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# Sea level change in the Gulf of Thailand from GPS-corrected tide gauge data and multi-satellite altimetry

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ABSTRACT

Investigation of long-term tidal data and short-term altimetry measurements reveals that sea level in the Gulf of Thailand is rising significantly faster than global average rates. Upward land motion detected from repeated precise GPS campaign measurements is used to correct the apparent sea level change from tide gauge, yielding absolute long-term trends as follows: Sattahip (1942–2004) 5.0 ± 1.3 mm/yr, Ko Sichang (1940–1999) 4.5 ± 1.3 mm/yr and Ko Mattaphon (1964–2004) 4.4 ± 1.1 mm/yr. Dual-crossover minimization of multi-mission altimetry data covering the 1993–2009 period reveals the following absolute sea level rates: Sattahip 4.8 ± 0.7 mm/yr, Ko Sichang 5.8 ± 0.8 mm/yr, Ko Lak 3.6 ± 0.7 mm/yr and Ko Mattaphon 3.2 ± 0.7 mm/yr. In other parts of the Gulf, the 1993–2009 rising rates are also in the range of 3 to 5.5 mm/yr. In the entire Gulf we don't find any evidence of sea level falling. At Ko Lak where the collocation of Topex-class altimetry ground track and the tidal station is extremely good, vertical land motion derived from the difference of sea level change rates detected by altimetry and tidal data is used to correct the apparent rate, yielding an absolute long-term (1940–2004) rate of 3.0 ± 1.5 mm/yr. The differences between the altimetry-based rates and the absolute tide gauge sea level trends can be explained by interannual variations like ENSO and decadal variations due to solar activity and lunar nutation. Post-2004 tidal data have been treated separately in our study because reliable values of region-wide vertical co-seismic displacements and post-seismic velocities caused by the 2004 Mw9.2 Sumatra-Andaman earthquake are still not accurately known. Exclusion of these data will not significantly change the determined long-term absolute sea level change rates because of the relatively short time span of post-earthquake sea level data compared to the complete tidal record. The impact of fast rising sea level combined with high rates of post-seismic downward crustal motions as indicated by GPS data makes coastal areas and river estuaries along the Gulf of Thailand highly vulnerable to flooding, particularly the low-lying city of Bangkok.



## 1. Introduction

The study of sea level change rate from tidal data is complicated by the fact that tide gauges are attached to the land and thus their measurements are affected by vertical land motion caused by natural or anthropogenic processes unrelated to variations in sea level. In the traditional approach of many global studies, *e.g.* Douglas (1997) and Peltier (2001), only a subset of tide gauges is carefully selected, having at least 60 years of record length and being far away from tectonically active areas. Corrections for Global Isostatic Adjustment (GIA) are then applied to obtain absolute rates of sea level change, which produce a consistent rising rate at around 1.8 mm/yr for the 20th century. The main problem with this approach is that the strict criteria screen out most tide gauges, leaving only around 25 stations for studying sea level change. Moreover the locations of these qualified stations are concentrated in the Mediterranean, the North Atlantic and the East Pacific. No tide gauges from the Indian Ocean and West Pacific are included and the serious question arises whether this rate can be truly regarded as global.

More recent studies on the trend and acceleration of global sea level change mitigate this under-sampling problem by incorporating as many tide gauges as possible, excluding only those in locations where vertical movements (caused by tectonic activities or land subsidence) are known to exist but with rates that cannot be modelled. In Church and White (2006) the global sea level rise rate and acceleration were determined from sea level reconstructed from the amplitude derived from tidal data and the covariance obtained from empirical orthogonal function analysis (EOF) of altimetry data. Jevrejeva et al. (2006) and Jevrejeva et al. (2008) used a method based on Monte Carlo Singular Spectrum Analysis (MC-SSA, quite similar to EOF), to decompose the original tide gauge time series to detect multi-decadal oscillations of sea level change and its acceleration, which was

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estimated at about 0.01 mm/yr$^2$. Undoubtedly, the traditional approach is not capable of dealing with these decadal variations, which might obscure the acceleration signal in sea level rise. However, the global rate of sea level change of 1.8 ± 0.3 mm/yr found in Church et al. (2004), based on reconstructions from combined tide/altimetry data for the period 1950–2000, and that of 1.7 ± 0.3 mm/yr for the 20th century found in Church and White (2006), are almost identical to the 1.8 ± 0.1 mm/yr found in Douglas (1997), based on the straightforward approach for the period 1880–1980. This demonstrates the capability of the simpler traditional method in determining the linear trend of sea level change and therefore it is adopted for our study. Further, we have access to data for a reasonable number of tide gauge stations in the Gulf of Thailand that suit the method well, although we lack tidal data in part of the eastern Gulf (Cambodia and Vietnam).

