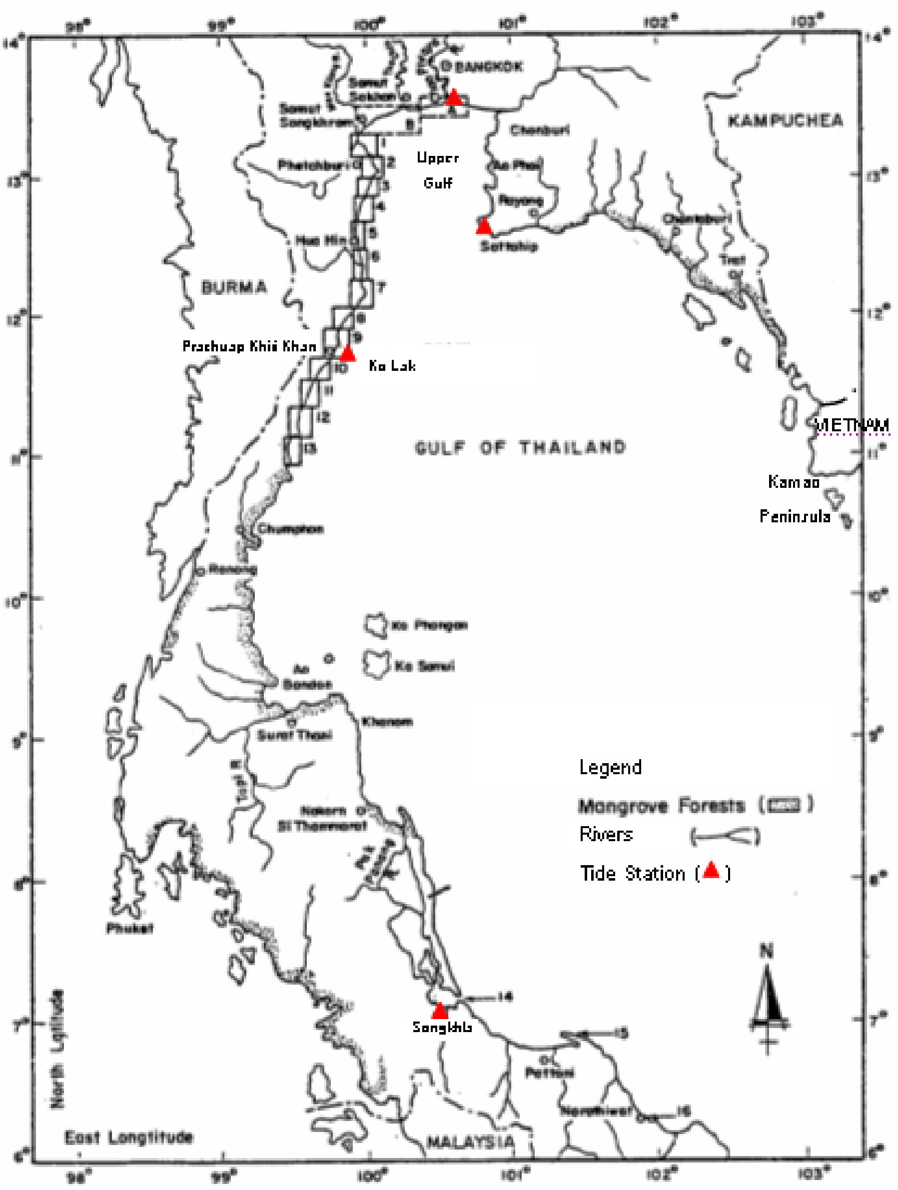


Figure 9. Location map of coastal erosion studies and tide stations in the Gulf of Thailand (NRCT, 1989).

peninsula. The decrease of the silt supply from the Chao Phraya river resulted in a net erosion since the accretion by the silt supply is less than the erosion by the wave action, while the decrease of sand supply alongshore or from nearby streams and the construction of rigid walls on beaches are the causes of erosion along the shorelines of Phetchaburi and Hua Hin. Headlands or offshore breakwaters are recommended to remedy the shoreline erosions of Phetchaburi and Hua Hin. Figure 10 shows the western and eastern shorelines of the Chao Phraya river mouth in the years 1969, 1973, 1979 and 1987. Results of shoreline changes in two respective years provided erosion areas showing areas, length and width of erosion rates. The western shoreline had been eroded from 1969 to 1987 with the maximum eroded distance of -500 m.

Coastline of Bang Khun Thian mostly mangrove forest on the west of the Chao Phraya river mouth has suffered from severe erosion for about -1,000 m in 30 years. Mangrove revival study is made by Japan International Cooperation Agency, JICA (2001) using satellite images in 1986 and 1994 together with topographic map of 1969 and aerial photograph of 1987 shown in Figure 11.

The length of coastal area stretching from Phetchaburi River-Mouth in Phetchaburi Province, to Pranburi River-Mouth in Prachuab Khiri Khan Province, is about 110 kilometers. Along this coastline, many important historical places, temples, communities, aquaculture and agriculture areas, fishery, and other marine life habitats are situated; not to mention various well-known tourist attractions with economic significance, which have been, throughout the years, sources of incomes to the local communities. The causes of coastal erosion in many areas of the above-mentioned provinces are seasonal wave actions and construction of

