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PALEOGEOGRAPHY, GLOBAL SEA LEVEL CHANGES, AND THE FUTURE COASTLINE OF THAILAND

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ABSTRACT

Today, the sea level is higher than it has been for 98% of the last 2 million years and in the next few hundred years it will rise even higher. We describe the changes in global sea level and the variable position of Thailand's coastline over the last few million years. Maps are used to illustrate the position of the coastline when sea levels were lower and higher relative to today's level: –120 m (20,000 years ago during the last glacial maximum), –60 m (the average level during the last million years), +5 m (125,000 years ago during the last interglacial period), +25 m (before ~3 million years ago. when the Greenland ice sheet began to form), and +50 m (briefly 5.4 million years ago, and earlier, before the Antarctic ice sheets began to form 35 million years ago). The paleobiogeographic implications of these historical changes for plants, animals and early humans are discussed. The projected increases in sea level with global warming and the partial melting of polar ice sheets (1.0–2.0 m (meters) by 2150 and 2.5–5.0 m by 2300) and the associated changes in the coastline's position will be described by reference to the historical changes. The impact of the sea level rise on Bangkok will be exacerbated by local subsidence and increased risk of storm surges. The reasons why the sea level rise projections used here are higher than those adopted by the Intergovernmental Panel on Climate Change (IPCC) in 2007 are explained.

Key words: climate change, coastal flooding, glacioeustasy, global warming, shoreline, Sundaland.

INTRODUCTION

Who would have thought that events in Greenland would affect lives in Bangkok? "As long as it's ice nobody cares except us...However, the minute it starts to thaw and becomes water, then the whole world is interested." (Sheila Watt-Cloutier, Chair of the Inuit Circumpolar Council, quoted in DOW & DOWNING, 2007: 23). Today, the ruins of Ayutthaya, the former capital of Siam, are only 2.5 m (meters) above sea level. In the last 200 years the planet warmed half-way to the conditions that prevailed during the previous interglacial period, 120,000 years ago, when global sea level was ~6 m above today's level.

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In May 2007, Thailand hosted the major Intergovernmental Panel on Climate Change (IPCC) conference. The IPCC met in Bangkok and hammered out a series of policy recommendations based on the latest peer-reviewed research of thousands of scientists. Most importantly, the delegates overcame decades of political inertia and recognized that global change is real and of human (anthropogenic) origin. Later in 2007, the Physical Science Basis Report, the Impacts, Adaptation and Vulnerability Report, the Mitigation of Climate Change Report, and the Synthesis Report were published (IPCC, 2007) and made freely available on the internet. Climate forecasting is dealt with specifically by CHRISTENSEN *ET AL.* (2007) and MEEHLE *ET AL.* (2007). Although Thailand has probably contributed only about 1% of the current global warming, her leaders, like those of every other nation, must now prepare a national response to ongoing environmental changes. This review focuses on one of those changes—the projected rise in sea level.

Most people assume that the seashore is an ancient feature that can be represented on a map as a line of fixed character. The tides come and go but, apart from occasional storm surges and tsunamis, the seashore remains fairly fixed in position. This is especially true in Thailand where, aside from subsidence near the mouth of the Chao Phrya, the coastline has been rather stable. Unfortunately, this view of the land-sea margin is wrong. Today's sea level is typical of only the last 3,000 years; for 98% of the last 2 million years sea levels have been lower. This has important implications for those reconstructing paleoenvironments, paleoclimates and the past distributions of plants and animals. More significantly, ongoing changes in sea level will have major implications for coastal biota, people and infrastructure. The purpose of this review is to draw attention to the global sea level curve and current projections of the inevitable sea level rise in the next few centuries. We have tried to keep the text free of jargon and scholarly references except where they are critical to the arguments; readers unfamiliar with the basic evidence will find the introductory accounts by GORE (2006) and DOW & DOWNING (2007) very useful. At the most elementary level one needs to understand that the concentration of carbon dioxide (CO_2) in the atmosphere is related to temperature. CO_2 levels rise and fall seasonally with plant photosynthetic activity. This invisible gas and a few others prevent solar radiation from being reradiated back from the earth's surface into space; like the glass on a greenhouse roof they trap the heat in the air. CO_2 levels have risen and fallen over thousands and millions of years as the planet warmed or cooled in response to terrestrial and extraterrestrial changes. The problem under discussion here arises as human activities have caused the CO_2 concentration to jump from 280 ppm (parts per million) 150 years ago to 384 ppm in 2007. Atmospheric carbon dioxide gas content is increasing as a result of deforestation and the burning of fossil fuels (20% and 80% of the effect, respectively). CO_2 levels are expected to reach double their pre-industrial level over the next 50 years and inevitably trap more heat from the sun. A correlate of this global warming will be a global rise in sea level.

To understand the effects of sea level change on the biota and human inhabitants of Thailand it is necessary to take a broader geographic view. For that reason some of the maps presented here will be of the larger Southeast Asian region; a biogeographic region termed Sundaland after the Sunda Shelf, a landform that underlies the Gulf of Thailand and the islands of Sumatra, Java and Borneo. In 1869, Alfred Russel Wallace, the "Father of Zoogeography," recognized that the islands of Sumatra, Java, and Borneo were once joined by dry land with peninsular Malaysia, Thailand, Cambodia and Vietnam. In the 1920's, Mollengraaf explained how this geographic region came into being during an ice age when sea levels fell by over 100 meters. Subsequently, a great deal of research has been based on the understanding that only 18,000 years ago the land area of Southeast Asia expanded to cover an area the size of Europe. At that time, during the last ice age, there was no Gulf of Thailand or South China Sea, and Thailand's Pacific Ocean shoreline disappeared. To understand Thailand's current geography one has to consider land-sea boundaries over this larger area.

HISTORY AS A GUIDE TO THE PRESENT

History is a useful guide to the future in the sense that the current human-environment condition is shaped by preceding conditions, and past biosphere-environment interactions are instructive with respect to connections, forcing functions, thresholds, tipping points and the rates of change.

The shorelines and paleogeography of Southeast Asia can be reconstructed in general form over the last 10 million years using the global sea level curve shown in Figure 1. Extrapolating this global sea level curve to the conditions in the Gulf of Thailand requires the assumption that this region has been relatively stable during this time period. This assumption is generally supported by the geological record for Thailand and the Thai-Malay peninsula (TJIA, 1995; HALL, 2001, 2002; HUTCHINSON, 2005), but clearly does not apply to other parts of Southeast Asia, like Sumatra. Nevertheless, it is important to note that all

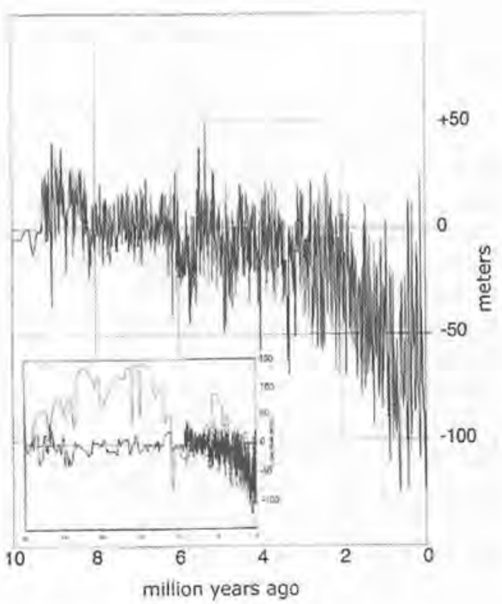

Figure 1. Global sea level curve for last 10 million years based on MILLER *ET AL.* (2005: Supplement: Table: best estimate data). Inset shows the Miller curve (solid line) and the earlier Exxon curve (dotted line) (HAQ *ET AL.*, 1987) for the last 30 million years.

paleogeographic reconstructions and projections about the future rest on assumptions about tectonic stability, land subsidence rates, sedimentation rates, and glacial isostatic adjustment. The latter includes both local effects and global geoid shape change, as the weight of water on the crust shifts in position. All these factors impact both local geography and the relative sea level values estimated for the model World Ocean (WOODROFFE & HORTON, 2005).