Since late 1992, a series of altimetry satellites have provided well-distributed precise sea level measurements unaffected by vertical land motion over almost all oceans. Cazenave and Nerum (2004) show on basis of satellite altimetry analyses that short-term (1993–2003) linear trends of sea level change in the open ocean are not geographically uniform. Accordingly, it is not reasonable to assume that rates of long-term sea level change in different oceanic regions are invariable and more studies on both long-term trends from tide gauges and short-term rates from altimetry are needed. This need is imperative for many low-lying coastal cities and estuaries along the Gulf of Thailand. Of particular concern is Bangkok, the megacity capital and economic powerhouse of Thailand, which is situated at the northern tip of the Gulf. This is a river mouth flood plain area that is extremely low, with an average surface height only 1 m above sea level. Coastal erosion is now clearly evident and over the last 20 years there are places where sea has intruded more than 1 km into the land. Sea level rise and land subsidence are believed to be major causes. However, proper mitigation and prevention measures can only be devised when the actual magnitudes of these phenomena are better known.

Only a few studies (partially) address sea level change in this westernmost region of the North Pacific. A study by Yanagi and Akaki (1994) shows that sea level change rates during 1950–1991 at Ko Sichang and Ko Lak are 0.6 ± 0.4 and −0.8 ± 0.2 mm/yr respectively. Another study by Vongvisessomjai (2006), who used monthly-averaged sea level data during 1940–1996 of Sattahip and Ko Lak, reports rates of −0.36 mm/yr at both stations. This study has stirred wide debate in Thailand regarding the actual sea level trend in the Gulf of Thailand. Ko Lak was included as a site in the Southeast Asia region in the study of global sea level change by Holgate and Woodworth (2004). The sea level change rate determined at this station, after GIA correction, is −0.66 mm/yr (Simon Holgate, 2010, personal communication).

The geographical extent of the Gulf of Thailand is relatively small compared to other ocean basins. Ko Lak and Ko Sichang are closely situated in the inner part of the Gulf. It is therefore reasonable to assume that these two stations sample the same water mass and should provide a more comparable sea level change. Opposite rates thus indicate that at each location vertical land motion from differing causes may have come into play. Yanagi and Akaki (1994) and Vongvisessomjai (2006) did not deal with vertical movements, presumably because of the lack of geodetic measurements. The situation has changed in the last couple of years by studies from Vigny et al. (2005) and Simons et al. (2007) who utilize precise GPS measurements at many locations in Southeast Asia. The availability of a Thai subset of these data opened up the opportunity to determine vertical motion at some tide gauges in the Gulf and they have been included in our study.

Our investigation begins in Section 2 with a thorough review of tide gauge stations in the Gulf of Thailand. A robust regression technique was employed to determine the long-term apparent rates of sea level change at selected stations. Section 3 describes the computation of vertical land motion from precise campaign GPS measurements. Vertical movement trends before and after the 2004 Mw9.2 Sumatra-Andaman earthquake are revealed, and implications on the correction of apparent sea level change rates are discussed. Section 4 shows the rates of absolute long-term sea level rise based on the combination of tide gauge results and GPS results. Extensive analysis of satellite altimetry data to determine recent-period rates then follows in Section 5, in which we also evaluate rates and patterns of vertical land motion based on the analysis of combined altimetry and tidal data. Section 6 concludes our study.

## 2. Tide gauge selections and apparent sea level change rates

The Gulf of Thailand is bordered by Vietnam, Cambodia, Thailand, and Malaysia. In the south it is demarcated by a line running from the western extreme of Camau Point (8° 36′ N) in Vietnam to the northern extreme of a point on the east side of the estuary of the Kelantan river (6° 14′ N, 102° 15′ E) in Malaysia (International Hydrographic Organization, 1953). The covered area of the Gulf is about 320,000 km$^2$. The sea floor is shallow with an average depth of 40 m.