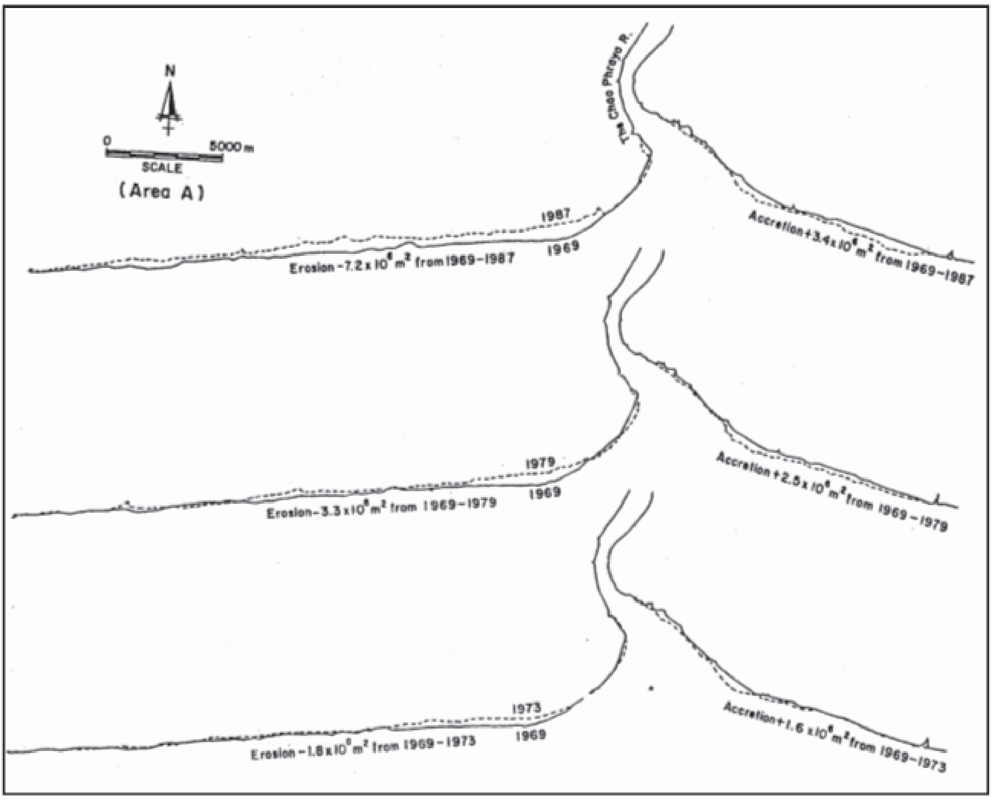


Figure 10. Shoreline changes at the Chao Phraya river mouth (Area A) (NRCT, 1989).

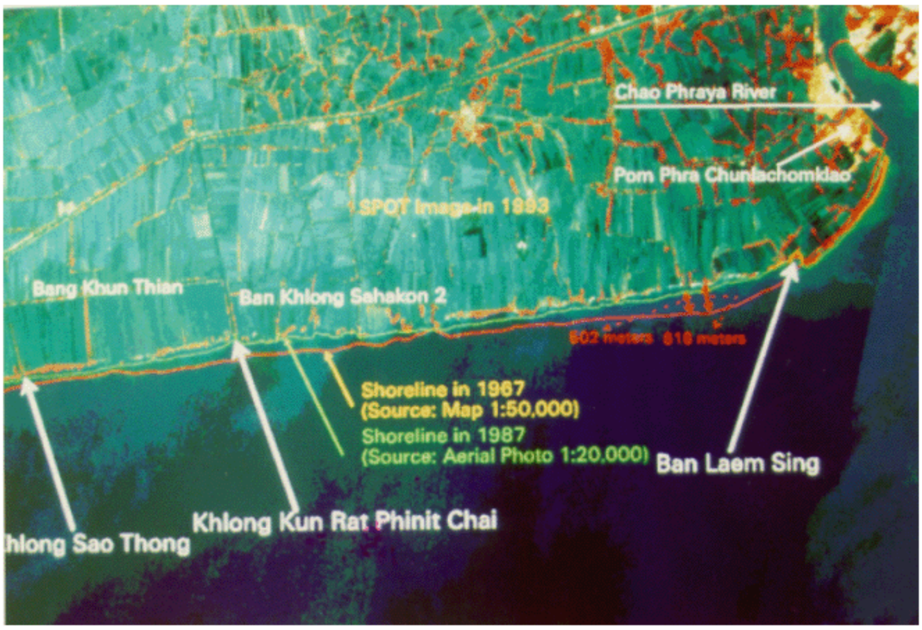


Figure 11. **Spot image taken in 1993 showing coastal erosion at Bang Khun Thian (JICA, 2001).**

coastal structures which encroach the beaches, such as seawalls along the sea-front boundaries of private properties, rubble-mound revetment, offshore breakwaters or groins built perpendicular to the shoreline. These construction activities in the affected areas take place, without prior study, proper knowledge, correct theoretical understanding, and systematic planning, including environmental impact assessment of the whole coastal area. These shortcomings have subsequently caused severe erosion of the adjacent coastal areas, resulting in narrower beaches and lower beach levels. The top layer of sand has been washed away by wave action so much so that the hard clay layer underneath becomes exposed. In some places, the sandy beach has to be covered with rocks to stop the erosion.

ONREPP(2003) has therefore commissioned this master plan study to AIT and SEATEC in order to determine suitable remedial measures for coastal erosion, and to systematically and continuously rehabilitate and restore the above-mentioned coastal areas to their original natural beauty. Examples of Aerial Photographs showing shoreline changes from the years 1954 to 1976 and 1976 to 1995 are shown in Figures 12a and 12b respectively. Accretion prevailed from Phetchaburi river mouth at Ban Laem to Ban Pakthale due to process of delta formation, and erosion prevailed from Ban Pakthale to Ban Bangkaew due to northeast monsoon waves and these eroded materials are deposited along the shoreline from Ban Bangkaew to Laem Phukbia. Severe erosion prevailed from Laem Phukbia to Cha-am and moderate erosion prevailed from Cha-am to Hua Hin due to decrease of sand and silt supplies to the shorelines.

Analysis

1. Meteorological Data

Analysis of monthly maximum temperature and monthly rainfall in summer months of March, April and May from 1951 to 2003 for the cities of Bangkok and Chiangmai show insignificant increase as shown in Figures 13 to 16. The meteorological data of monthly maximum temperature and monthly rainfall have no change of their mean values nor increase trend.