In reconstructing the geography of Thailand's relatively tectonically stable coastlines (1,920 km on the Gulf of Thailand, and 960 km on the Andaman Sea) the position of the seashore is largely regulated by global rather than local changes in sea level. The factors that affect global fluctuations in sea level result from changes in the volume and temperature of the water in the oceans, and the volume of the ocean basins themselves. Technically, long term global sea level changes are termed *eustasy* and the factors affecting eustatic change include tectonoeustasy (changes in the volume of the oceans due to earth movements), sedimentoeustasy (changes in ocean volume due to erosion from the continents), glacioeustacy (changes due to advances and retreats of the glaciers) and thermosteric (temperature) effects. MILLER *ET AL.* (2005), the authors of the sea level curve used here, review the causes of eustasy and show that, in the past 5 million years, water volume is 100 times more significant in affecting sea level than the slower processes affecting basin volume (sea floor spreading, sedimentation and continental plate collisions). During the last few million years, water volume changes are directly linked to the size of the continental ice sheets; the ones in Antarctica have been persistent and those in the Northern Hemisphere have fluctuated dramatically. These ice sheet fluctuations are associated with cycles in solar insolation that were discovered by Milankovitch and result from the periodic variations in the earth's orbit (tilt and wobble) and distance from the sun. Such orbital periodicity, coupled with still poorly understood shifts in deep ocean water temperature linked to the global carbon cycle, appear to account for the onset and termination of the growth of the Northern Hemisphere ice sheets and associated glacial periods.

The MILLER *ET AL.* sea level curve for the last 9 million years shown in Figure 1 is based on the analysis of the oxygen isotopic records in the fossil skeletons of benthic foraminifera from two deep-sea cores (ODP 846 & 982). These isotopes (alternative forms of the oxygen molecule) will be explained in more detail below, but for now we will simply note that the ratio of ^{18}O to ^{16}O is temperature dependent and serves as a proxy, or indirect measurement, for ice volume and therefore sea levels (LAMBECK & CHAPPELL, 2001). The general features of this 2-core curve are concordant with oxygen isotope patterns seen in an averaged "stack" of 57 deep-sea cores over the last 5 million years (LISIECKI & RAYMO, 2005). The periodic rises and falls of sea level are found consistently across many cores and oceans. MILLER *ET AL.* estimated the sea level equivalents of each of the 1,800 points (stable isotopic ratios) in their curve and dated the record by curve fitting to the orbital time scale (the Milankovitch curve based on 100,000-year cycles in the earth's orbit), and also on reversals in the earth's magnetic field and on biostratigraphy. Absolute values of MILLER *ET AL*'s estimated sea levels may be ±15 m; the errors of the combined stacked dataset should be smaller but LISIECKI & RAYMO did not calculate sea level equivalence. These new curves are significantly different from the Exxon Production Research Company sea level curve (HAQ *ET AL.*, 1987) that was widely used for the previous 30 years. The new curves validate the number and timing of many of the Exxon curve sea level changes for the last 100 million years, but not their amplitudes. Some of the rises and falls of sea level shown by the older Exxon curve were 2.5 times too large.

The new global sea level curve (MILLER *ET AL.*, 2005) and a revision to account for ocean basin changes (MULLER *ET AL.*, 2008) show that for millions of years before the onset of glaciation in Antarctica, about 35 million years ago, global sea levels were more than 50 m above today's level (defined as 0 m). From 30 million to 5 million years ago, mean sea levels fluctuated within 10 m of today's level. During most of the last 5 million years sea levels have remained below today's level, and the mean level has declined gradually to fluctuate around -62 m for the last million years. The multiple sea level fluctuations that occurred during the last 2 million years are largely due to glacioeustatic cycles associated with the periodic growth and decay of the Northern Hemisphere ice sheets associated with orbital variation (LISIECKI & RAYMO, 2007). Although the Antarctic continent has had permanent ice sheets for about 30 million years, the Greenland ice sheet did not begin to form until 3.0 million years ago. The North American and Eurasian ice sheets have been globally significant during only the last 900,000 years. Beginning about 900,000 years ago, the major climatic periodicity (traced to the eccentricity of the earth's orbit and temperature tracking variation in atmospheric CO_2) has been 100,000 years and the associated amplitude of ice volumes changes and sea level fluctuations (of ±50 m) have been much larger than in the previous million years, when they were typically ±10 m.

The geographic implications of these fluctuations in sea level and the position of Thailand's shorelines are well illustrated by a consideration of the maximal and minimal conditions. First, during the last glacial maximum, 18,000–21,000 years ago, sea levels fell to more than 120 m below today's level and the oceans retreated as shown in Figure 2. This map was prepared by SATHIAMURTHY & VORIS (2006) using a Digital Elevation Model and the ETOPO2 Global 2' Elevation data. This code refers to a U.S. satellite that gathers topographic and bathymetric data for each 2 minutes of latitude or longitude (sites ~3.6 km apart) with a vertical resolution of 1 meter. This map is one of a series of 26 published in Thailand showing the postglacial rise of the sea across the Sunda Shelf between 18,000 years ago and today (SATHIAMURTHY & VORIS, 2006).

During the last glacial maximum the Indian Ocean (Andaman Sea) coastline of Thailand moved out onto the continental shelf for a distance of up to 100 km. The Straits of Malacca emerged and the Thai-Malay peninsula was broadly connected by dry land to Sumatra. The Surin, Similan and Tarutao island groups would have been represented by isolated hills on the otherwise gently sloping coastal plain. On the other side of Thailand the situation was very different: the Pacific Ocean (Gulf of Thailand) coast simply disappeared. The sea retreated across the shallow gulf for over 1,000 km; fringing islands, including Koh Samui and Koh Chang, would have been outliers of the hills on today's adjacent mainland. Crossing the vast emergent plain (covering five times the area of today's Thailand) the large Siam River, an extension of today's Chao Phrya, drained much of today's northern, central, western and peninsula Thailand.

A second, extreme situation occurred about 122,000 years ago during the last interglacial period, from 128,000 to 116,000 years ago, when sea levels rose to 6 m above today's. This estimate is based on data from radiometrically dated fossil coral reefs elevated above sea level on the islands of the Bahamas, Barbados, Bermuda, and New Guinea, and from sedimentary evidence from the Atlantic coast of USA (OTTO-BLEISNER *ET AL.*, 2006; OVERPECK *ET AL.*, 2006; SIDDALL *ET AL.*, 2007; WRIGHT *ET AL.*, 2007). As explained below, the waters came from the partial melting of the Greenland and West Antarctic ice sheets (DUPLESSY *ET AL.*, 2007). The geography of a +6 m rise is approximated in Figure 3. Although much of the

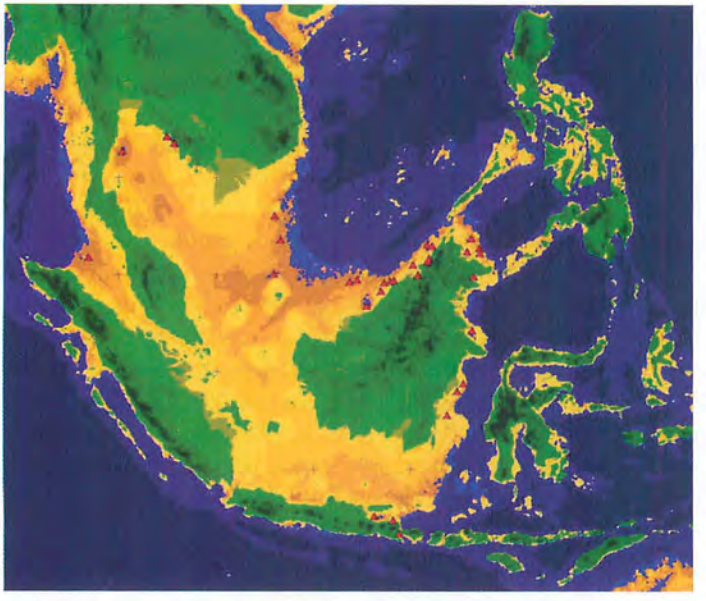

Figure 2. Map of Sundaland during the last glacial maximum about 20,000 years ago when sea levels, relative to today's, were at −120 m. From SATHIAMURTHY & VORIS, 2006 (elevations: above present sea level (greens), 0 – −116 m (yellows), below −116 m (blues), see source for details; triangles: paleo-lakes).