None of the five Vietnamese stations listed in the Permanent Service for Mean Sea Level database (PSMSL, http://www.psmsl.org) is situated in the Gulf area. Tide gauges at Ha Tien in Vietnam and Sihanouk and Kampot in Cambodia are known to exist but data from them are not available through PSMSL and are therefore hard to come by. As such the study is limited to the north and west coast of the Gulf where a substantial number of tidal stations exist along Thailand's coastline. Of the many Malaysian stations, only Geting is located in what has been commonly agreed as the Gulf of Thailand area. Fig. 1 shows the locations of tidal stations under consideration.

### 2.1. Classification of tidal stations

Adopting the same record-length criterion as in Douglas (1997) and Zerbini et al. (1998), all tidal stations are divided into two groups as shown in Table 1. Group 1 stations have at least 60 years of sea level record and although many have measurements since the early twentieth century (http://www.gloss-sealevel.org/publications/thailand_2001.pdf, more details can be found in Hydrographic Department, 2007), these early data are not available to us. An exception is Ko Mattaphon where sea level data are available from 1957 onwards. The justification of including Ko Mattaphon into group 1 is that the other stations in this group cluster in the northern part of the Gulf. The inclusion is a trade-off between record length and number of locations in aiming to reduce the spatial bias. Stations in group 2 have record lengths longer than 19 years, but less than 40 years.

Annual-average sea level time series of group 1 stations are shown in Fig. 2. Data from Bangkok Bar and Pom Phrachun exhibit patterns that are clearly different from the rest of the group and for convenience they have been categorized as 1A, as opposed to 1B for the rest. Sea level measurements in 1940 of group 1A stations were about half a meter lower than those of group 1B stations. Another irregularity is that sea level of Bangkok Bar was much higher before 1940 than in subsequent years. The magnitude of the difference implies a shift of the station's reference level due to maintenance or a change of equipment. Furthermore, the sharp rise and fall of sea level before 1940 is suspicious and unlikely to be a true effect of sea state variation. Sudden shifts after 2004 seen at both group 1A stations are due to an attempt to bring sea level readings back to their 1940 datum by compensating subsidence determined from a combined levelling-GPS campaign in September 2003 (Ongard Sudcharoen, 2009, personal communication). Nevertheless, it is clear that despite this