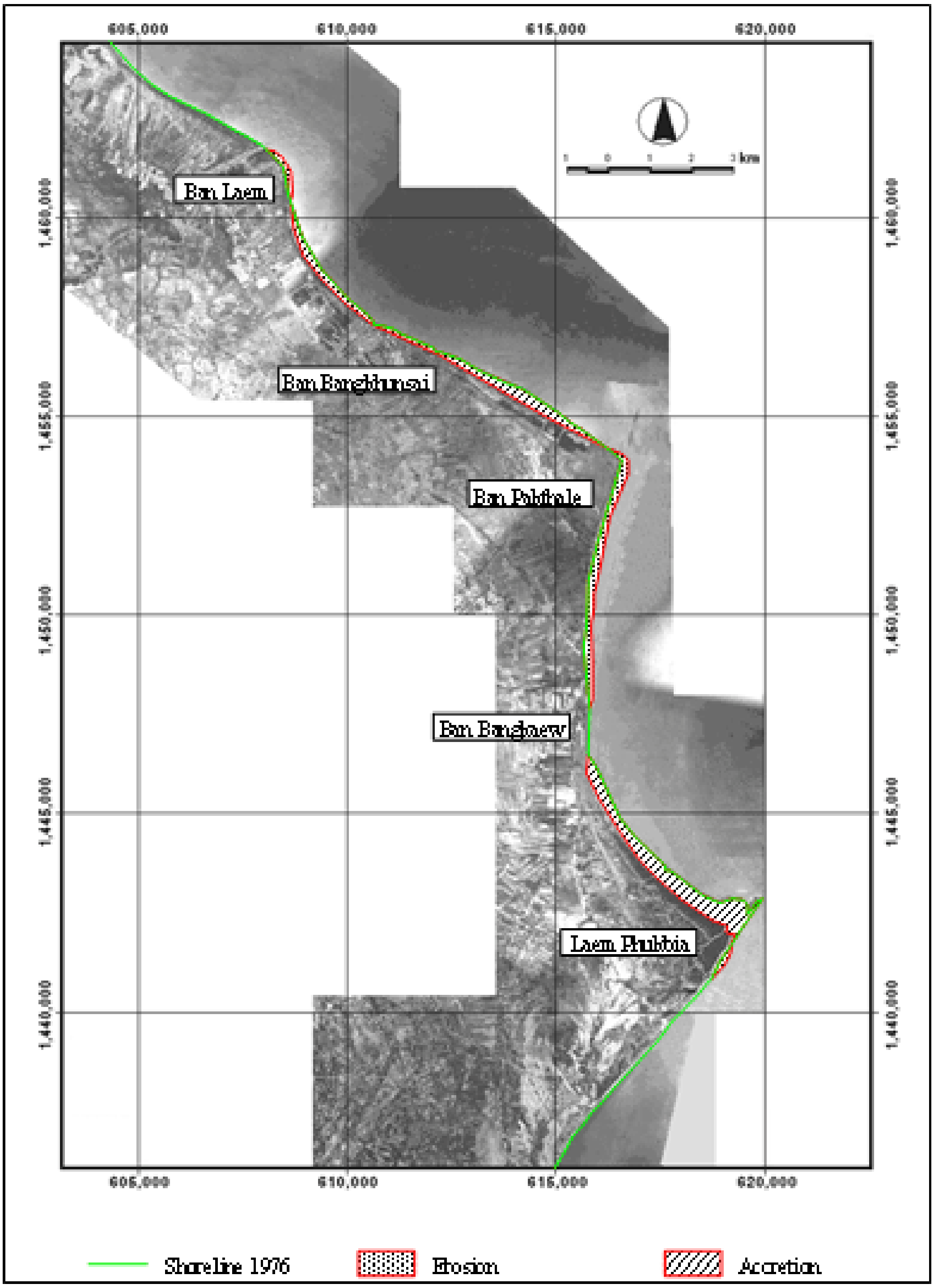


Figure 12a. **A set of aerial photographs of shoreline changes from 1954 to 1976 from Petchaburi river mouth at Ban Laem to Laem Phukbia (ONREPP, 2003).**