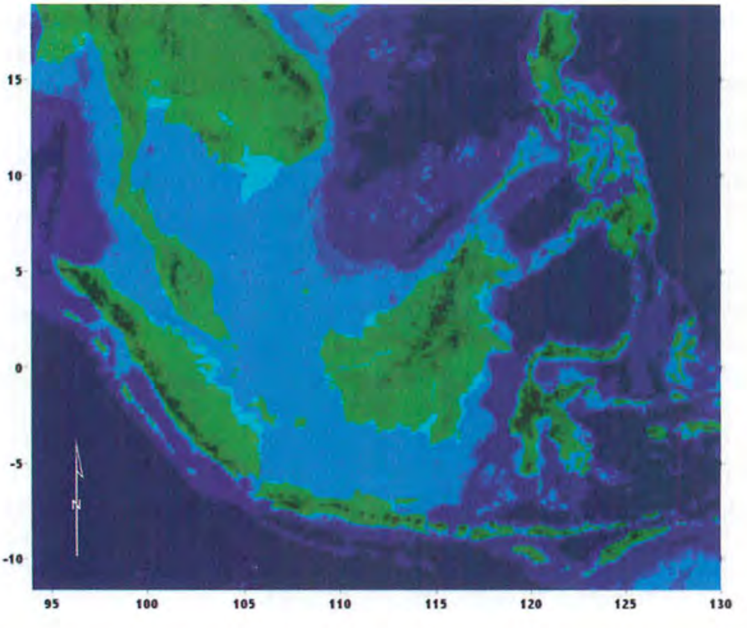

Figure 3. Map of Sundaland during the last interglacial (125,000 years ago) showing the +5 m transgression. This situation is projected to recur in the next few hundred years under some global warming scenarios. From SATHIAMURTHY & VORIS, 2006 (elevations: above +5 m (greens), 0 – +5 m (light blue), below 0 m (darker blues), see source for details).

Andaman and gulf coasts are recognizable, a significant marine transgression flooded the lower Chao Phrya and lower central plain. The seashore moved north, or inland, to beyond Ayutthaya (SINSAKUL, 2000).

To understand why scientists cannot yet make simple predictions about either past or future sea levels we must briefly digress into the details of the oxygen isotopic curve upon which Figure 1 is based. There are two common stable isotopes of oxygen (the atmosphere is typically 99.7% ^{16}O and 0.2% ^{18}O) and their relative abundance in seawater is temperature dependent. Small shifts in water temperature are predictably associated with changes in the ratio of these two isotopes. Unfortunately, conversion of oxygen isotope data to water temperatures to ice volumes to sea levels is not simple. Untangling the effects of global compositional changes in ^{18}O in seawater (the ice-volume effect) from deep-sea and upper ocean water temperatures has been called the "holy grail of Pleistocene paleoceanography". The oxygen isotope ratio in the carbonate in the shells of tiny marine organisms is a good indicator of the water temperatures in which they live. Single-celled protists called forams (Foraminifera) are abundant in the surface waters and after death they sink to become laid down on the sea floor as layers of microfossil shells. Such microfossils can be dated and provide information about surface water temperatures in the past. Today surface waters are warm, and deep waters are near freezing. However, during peak interglacial periods the bottom waters warmed rapidly by as much as 2.5°C. This temperature shift may explain the abrupt warming and cooling associated with peak interglacials but it also greatly complicates the conversion of isotope data into sea level estimates. To illustrate this, consider the situation during the last interglacial; a 12,000-year period referred to technically as Marine Isotope Stage 5e. Although most workers believe the evidence supports the +6 m highstand described above, Figure 1 shows a +24 m highstand at that time. (A *highstand* refers to a point in time when the sea advanced over the land to the maximal extent. In this review we will also use the term marine *transgression* to describe the flooding of coastal land.) This unexpectedly high estimate is now understood to be an artifact of the fact that the isotopic data were not corrected for the temperature difference in the deep sea between glacial and interglacial periods. Older isotopic calculations may have overestimated sea levels during peak interglacials when deep water was warmer (WRIGHT *ET AL.*, 2007; Miller, *pers. comm.*, 2007). When this effect is considered the data plotted in Figure 1 may exaggerate the highstands during the last million years of glacial cycles.

The purpose of the preceding paragraph was to explain why caution should be used in interpreting the last million years of highstands shown in Figure 1. Although we have confidence in the timing and number of fluctuations shown, until some significant earth systems analysis breakthrough is made in the understanding of interplay of isotopes and sea levels, each estimate will carry a significant error. For example, the sea level during last interglacial period is now thought to have been +6.0 ± 5.0 m (WRIGHT *ET AL.*, 2007). Earlier peak interglacial sea levels during the last million years were probably slightly lower than the present day, but typically between +5 and −15 m (SIDDALL *ET AL.*, 2007). BERGER (2008) analyzed the sea level proxy oxygen isotope values in a multicore 900,000-year dataset and found evidence for sea levels of up to ~5 m with a statistical upper limit of 12 m, not more. Thus, although there are published estimates for interglacial highstands of greater than 12 m during the last million years (e.g., a +20 m highstand 405,000 years ago was reported from Bermuda and the Bahamas by HEARTY & NEUMANN, 2001) it is unlikely that sea levels were much higher until about 3 million years ago, when more water was available to the World Ocean.

Regardless of the problem with the +24 m highstand 120,000 years ago shown in Figure 1, a +24 m marine transgression deserves consideration here as it certainly represents the paleogeography of ~3 million years ago (DOWSETT *ET AL.*, 1999, 2005). At that time the planet was ~2°C warmer and Southeast Asia may have been in the grip of continual El Nino conditions (drought) (FEDOROV *ET AL.*, 2006). Figure 4 shows the area of Thailand flooded by a +25 m transgression. We created this map (and the +50 m and +2 m maps in Figures 5 and 7) at the Yale University Sterling Memorial Library Map Collection using GTOPO30 data. The western (Andaman) coast is recognizable as in many places the land rises steeply behind the current shoreline. There are, however, minor marine transgressions near Krabi and Trang. Much of Thailand's Pacific (gulf) coast is also recognizable. Along the eastern shore of the peninsula there were narrow marine transgressions at the mouth of the Tapi River (Surat Thani) and between Nakhon Si Thammarat and Yala. All of the Thale Ban would have been under water (SOMBOON & PAPHAVASIT, 1993). The shoreline of eastern Thailand (from Chonburi to Trat) was also little changed from today's except around river mouths. In marked contrast, much of central Thailand would have been flooded by a +25 m highstand and beneath a shallow bay extending inland for 250 km. A +25 m interglacial coastline would probably lie between Uthai Thani and Nakhon Sawan; the Beung Boraphet swamp may have been under one meter of seawater. Such a transgression would not extend far to the west where the central valley (Mae Khlong river catchment) is bordered by hills, but in the east it would have extended up the Bang Pakong valley far beyond Prachin Buri (+5 m above sea level today), 135 km from Bangkok. We will return to this +25 m map in our discussion of projected future sea level rises, below.

The fourth paleogeographic map of interest represents a more extreme transgression (+50 m) that occurred in the more distant past before the onset of Northern Hemisphere ice sheets and before the completion of the growth of the Antarctic ice sheets. World Ocean sea levels of more than +100 m may have been the norm before the formation of the Antarctic ice sheets and during the Cretaceous when dinosaurs were abundant (MULLER *ET AL.*, 2008). Sea levels of +50 m were typical of the more recent past, from 60–40 million years ago. Figure 5 shows the probable position of the coastline if a +50 m transgression occurred on today's topography. The relevance of the +50 m sea level will become clearer later in this review when we consider future rises of sea level. Two features are noteworthy. First, most of central Thailand lay under the sea. The Gulf of Thailand extended nearly 400 km north of Bangkok to near Phisanulok. To the east of Bangkok, the sea extended around the southeastern hills to beyond Sa Kaeo near the border with Cambodia. These hills and their extension in Cambodia (the Cardamom Mountains) were isolated from the uplands of the Khorat Plateau to the north and bounded further east by a marine incursion that flooded all of the lower Mekong River and the Tonle Sap (Great Lake) of Cambodia. Second, the peninsula coast of Thailand is no longer recognizable as most of the coastal plain was flooded by marine incursions from both the Andaman Sea and Gulf of Thailand. A marine transgression of +50 m did not cut completely across the peninsula. Nevertheless, the land between Surat Thani and Krabi was limited to very narrow strips in at least two places and, overall, the central section of the Thai-Malay peninsula (the area from Surat Thani and Phangnga in the north to Satun and Yala in the south) would have lost half its area during a +50 m highstand.