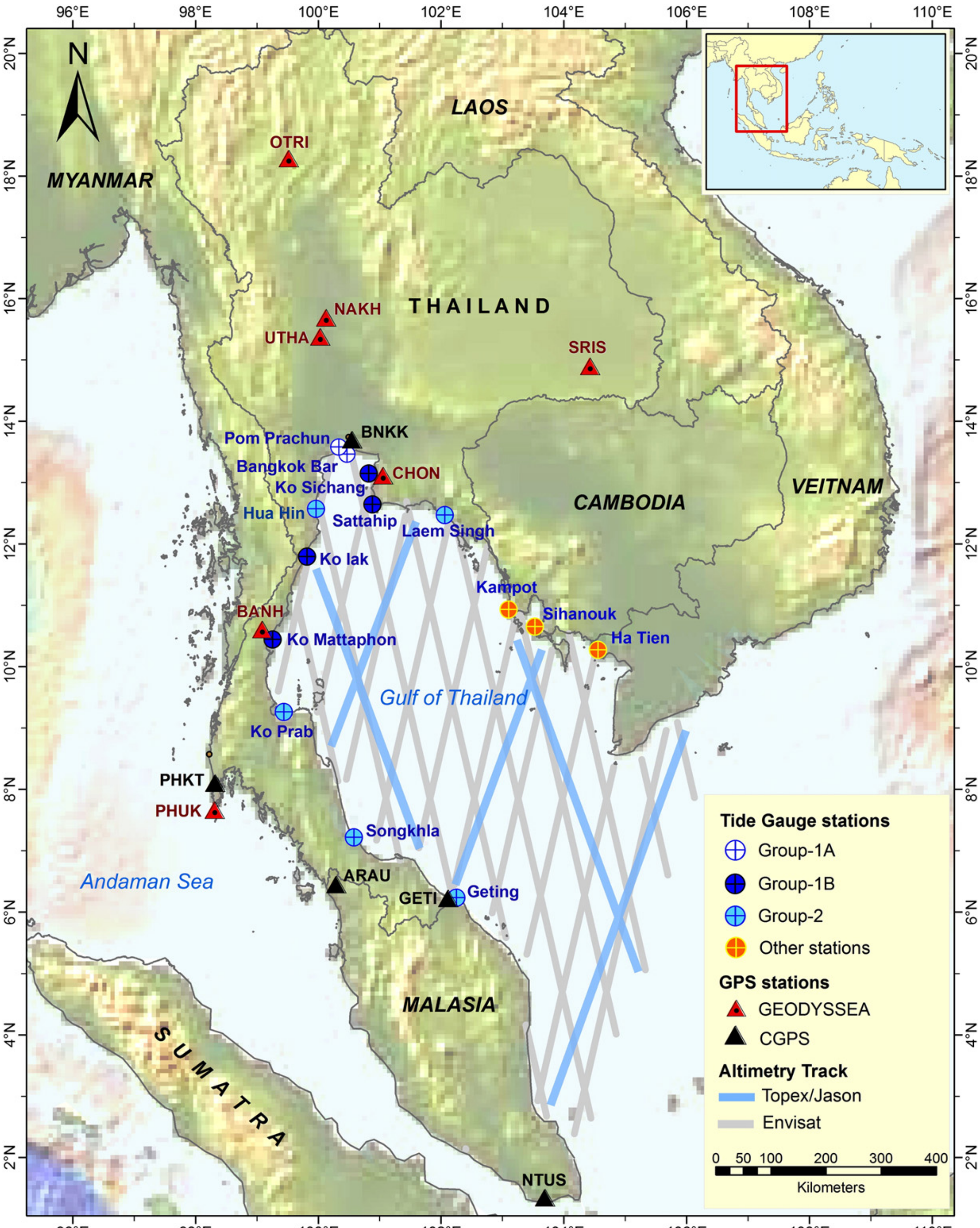


**Fig. 1.** Locations of tide gauge stations, GEODYSSEA/THAICA campaign GPS sites, CGPS stations and ground tracks of altimetry satellites used or referred to in this study.

correction the 1940–2005 trends of group 1A are still significantly greater than those of group 1B.

A linear regression fit gives rates of relative sea level rise of 12.6 and 14.8 mm/yr at Bangkok Bar and Pom Prachun respectively. These large rises were not observed at group 1B stations, not even at Ko Sichang, which is located nearby, 45 km to the southeast. Geological settings provide an explanation for these differences. All group 1B stations are situated on outcrop islands (Ko Sichang, Ko Lak and Ko Mattaphon) or in areas of shallow bedrock (Sattahip). In contrast, both Bangkok Bar and Pom Phrachun are situated in the estuary of the Chao Phraya River, which is an area of nearly 2000 m thick alternating layers of soft clay, stiff clay and sand. With such sediment depths, it is not economically feasible to construct the foundations of any building or structure on the bedrock. Instead, a structure load needs to be supported by piles standing on a sand layer around 20 m beneath the surface. It was first reported in 1968 that Bangkok was subsiding, and pronounced land subsidence of the city started in the 1970s (Phien-wej et al., 2006). The trend lines of Bangkok Bar and Pom Phrachun exhibit faster relative sea

**Table 1**
Classification of tide gauge stations in the Gulf of Thailand. Group 1 (long-record) stations have more than 60 years of record length except Ko Mattaphon and are further classified into group 1A (affected by land subsidence) and group 1B (stable bedrock-fixed platform). Other stations having shorter record length are categorized as group 2.

| Group | Station | Year established | Earliest record | Latest record | Responsible agency |
|---|---|---|---|---|---|
| 1A | Bangkok Bar | N/A | 1926 | 2006 | PAT[a] |
| 1A | Pom Phrachun | N/A | 1940 | 2008 | HD[b] |
| 1B | Sattahip | April 1939 | 1940 | 2008 | HD |
| 1B | Ko Sichang[c] | N/A | 1940 | 2002 | PAT |
| 1B | Ko Lak | October 1910 | 1940 | 2008 | HD |
| 1B | Ko Mattaphon | January 1954 | 1957 | 2008 | HD |
| 2 | Laem Singh[d] | September 1941 | 1981 | 2006 | HD |
| 2 | Hua Hin | December 1969 | 1992 | 2008 | HD |
| 2 | Ko Prab | December 1969 | 1971 | 2008 | HD |
| 2 | Songkhla[d] | January 1986 | 1986 | 2005 | HD |
| 2 | Geting | N/A | 1987 | 2008 | DSMM[e] |