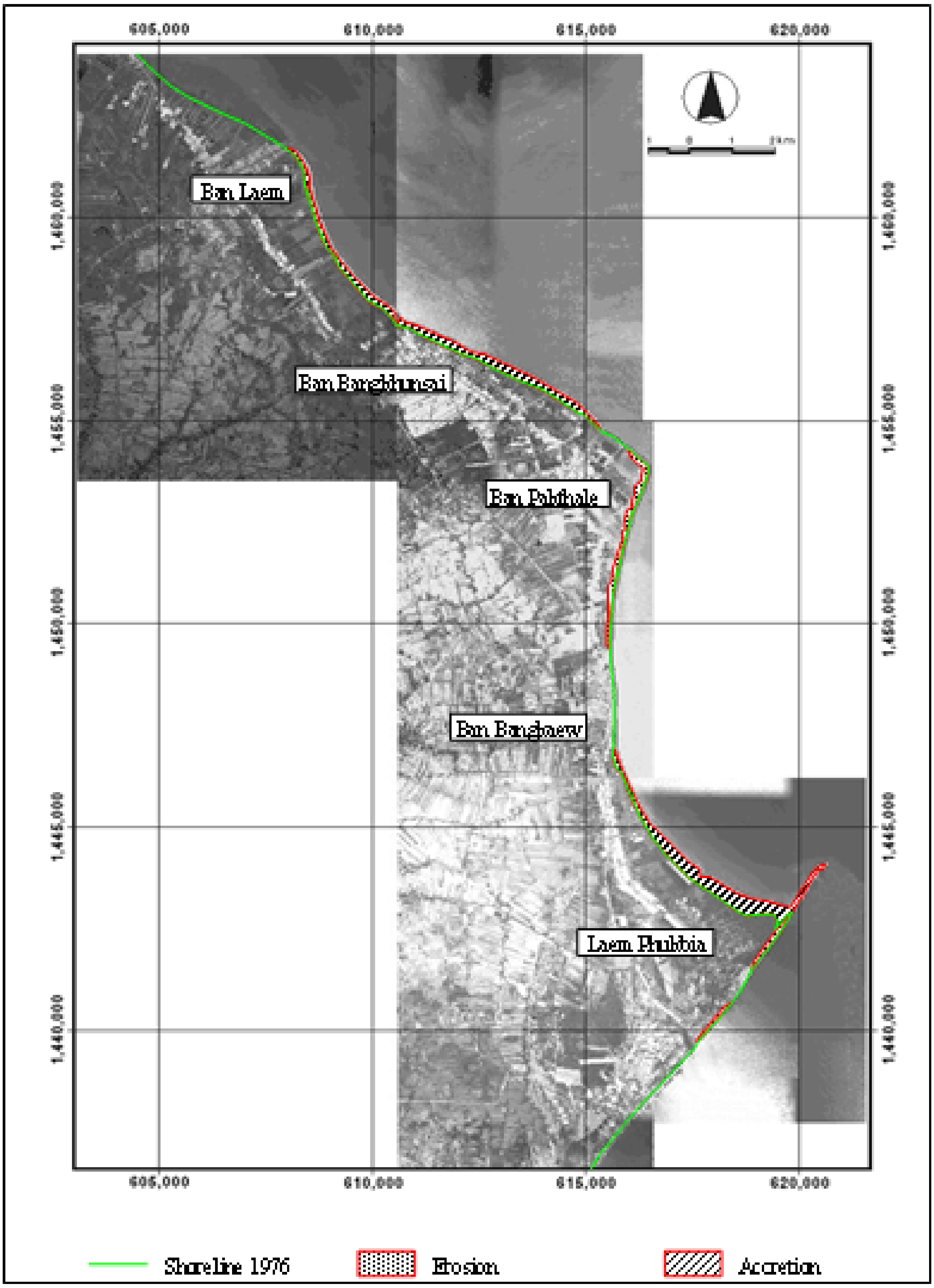


Figure 12b. A set of aerial photographs of shoreline changes from 1976 to 1995 from Petchaburi river mouth at Ban Laem to Laem Phukbia (ONREPP, 2003).

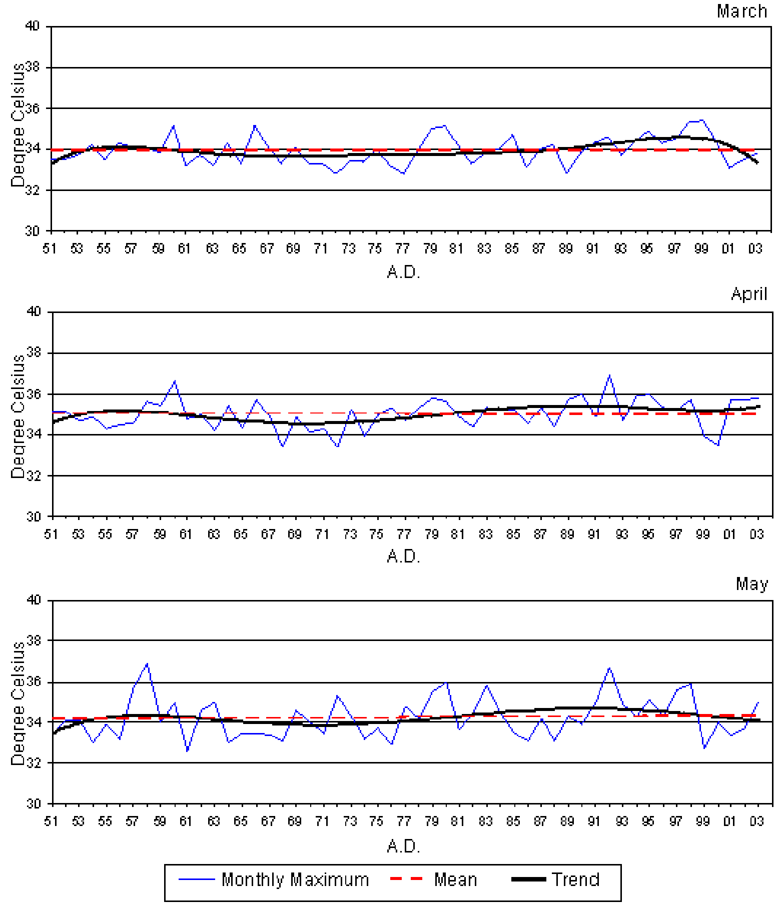


Figure 13. **Monthly maximum and its mean and trend of temperatures of Bangkok in March-May from 1951-2003 (TMD, 2004).**