The major lesson from the last few million years is that today's sea level is unusually high and it has been much lower during most of the past 2 million years. Sea levels have been oscillating dramatically around a mean of –62 m below today's level for the last million

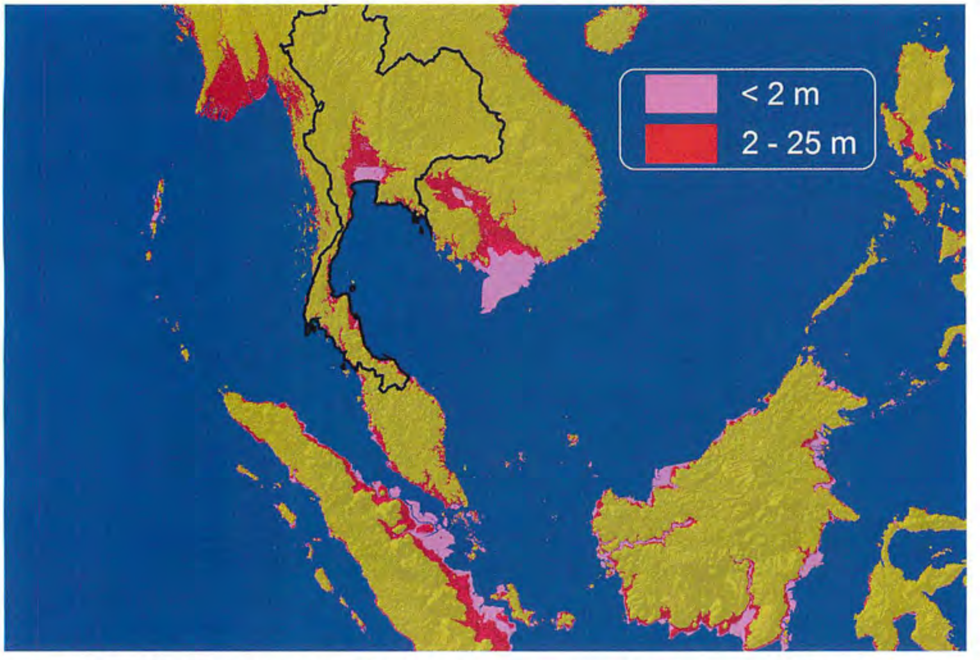

Figure 4. Map of Sundaland with +2 m and +25 m marine transgression on today's topography. The +25 m coastlines last occurred about 3 million years ago.

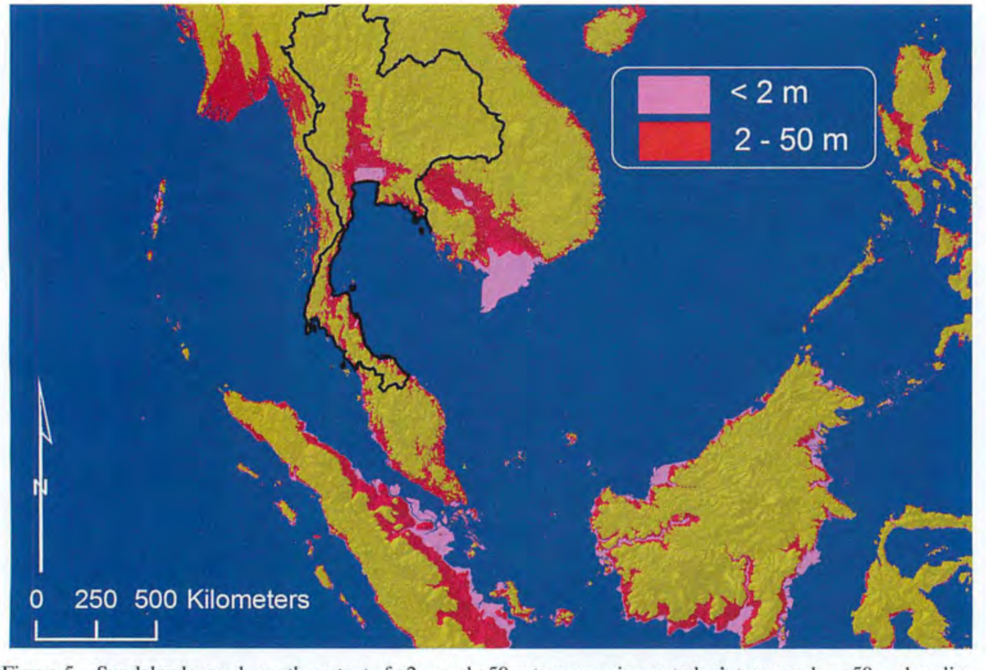

Figure 5. Sundaland map shows the extent of +2 m and +50 m transgression on today's topography. +50 m shorelines were typical of the period 60–40 million years ago, and may have occurred briefly 5.4 million years ago (Fig. 1). A +50 m highstand would not flood completely across the peninsula today.

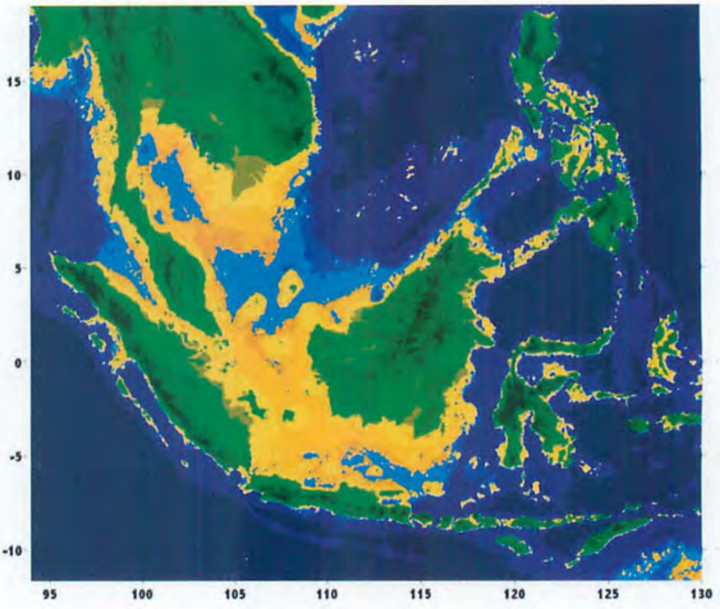

Figure 6. Sundaland when sea levels were at –60 m. Sea levels fluctuated ±50 m around this level for the last million years. From SATHIAMURTHY & VORIS, 2006 (elevations: above present sea level (greens), 0 – –60 m (yellows), below -60 m (blues), see source for details).

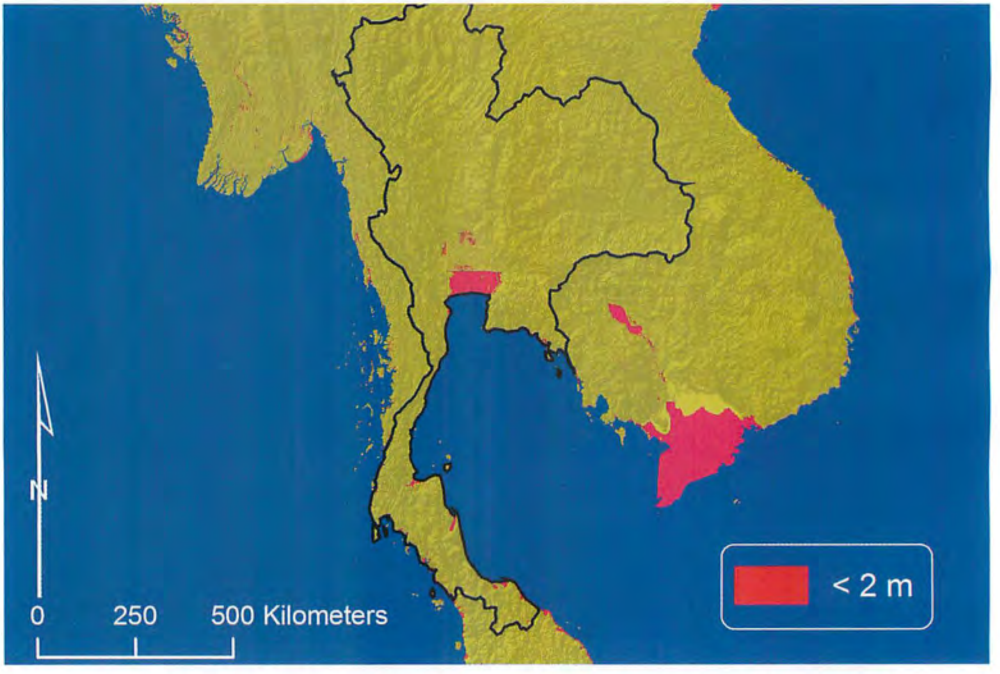

Figure 7. Thailand and neighboring countries showing the flooding associated with the +2 m rise in sea level projected to occur between 2100 and 2150 under some models of global warming.