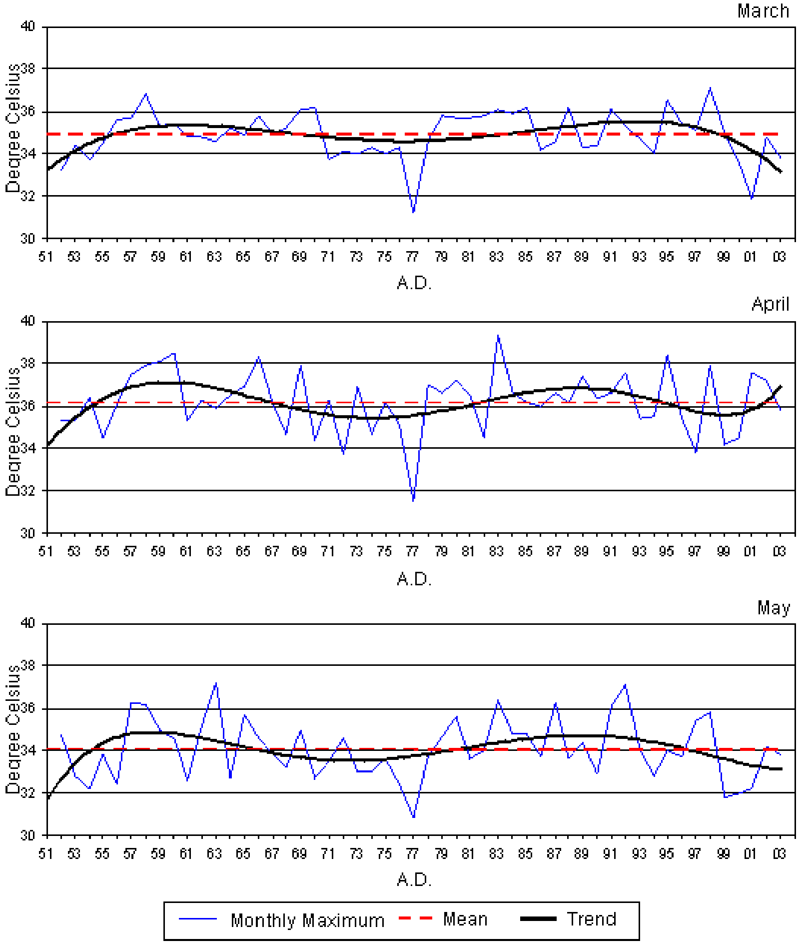


Figure 14. **Monthly maximum and its mean and trend of temperatures of Chiangmai in March-May from 1951-2003 (TMD, 2004).**

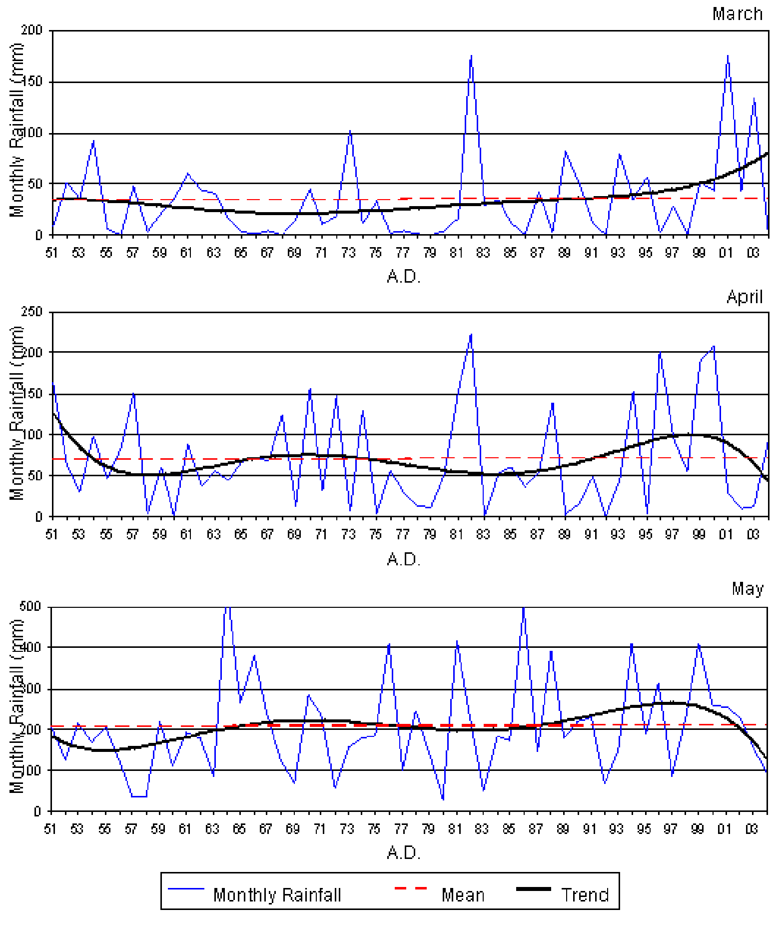


Figure 15. **Monthly rainfalls, its mean and trend of Bangkok in March-May from 1951-2003 (TMD, 2004).**

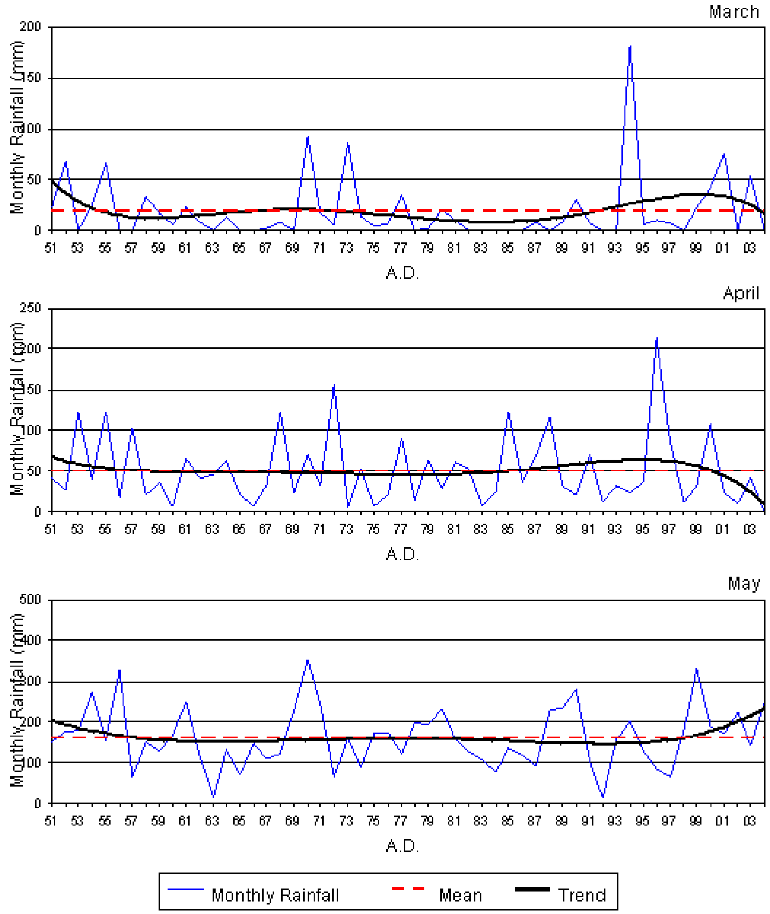


Figure 16. **Monthly rainfalls, its mean and trend of Chiang Mai in March-May from 1951-2003 (TMD, 2004).**

2. Oceanographical Data

The seawater levels in the Gulf of Thailand are controlled mainly by astronomical tides, meteorological winds and pressures and hydrological discharges of large rivers draining into the Gulf of Thailand.

The tidal waves enter the Gulf of Thailand (Figure 9) from the south passing Kamao Peninsula of Vietnam and Malay peninsula and reflect from the northern shoreline at the Upper Gulf. The incident tides from the south and the reflected tides from the north create standing tides in the Gulf of Thailand having large tidal ranges along the reflective shoreline along the head of the Upper Gulf and small tidal ranges at amphidomic points near to Songkhla and shown as tidal profiles in the Gulf of Thailand in June 1993 in Figure 17 while the whole year water levels in 1993 at Sattahip and Ko Lak are shown in Figures 18 and 19 respectively.

The mean monthly water levels due to these tides in 1993 at Bangkok Bar, Sattahip, Ko Lak and Songkhla are shown in Figure 20 which has higher values of 0.2 m.MSL at the beginning of the year and lower values of -0.2 m. MSL at the middle of the year while the mean annual water levels due to these tides are zero due to their harmonic characters. Analysis of these tide gauge data using mean annual values would reveal the change of sea-level.

The higher mean monthly water levels in January and December of 0.4 m (0.2 m + 0.2 m) than the lower mean monthly values in May and June can be seen in Figures 18 and 19 at Sattahip and Ko Lak respectively. These higher water levels at the mouth of the Tha Chin river in Samut Sakorn which is the critical zone 1 of land subsidence (Figure 8) resulted in flooding of salt-farm areas as well as the mouth of the Chao Phraya river in Samut Prakan which is the critical zone 2 of land subsidence.

The monthly mean water levels of 56 years from 1940 to 1996 at Sattahip and Ko Lak stations are plotted in Figure 21 which reveals that the sea levels in the Gulf of Thailand are falling at the rate of -0.36 mm/yr or -3.6 cm/century at Sattahip and Ko Lak. These results are consistent with results of Neelasri *et al.* (1998) who used 25 years data from 1963-1987. The seawater levels at the Chao Phraya river mouth is not used in this analyzed due to land subsidence effect. These two tide stations are located on firm grounds not affected by land subsidence.

Conclusion

1. It was firstly shown that sea-level changes due to climate changes vary according to latitudes: namely (i) in high and middle latitudes, successive glacial, interglacial and interstadial conditions occurred with significant sea-level rises, and (ii) in low latitudes, successive humid and arid conditions occurred with small sea-level rises or falls, Clark *et al.* (1978).

2. In the Gulf of Thailand, located in the low latitudes with insignificant effect of glacio-eustasy, other processes were found dominant, as shown by Warrick *et al.* (1993), i.e. (i) manmade activity on groundwater abstraction resulted in land subsidence below the high tide levels in Samut Sakhon and Samut Prakan, (ii) long records of tides at Ko Lak and Sattahip showed that sea-levels were falling slowly, which might be due to plate tectonics in which the earth's crust rose along the Gulf of Thailand found by Yanagi and Akaki (1993) and (iii) ocean-atmosphere effect (El Nino) found by Gregory (1993) to be the cause of slow fall of sea-level 0-50 mm in the Gulf of Thailand consistent with the magnitudes obtained from long records of tides at Ko Lak and Sattahip.

3. In conclusion, the sea-level in the Gulf of Thailand was found preliminarily falling slightly or not changing, contradicting to the belief that sea-level is rising in the Gulf of Thailand at the same rate as that in the high and middle latitudes.

4. More comprehensive investigation on sea-level fall in the Gulf of Thailand should be made as follows: (i) the similar land-subsidence surveys by the Royal Thai Survey Department in Bangkok and nearby areas reported by DMR (1998) should be made along shoreline areas of the Gulf of Thailand from Laem Ngob in Trat to Sattahip, Chonburi, the head of the Upper Gulf and