years (MILLER *ET AL.*, 2005; WOODRUFF & TURNER, 2008). Figure 6 shows the position of the shoreline at –60 m. During the last glacial maximum and throughout most of the last million years, Thailand did not have a gulf coastline in any meaningful sense; the sea lay 1,000 km southeast of its present position. Today's geography was not recognizable until less than 10,000 years ago. More recently, there was a brief mid-Holocene hypsithermal highstand or transgression peaking about 6,000 years ago at +1 m, when the Chao Phraya delta and the Thale Ban were inundated (SOMBOON & PAPHAVASIT, 1993; SOMBOON & THIRAMONGKOL, 1992) (Figure 9). HORTON *ET AL.* (2005) have up-dated this analysis based on a new study of the Thale Ban and a new calibration of regional radiocarbon dates. They show how sea level highstand estimates around the Gulf vary over 3 meters because of hydro-isostasy, the changing weight of water causing the adjacent continent to rise and fall, a process called continental levering. They place the maximum transgression at 1–4 m between 4,450 and 4,850 years ago. The range of values reflects the fact that altitude and age estimates cannot be accepted on their face-value but require multiple corrections. A single sea level history for the peninsula cannot be based on a single site, as the signal from each site will have a different hydro-isostatic component. Nevertheless, after the hypsithermal, global levels then fell slightly and stabilized just below today's level about 3,000 years ago. They remained stable until about 1900 and since then they have begun to rise as a result of anthropogenic emissions and deforestation.

FUTURE CHANGES IN SEA LEVEL

Forecasting future sea levels, and the global temperatures that control them, is a difficult science. Projections are generated using thousands of slightly different computer simulations of climate models that are judged against their ability to retrospectively predict what is known to have happened in the last century. The scientists who advise the IPCC currently use six different scenarios to frame their projections. These involve different fundamental assumptions about population growth, economic growth and most importantly, greenhouse gas emissions. These different scenarios produce a range of projections and it is important to recognize this variability in addition to the geophysical issues affecting scientific confidence (uncertainty). For example, the IPCC's projections in 2001 were for global sea level rise of between 0.09 and 0.88 m in the next 100 years (IPCC, 2001). The newly released 2007 projections are +0.22–0.44 m by 2100, and +0.3–0.8 m by 2300 (BINDOFF *ET AL.*, 2007). These projections assume that global emissions of greenhouse gases will be reduced to 5% below 1990-levels by 2012. Failing that, the alternative scenarios will yield projections for higher rises in sea levels.

Several scientists have shown that the official IPCC projections underestimate future sea level rise (RAHMSTORF *ET AL.*, 2007). The observed sea level rise during 1993–2006 of 3.3 mm/yr was nearly twice the IPCC 2001 best-estimate projection of less than 2 mm/yr. RAHMSTORF (2007) found a proportional relationship between temperatures and sea level rise of about 3.4 mm/yr per degree of temperature (°C) over the last century and concluded that a rise of 0.50–1.40 m by 2100 was likely. Others have shown that the rates of ice flow and melting of the Greenland and West Antarctic ice sheets (assumed to be constant in the IPCC projection) have doubled in the last decade (RIGNOT & KANAGARATNAM, 2006). Based on a rise in global temperature of only 3°C (followed by stabilization) the group advising the German government made projections that are an order of magnitude higher than the IPCC (WBGU, 2007). According to the WGBU, sea level will eventually rise 10s of meters based on a modest 3°C increase in mean global temperature. They predict Greenland may melt completely after the global temperature rises only 1.2°C. For these reasons and others explained below we reject the IPCC projections as too low and will argue that a rise of between 1–2 m may occur by 2150.

Based on Milankovich cycles (the periodic changes in the amount of solar energy reaching the earth), scientists expected the next glacial period to begin and sea levels to begin to drop in perhaps 20–30 thousand years' time. Unfortunately, simple Milankovitch forcing does not completely explain the glacial-interglacial cycles because of slow and nonlinear responses of the continental ice sheets, and because of the impact of atmosphere-ocean interactions like the ENSO (El Nino Southern Oscillation). This adds uncertainty to future global temperature and sea level projections. Nevertheless, a return to icehouse conditions is unlikely because humans have dramatically perturbed global atmospheric chemistry and shifted the planet into a period of prolonged greenhouse conditions. *Icehouse* and *greenhouse* are terms used to describe the contrasting conditions on the planet at times when polar ice caps and Northern Hemisphere ice sheets formed, and at times when the earth was almost ice-free.

The magnitude of the projected 21st century sea level change we are discussing here (1–2 m) is trivial compared to the 120 m change that occurred since the last glacial maximum. The 120 m of water entering the World Ocean in the last 18,000 years came from the North American and Eurasian Ice Sheets (~83 m and 12 m respectively), Greenland (3 m), Antarctica (16 m), and a few scattered sources (6 m) (PAYNE, 2004). Where will additional water come from as the planet warms another ~3°C in the next 100 years? The rapid melting of the Arctic Ocean ice will not affect global sea levels as floating ice already displaces the same volume of water as it produces. In contrast, the melting of mountain glaciers and ice sheets on land introduces new water into the World Ocean. Melting ice sheets will contribute almost all the new water expected to enter the oceans. Thermal expansion of the warmer water will, in addition, contribute fully half the projected increase in sea level; at least 0.5 m in the 21st century. Ignoring mountain glaciers that have been retreating for over 100 years (and will only raise sea levels ~0.4 m), the main ice sheets are found today in Greenland and Antarctica and both are still 3–4 km thick in places. If or when the Greenland ice sheet melts completely, global sea levels will rise about 7 m. This is projected to happen before there is a meltdown of the West Antarctic ice sheet. The West Antarctic ice sheet is currently stuck or grounded on rock that is below sea level but there is a fear that if and when it does break up and float off into the Southern Ocean it may raise sea levels 5–6 m rapidly. This may have happened 119,000 years ago during a brief 600-year highstand at the end of the last interglacial period (SIDDALL *ET AL.*, 2007). Finally, there is the very large East Antarctic ice sheet (with a sea level equivalent of greater than 50 m) that most scientists believe will persist for centuries. However, if all major ice sheets melted, global sea levels will rise 70–80 m above today's level, as it was until ~40 million years ago.

The meltdown of these ice sheets is not projected to occur in the next 100 years but the probability increases dramatically if global average temperatures increase above ~3°C, and this could happen during this century if greenhouse gas emissions are not reduced. In the case of the Greenland ice sheet, there is a concern that an irreversible threshold could be passed in the 21st century to bring about complete meltdown, even though the actual process could take centuries. In the case of East Antarctica, some modeling suggests it will remain frozen until the global temperatures rise by 15°C (WATSON *ET AL.*, 2004) but observations tend to disprove this model. The ice mass of the continent is now shrinking by 150 km^3/yr and the dramatic collapse of the Larsen-B ice shelf in 2002 could be seen from space. The flow rates beneath the ice sheet are accelerating in the short time they have been monitored. All recent observations suggest Antarctica could contribute significantly to sea level rise much sooner than widely believed.