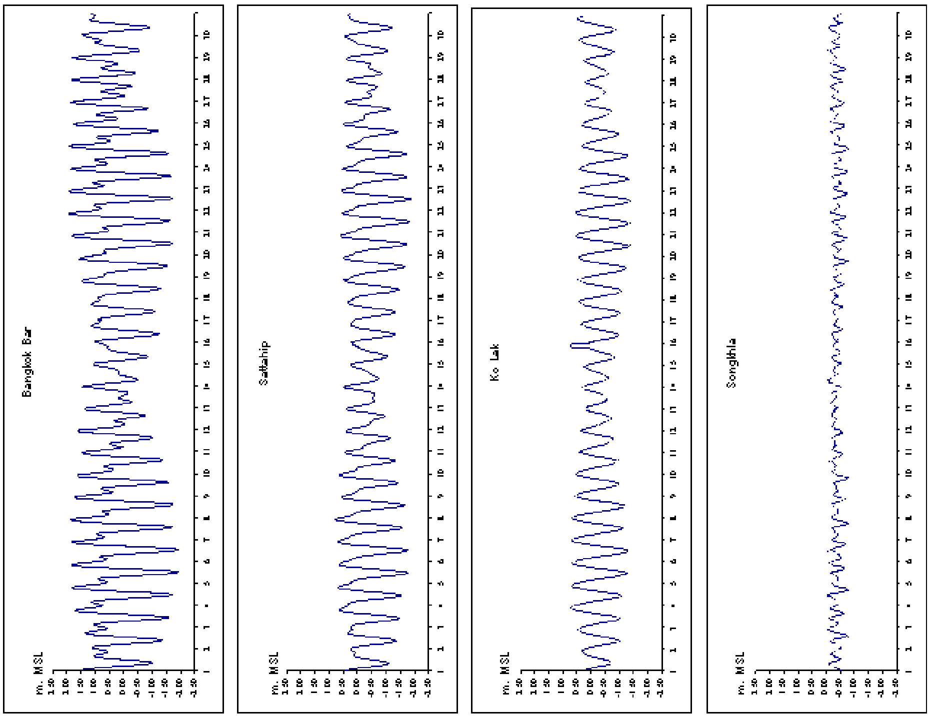


Figure 17. Tidal levels at Bangkok Bar, Sattahip, Ko Lak and Songkhla in June 1993 (HD, 1998).

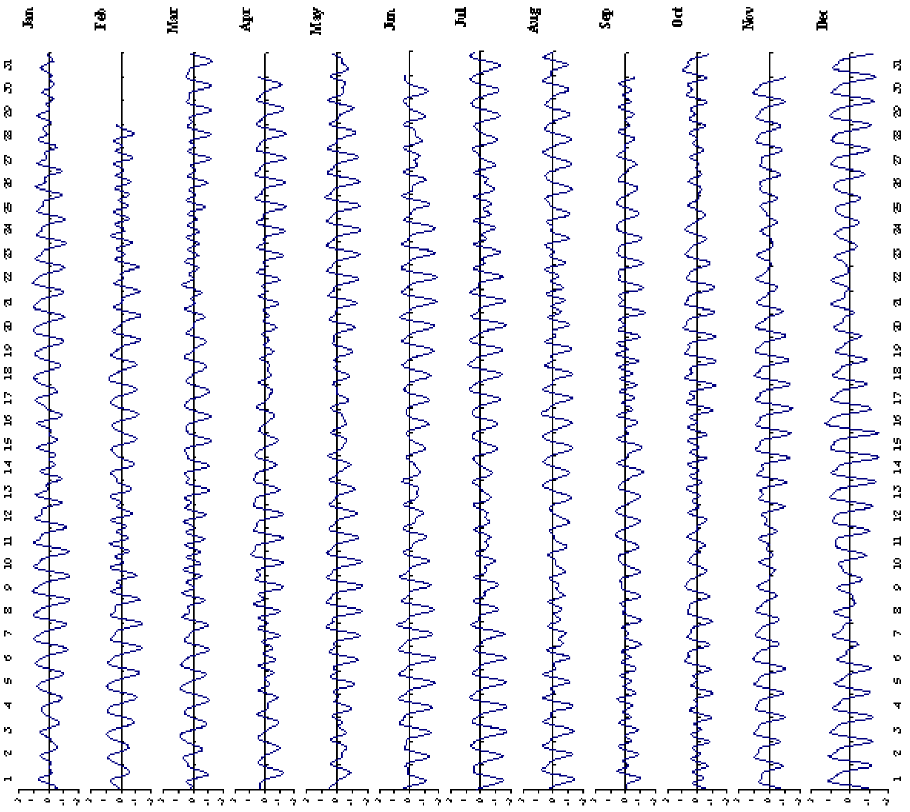


Figure 18. Water levels at Sattahip in 1993 (HD, 1998).

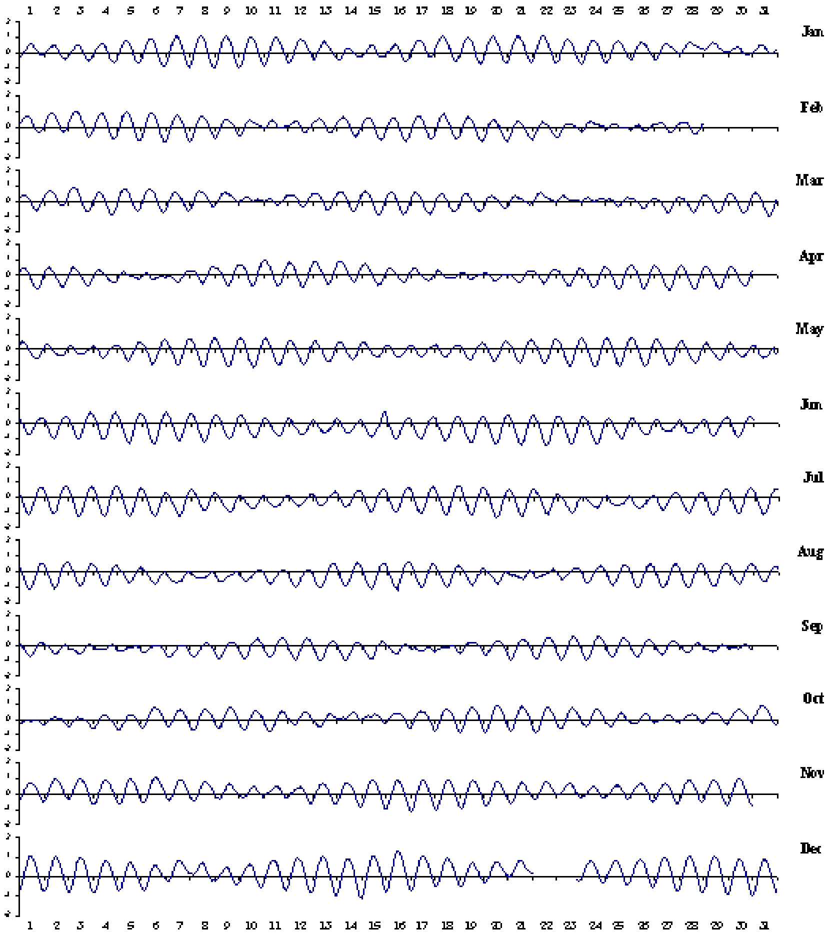


Figure 19. Water level at Ko Lak in 1993 (HD, 1998).