The available evidence today indicates that the planet may experience a sea level rise of 0.5–2.0 m in the next 150 years. There is, of course, some variance in this projection and it is very important that planners recognize both the certainty (predictability) of the ongoing trend and the magnitude of the variance of the projections, even though they are improving on a monthly basis. Few scientists consider the low projections realistic and, as will be seen below, even the current high projections may be too low. From a planning point of view, the use of low or average projections may lead to costly disasters. The recent accelerated losses from Greenland and parts of Antarctica (APPENZELLER, 2007) are clearly a cause for concern above and beyond anything projected by the IPCC estimates or the 1–2 m estimate we favor here. How fast can the sea level rise? We now know that it rose 5 m/100 years between 14,600 and 14,300 years ago (HANEBUTH *ET AL.*, 2000). Thus a rise of 1–2 m in 100 years would be less than half what plants and animals have experienced in the recent past. Although our own ancestors survived such "floods" (they give substance to the almost universal recollection of floods in human mythology), they were not encumbered by a 100,000-fold increase in population size, and the infrastructure associated with modern civilization.

These projections are based on current atmospheric levels and rates of carbon dioxide emission. The 20th century increase in CO_2 and its radiative forcing occurred more than 10 times faster than any sustained change in the past 22,000 years (JOOS & SPAHNI, 2008). Any further increase in the rate of emissions will lead to an upward revision of the projections. If and when China and India develop to the point that they release greenhouse gases at the same per capita rate as the U.S.A., sea level may rise by as much as another few meters before anything can be done to reverse the trend. From a policy point of view some sea level rise cannot now be stopped, and there is no hope of returning to today's "normal" level for hundreds or possibly thousands of years. The global changes now underway will continue for hundreds of years, even if the emission of greenhouses gases were quickly reduced to pre-industrial levels. This inconvenient truth (to use Nobel Laureate Al Gore's phrase) is widely unrecognized so needs to be repeated: even if CO_2 levels are rapidly reduced after 2050, and CO_2 concentrations in the atmosphere are stabilized within 100 years, sea levels will continue to rise for at least a thousand years, temperatures will continue to rise (although more slowly), and CO_2 levels in the atmosphere and oceans will not fall appreciably for thousands of years (IPCC, 2007).

Another contributor to sea level rise has been identified recently: natural out-gassing from the permafrost, frozen soils and lakes of the Arctic (WALTER *ET AL.*, 2006, 2007). The quantities of CO_2 and methane that are sequestered in the soils and lakes of Siberia and Alaska are staggering and greater than the total 750 gigatonnes of CO_2 already in the atmosphere. With the disproportionate rise of temperatures in the Arctic these long sequestered gases are being released into the atmosphere in ever increasing quantities. Scientists have only just begun to try to estimate the rates of emission, but preliminary results are double the current rate factored into IPCC projections. The methane emitted from Arctic wetlands is of major concern as the volumes are large (~4 teragrams/yr), the out-gassing rate has increased in one area by 58% since 1974 (WALTER *ET AL.*, 2006), and methane is 23 times more potent as a greenhouse gas than CO_2. If 60–90% of the permafrost melts by 2100 (as current trends suggest), the methane time-bomb could contribute significantly to global warming and sea level rises of more than 6 m by 2200, levels much higher than projected by the IPCC in 2007.

What does this mean for the position of the Thai shoreline in 100 years time? The answer depends largely on whether humans are proactive or responsive in their mitigating actions. A responsive action is one taken after the fact. The situation during the last interglacial period when the sea level was at about +5 m would be a worst case scenario (Figure 3), but if humans are very proactive, the 2100 shoreline will be closer to the +2-m level (Figure 7). Although much of the Andaman and Gulf coasts are recognizable, a significant marine transgression will flood the lower Chao Phrya and central valley and the seashore will move north towards Ayutthaya (VAN BEEK, 1995; SINSAKUL, 2000). But we may not be so lucky or proactive and, in that case, seas may have already passed the +5 m level, and be headed towards +15 or even 25 m (Figure 4) over the next 1000 years.

HISTORICAL BIOGEOGRAPHIC IMPLICATIONS

From a biogeographic point of view the changing sea levels in Southeast Asia have alternatively created water barriers and dry land bridges for the dispersal of terrestrial plants and animals. The region has been an ecological theater in which a southern Sundaic (Indomalaysian) biota evolved, distinct from that of the northern and currently continental Indochinese biota. Today, these two biotas meet on the Thai-Malay peninsula and for more than a century zoogeographers have thought there was a major faunal transition in the northern part of the peninsula near the Isthmus of Kra (WOODRUFF, 2003a). Their evolutionary divergence from one another is not yet understood although changes in sea level have been proposed as a cause. Although there is no current evidence for a seaway at Kra that could have caused the isolation and divergence of the two biotas, the position of the peninsula's paleo-coastline warrants discussion here.

Biogeographic implications of the past fluctuations in sea levels in Southeast Asia have been the subject of many reports (e.g., WHITMORE, 1981, 1987; HALL & HOLLOWAY, 1998; METCALFE *ET AL.*, 2001; HEANEY, 2004). When sea levels were low, extensive land bridges formed between today's continental mainland and the Sundaic islands. *Homo sapiens* walked from Africa along the coast of South Asia, down the west coast of the Thai-Malay peninsula and out to Java about 70,000 years ago (HILL *ET AL.*, 2006). Our predecessor, *Homo erectus*, made the same journey 1.2–1.9 million years ago but their travel details remain unknown. Many other mammals made the same journey from Indochina to Java and Borneo including elephants, tapir, and orangutan. In contrast, when sea levels were high, as they are today, habitats shrank in extent and marine barriers to dispersal appeared.

The prevailing landform of Southeast Asia during most of the last million years has been a large extension of the continent out to Borneo (Figure 6). To the east of Borneo was the deep and permanent marine barrier that separates the Australian and Oriental biogeographic regions. The subaerial exposure of the Sunda Shelf would have affected the regional climate, as the winds would not have picked up moisture as they blew across the area now flooded by the South China Sea. It is probable therefore that the region was drier than it is today and that both monsoons brought less rain. There are several lines of evidence that the vegetation changed and that rainforest was limited to riverside corridors and a few mountains, and that savanna/grassland dominated the wide plains (HEANEY, 1991; TOUGARD, 2001; MEIJAARD, 2003; BIRD *ET AL.*, 2005; MEIJAARD & GROVES, 2006; KERSHAW *ET AL.*, 2001, 2007; MORLEY, 2007). If the rainforest retreated into "glacial refugia" and river edges, then animals associated with the forest may also have become fragmented in their distribution. So although far more terrestrial habitat was available, much of it may have been inhospitable to rainforest animals.

Much research has gone into the effects of the last 120 m rise in sea level from the last glacial maximum 18,000 years ago. The water at times rose vertically at rates of up to 40 mm/yr and on the flat shelf that caused the shoreline to move up to 40 cm per week. Most terrestrial plants and animals would have little trouble escaping such a flood except when they became trapped on hills that became isolated islands of diminishing area (MEIJAARD, 2003). In contrast, seashore communities would have been constantly disrupted for thousands of years.

Some current research is directed to deciphering historical patterns of plant and animal distributions and evolution by studying genetic variation in living populations. The resolving power of such phylogeographic analyses is well-illustrated by reports on southeast Asian primates (ZIEGLER *ET AL.*, 2007) and insects (PRAMUAL *ET AL.*, 2005; QUEK *ET AL.*, 2007). Most of these studies are concerned with demonstrating affinities between populations on the mainland of Southeast Asia and those now isolated on the islands of the Sunda Shelf. They test hypotheses about environmental conditions when sea levels were low and Sundaland was emergent. Typically, researchers are finding clear evidence for patterns of gene flow between the now isolated populations that are concordant with the hypothesis that individuals or groups of animals walked back and forth across a land bridge.

Several researchers have sought genetic evidence for the opposite circumstance: times when high sea levels served as barriers to dispersal and permitted isolated populations to diverge (e.g., DE BRUYN *ET AL.*, 2005). In particular, the possibility that the Thai/Malay peninsula was cut during periods of high sea levels has been examined. WOODRUFF (2003b) used the old "standard" Exxon global sea level curve and concluded that +100 m marine transgressions had severed the peninsula on two occasions in the past 15 million years. The seaways connecting the Andaman Sea and Gulf of Thailand were not at the Isthmus of Kra, but further south; between Krabi and Surat Thani and between Satun and Songkhla. He argued that these seaways persisted for long enough (greater than 1 million years) to serve as barriers that permitted the faunas of Indochina and the Sundaic subregions to diverge from one another. Unfortunately, as noted above, the revised sea level curves (and local geology) provide no evidence for +100 m sea levels in the last 10 million years.

Woodruff employed the hypothetical +100 m seaways to explain the divergence of Indochinese and Sundaic forest birds (HUGHES *ET AL.*, 2003a; ROUND *ET AL.*, 2003) and his hypothesis has been widely used by other workers subsequently. The collapse of the evidence for the seaways has necessitated a re-interpretation of the biogeographic data; this has now been provided in the context of an analysis of mammal distribution patterns (WOODRUFF & TURNER, 2008). Using the new global glacioeustatic curve, they argue that there were more than 58 rapid sea level rises of greater than 40 m each in the last 5 million years (Figure 1). Each of these rapid sea level rises would have resulted in significant faunal compression in the narrow central and northern parts of the Thai-Malay peninsula. This would cause local population extinction. These rapid changes in sea level appear to account for the observed patterns of mammal species latitudinal diversity, the concentration of species range limits north and south of this area, the nature and position of the transition between biogeographic subregions, and possibly the divergence of the faunas themselves during the last 10 million years. This sea level rise compression effect was not noticed by earlier workers who focused on just the last 120 m rise.

PREDICTABLE EFFECTS OF SEA LEVEL RISE IN THE NEXT 300 YEARS

As explained above, there is still considerable uncertainty about the projected sea level rise by 2100. Best-estimate projections of the 100-year rise currently vary 4-fold (0.5–2.0 m), and for the 1000-year rise by as much as 20-fold (0.5–20 m). The German Advisory Council on Climate Change predicts a 2.5–5.1-m rise by 2300 with the melting of one third of the Greenland and West Antarctic ice sheets (WGBU, 2007). The components of their estimate are: thermal expansion 0.4–0.9 m, mountain glaciers 0.2–0.4 m, Greenland 0.9–1.8 m, and West Antarctica 1–2 m. Our personal view of these various estimates and projections is that planning for and mitigating for a 2-m rise this century would seem prudent.

The German WGBU view is that planning for the next hundred years is inappropriate given the uncertainties involved and the inevitability of continued sea rise over the next few centuries. Allowing for the lags in thermal expansion of the World Ocean and the meltdown of the ice sheets, they accordingly project changes for the year 2300. Their model assumes that global temperature will rise 3°C and then stabilize. At that point the atmospheric CO_2 content will have risen to 560 ppm, double the pre-industrialization level.

Global sea levels have risen nearly 200 mm since 1870. They rose at 1.7 mm/yr for the last 100 yrs, but the rate has accelerated since 1993 when more accurate satellite altimetry methods became widely used. During 1993–2003, the rise in sea level from thermal expansion and from ice melt was 3–4 mm/yr (with about half contributed by each source). Over the long-term thermosteric expansion may be 70% more significant than previously thought, and some calculations show it could add 4 m to current sea levels over the next 1000 years. Sea level change is very uneven around the globe because of local differences in water temperature, salinity and glacial isostatic adjustment. Sea levels are, for example, currently falling in the Maldives (postponing their inevitable inundation). Ocean currents take 100's–1000's of years to even out the World Ocean level. In our discussion we have assumed that Thailand's coastlines will track the global average conditions.

We have used the term *projections* throughout this discussion to reflect scientific uncertainties and the assumptions made in the different models and simulations. *Predictions* are projections that have a higher or much higher probability of occurring. We can make some predictions about the effects on Thailand of sea level rise and coastline change. These predictions are, however, premised on their being no proactive response to the foreseeable environmental changes. If a coastline is diked, or a river mouth barraged, or a population evacuated from an area, then clearly the predictions become meaningless. Proactive responses may be grouped into three categories: protection, managed retreat, and accommodation. In the absence of such proactive responses the predicted change in sea level will result in a loss of coastal habitat especially in the fertile areas around river mouths. Much valuable land devoted to field crops and aquaculture will be lost to erosion by wave attack and by inundation. The ecological services provided by the natural coastal communities (seashore, seagrass beds, mangroves, reef-building corals) may be diminished with losses of coastal protection, natural fish hatcheries and coastal fisheries, and biodiversity. The prior clearing of coastal forest, mangroves and wetlands will increase flooding risk and amplify storm-related damage. Coral bleaching and disease due to rising atmospheric CO_2 and water temperatures are already global problems and coral reef communities will undergo significant change or disappear by 2100 (HUGHES *ET AL.*, 2003b; PANDOLFI *ET AL.*, 2003; CARPENTER *ET AL.*, 2008). As saltwater intrudes into coastal aquifers there will be a loss of potable ground water and soil quality. The beaches, for which Thailand is famous, and infrastructure of coastal tourism are also at risk in low-lying areas.

There are still very few studies of the current economic (market and nonmarket) value of ecological services and almost no analyses of the inevitable changes in such valuations in the future. One recent study of the economics of converting mangrove-protected shorelines in Thailand into shrimp farms underscores the non-linear relationships between costs and benefits and the difficulties of ecosystem-based management. BARBIER *ET AL.* (2008) found that the economic value of mangroves in protecting coastal communities from storm waves (wave attenuation) outweighed the value of shrimp farming when ponds replaced more than 20% of a mangrove area. Such economic modeling is valuable in planning future coastal land use even though this particular study does not take into account the fact that shrimp farming may not be sustainable (as practiced), or the long-term costs associated with abandoned shrimp ponds and habitat restoration (PIYAKARNCHANA, 1999; WONG, 2005).

The direct effects of sea level rise on terrestrial biodiversity are difficult to separate from the broader threats of climate change (WOODRUFF, 2001). The reader is referred to LOVEJOY & HANNAH (2005), PARMESAN (2006) and BUSH & FLENLEY (2007) for a series of technical reviews of the ways climate changes are impacting biodiversity. Range shifts and phenological changes are ongoing and will become "normal" features of individual species and their increasingly no-analog community assemblages (WOODRUFF, 2001). By that we mean that history teaches us that species respond individually to change and not as fixed assemblages (communities) that we think of as quasi-stable. Coastal organisms are particularly vulnerable to change when plants and animals cannot move inland because of human infrastructure. Much of Thailand's gulf coast shore-life is now trapped and can no longer move freely. The very significant loss of remaining coastal wetlands will also have a negative impact on the migratory birds that spend a critical part of the year in Thailand. The predictable result will be for much local population extirpation and a decline in biodiversity and the services it provides. Marine and coastal reserves, including 10 Ramsar Convention on Wetlands of International Importance sites, may require rethinking as the wetlands relocate themselves. Marine communities will be affected by increased salinity, especially in the warmer surface waters around Thailand, and by acidification due to increased dissolved CO_2 (WGBU, 2007).

The social implications of even a small rise in sea level are enormous. Fortunately, Thailand does not face the same challenge as do low-lying island nations where whole populations of "sea level refugees" will have to be evacuated (Tuvalu, Vanuatu, Kiribati, and the Maldives, for example). Nevertheless, millions of Thais currently live in areas that are threatened by the change in shoreline. Major population centers at risk of inundation to varying extent include Pattani, Songkhla, Nakhon Si Thammarat, Krabi, Phuket, Surat Thani, Hua Hin, Petchaburi, Chonburi, Pattaya, Rayong, Trat and, of course, Bangkok. The

Figure 8. Areas of Bangkok covered by seawater in the year 2100 according to Somboon & Thiramongkol (1993: 11). This projection, made before global warming was widely appreciated, involves land subsidence and a 1 m rise in sea level.

rise in global sea levels threatens to submerge much of the area on which the city of Bangkok has been built, 25 km from river mouth.