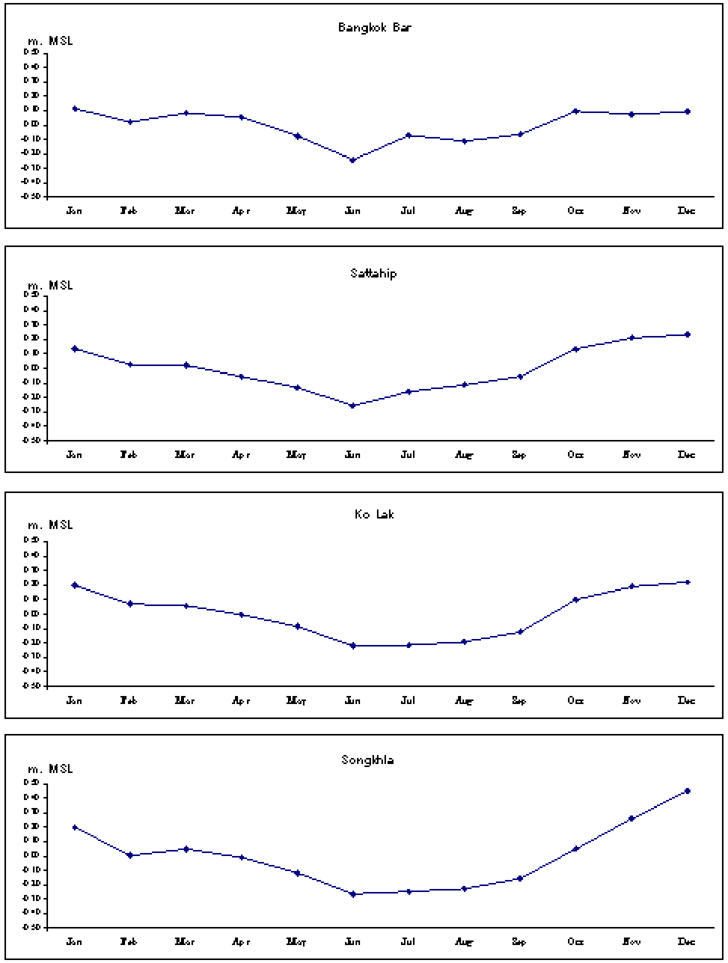


Figure 20. Monthly mean water levels at Bangkok Bar, Sattahip and Songkhla in 1993 (HD, 1998).

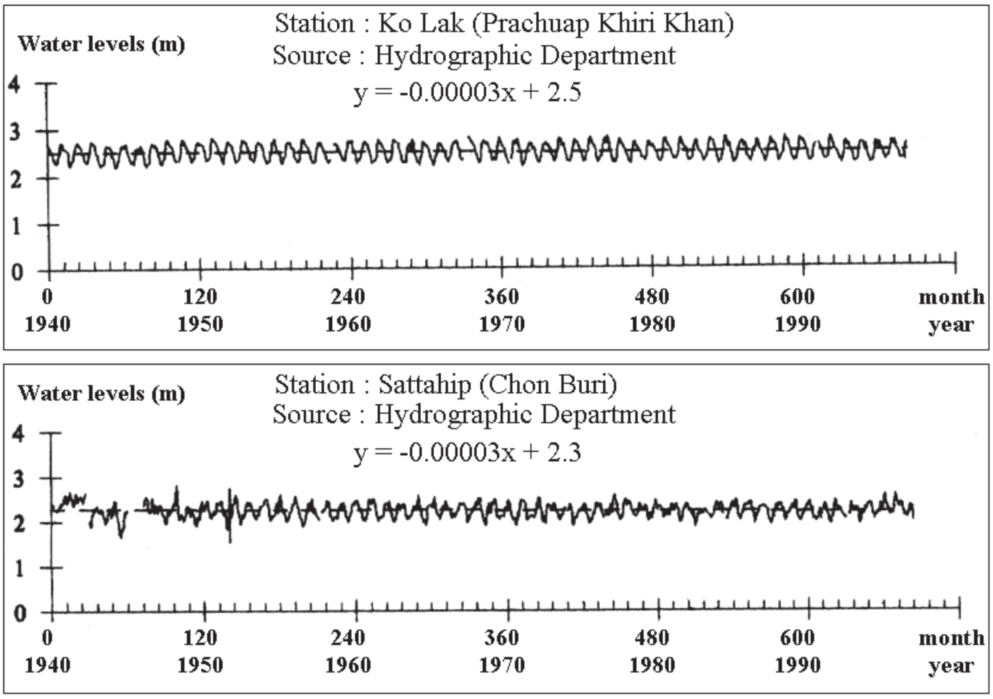


Figure 21. Monthly mean water levels at Ko Lak and Sattahip from 1940-1996 (HD, 1998).

western shoreline to Ko Lak in Prachuap Khiri Khan in order to find the vertical land movements, (ii) more comprehensive investigation of all meteorological and oceanographical data in the Gulf of Thailand, and (iii) more detailed investigation of ocean-atmosphere effect (El Nino) using Coupled Ocean-atmosphere General Circulation Models, Gregory (1993).

Acknowledgements

The author is grateful to Thai Meteorological Department and Hydrographic Department of the Royal Thai Navy for kind provisions of data on meteorology and oceanography respectively.

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