The threat to Bangkok is unfortunately exacerbated by ground subsidence and seasonal river flooding (Phienwej & Nutalay, 2005). Subsidence, of up to 700 mm since 1978, is due primarily to the pumping of groundwater from over 14,000 wells. Although regulations now curb pumping in the city and subsidence peaked at 120 mm/yr in 1981, it continues at 5–10 mm/yr in the city and 45 mm/yr in the suburbs (Phienwej & Nutalay, 2005). A military mapping study recently found subsidence rates of 50–80 mm/yr (Bangkok Post, 27 November 2007). This subsidence has produced a depression extending over 60 km on the east side of the river from Pathumthani to Samut Prakan. It has contributed, together with deforestation, aquaculture and sand-mining, to the loss of a strip of seashore 500–1000 m wide along the entire top of the gulf. Many years ago Somboon (1990, Somboon & Thiramongkol, 1993) warned that this subsidence, coupled with the projected sea level rise in the 21st century, could result in the inundation of most of the city (Figure 8). Even without sea level rises and local subsidence Bangkok also has a problem with seasonal river flooding. A flood crest of +2.3 m in 1942 is the worst in recent history; but lesser floods in 1983 and 1995 each caused over 8 billion baht (US$250 million) in damage. Extensive dykes, pump stations, and regulated retention basins (Monkey Cheek project) now ring the inner city and afford temporary protection for areas that have now subsided to or below sea level (Phienwej & Nutalay, 2005). Clearly, adding the sea level rise to subsidence and flooding put much of Bangkok's critical urban infrastructure (transportation, power, gas and water), housing, retail, financial, and administrative sectors, port facilities and many cultural treasures at risk. Secondary problems include the increased public health risks of infectious diseases associated with contaminated water and malaria-transmitting mosquitoes that breed in brackish water.

The risk to Bangkok is unfortunately further magnified by the city's location at the head of a shallow gulf; it is especially vulnerable to storm surges. Cyclones (typhoons) are expected to become stronger and possibly more frequent with the ongoing rise in sea surface temperature, and elsewhere such violent storms have temporarily raised sea levels +5 m. It is worth remembering that a doubling of wave height caused by these storms is equivalent to a 4-fold increase in wave energy. The tide range at the mouth of the Chao Phrya is 2 m (SINSAKUL, 2000) and a storm surge at high tide could rapidly flood the coastal plain and city. We have to recognize that a 100-year storm (one that occurs every 100 years, on average) today becomes a 4-year storm tomorrow, with a sea level rise of only one meter. The most destructive results of sea level rise will be from storm surge associated floods, and not from slow inundation. For that reason, we recommend planning for a 1–2-m rise with additional threats in some areas associated with storm surges, and for the long term threats of a 5 m rise as outlined above and by the World Bank (2006). Some idea of the local shoreline shift associated with a 2–5-m rise can be seen in Somboon's reconstruction of conditions during the Holocene highstand about 7,000 years ago (Figure 9). A recent proposal to build a 100-billion baht (more than US$3 billion) flood prevention wall south of Bangkok, placed 300 m offshore and extending for 80 km across the top of Bangkok Bay (Bangkok Post, 27 November 2007), gives a rough idea of the magnitude of the possible economic losses in that one area.

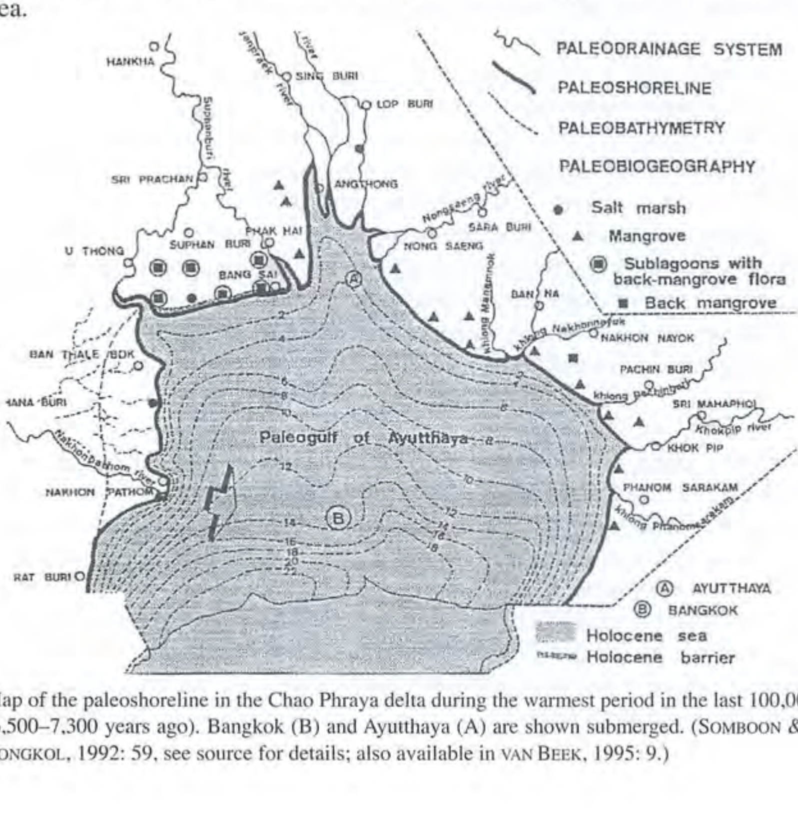

Figure 9. Map of the paleoshoreline in the Chao Phraya delta during the warmest period in the last 100,000 years (6,500–7,300 years ago). Bangkok (B) and Ayutthaya (A) are shown submerged. (SOMBOON & THIRAMONGKOL, 1992: 59, see source for details; also available in VAN BEEK, 1995: 9.)

Public policy must unfortunately be built around the current scientific uncertainties. In the field of climate change some aspects are predictable and others much less so. Sea level and shoreline changes fall in the latter category. Planning societal responses around fixed end-point scenarios will not work in this case, or for almost any dynamic problem. Even with the dramatic improvement in projections in the last few years, the innate non-decomposability and nonlinearity of the complex earth system, the time scales involved, and the possibility of "nasty" irreversibilities, make *proactive adaptive response* much preferable to after-the-fact *reactive response.*

We are deliberately not providing more detailed predictions about the position of the Thai shoreline in 2100 or 2300 for four reasons. First, the greater cartographic precision needed to produce useful +0.5 m, +1 m and +2 m projections is best done in-country with on the ground verification and information about tides, storm surges and coastal effects like subsidence. In the meantime, readers can get rough impressions of what each additional meter of sea might do on satellite images of this part of the world derived from NASA's Shuttle Radar Topography Mission and available at ROHDE (2007). Second, any detailed mapping has to fully account for the known scientific uncertainties associated with all sea rise projections, and the confidence limits of the estimates that can exceed the actual estimates in this range of values. Such detailed reconstructions are beyond the scope of this review. Third, we therefore choose not to speculate about the details, given the potential social, economic, and political costs of error. Four, we suspect (hope) more detailed projections have already have been prepared by the Military Mapping Office or other government agencies, but they do not appear to be in the public domain. We know that increasing numbers of government officials, academics and NGO's are working on these problems in Thailand and applaud their efforts.

Successful coastal zone management requires the participation of five sectors: local people, government authorities, non-governmental organizations (NGOs), scientists and investors (SUDARA, 1999). Whether the Thai coastline can be managed by existing government units in cooperation with the other sectors, or whether a more integrated approach is necessary, deserves attention (WONG, 2005). NGOs like the Siam Society can play an important role in providing opportunities for all sectors to meet and talk with each other. The Society has a tradition of organizing special symposia that bring academic experts and government officials together in a synergistic non-adversarial atmosphere. Although the focus of our review has been on one technical aspect of the environmental side of global change, the humanitarian and social aspects are just as challenging and also of interest to the Society.

Postscript: Since this manuscript was prepared 3,500 scientific papers have been published on climate change and global warming and over 200 on sea level rise; the new findings are generally concordant with the above review except that accelerated ice sheet melting is reported from Greenland and Antarctica. Also in the interim, we became aware of the following local news stories that offer radically different views: "global warming is not likely to cause the sea level in the Gulf of Thailand to rise because we are too far from melting glaciers or ice sheets." (THE NATION NEWSPAPER, 2007) and "Thai official: Bangkok will be underwater in 20 years" (FOXNEWS, 2007). Taken out of context such stories are very confusing. We recognize that the media has its own agenda in writing headlines and hope that our review will be useful to those who seek to inform the public and policymakers.

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