[a] Port Authority of Thailand.
[b] Hydrographic Department, Royal Thai Navy.
[c] Last record for Ko Sichang station is end of 2002 as Port Authority of Thailand (PAT) shut down the station and moved operation to new deep-sea port (Ongard Sudcharoen, 2009, personal communication).
[d] Songkhla station was demolished in 2005 for the construction of a new facility and Laem Singh station stopped operating in October 2006 due to heavy sedimentation (Suppasit Kongdee, 2009, personal communication).
[e] Department of Survey and Mapping, Malaysia.

level rise starting at the end of the 1960s. This pattern strongly suggests that settling of the sand layer has affected the sea level readings.

Because of its presence in the PSMSL database, the long data record for Pom Phrachun station appears in many studies, *e.g.*, Yanagi and Akaki (1994), and Holgate and Woodworth (2004). While the latter work included the station in their analysis, the former simply cited it as an example of relative sea level rise due to anthropogenic activities. Both Pom Phrachun and Bangkok Bar can be useful for subsidence studies as there are virtually no other monitoring points within 15 km. However for sea level change studies it seems more appropriate not to include these two stations into sea level change analyses until the above-mentioned anomalies and rate discrepancies are resolved. Therefore, only the group 1B stations are employed in our long-term sea level change study.

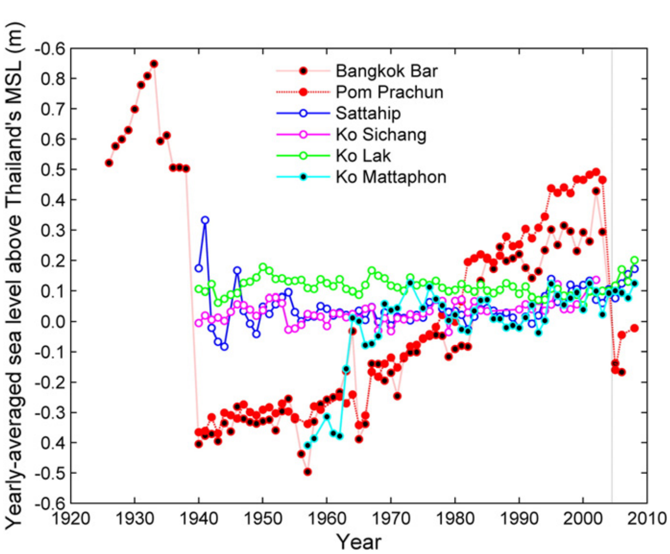


**Fig. 2.** Sea level time series of group 1 tidal stations. Dotted horizontal lines mark boundary values of yearly-averaged sea level of group 1B stations.

## 2.2. Apparent sea level change from selected tide gauge stations

From comparison to the four tide gauge stations in group 1B, fluctuations in the early years of Sattahip and the very low sea level at Ko Mattaphon between late the 1950s and late 1960s, can be considered erroneous or at least inaccurate. Again, information that may lead to the explanation of these deviations is not available. The vast majority of sea level measurements of all stations in this group are within −0.2 and 0.1 m. The first six observations of Ko Mattaphon are outside this range. Moreover, the 1941 sea level records of Sattahip are much higher than the rest of group 1B. These observations can be confidently classified as outliers but large variation in the time series of both stations still remain. However, the deviations are not so pronounced, making it difficult to rely only on visual inspection to detect outliers.

A standard statistical technique that simultaneously deals with solution finding and outlier detection is applied. In this robust fit approach, a linear trend is fitted to the annual sea level time series of each station in an iteratively re-weighted least square (IRLS) procedure (Holland and Welsch, 1977). Depending on the deviations from the trend line, weights of measurements are modified accordingly. The trend line is then re-fitted and the process repeated until the solution converges. The weights of observations ($w_i$) are re-adjusted by the adopted bi-square weight function, whose relationship with normalized residuals ($u_i$) is defined as:

$$w_i = \begin{cases} \left(1-(u_i)^2\right)^2 & |u_i|<1 \\ 0 & |u_i|\geq 1 \end{cases} \tag{1}$$

where

$$u_i = \frac{r_i}{K \cdot S \cdot \sqrt{1-h_i}} \tag{2}$$

In Eq. (2), $r_i$ are residuals, $h_i$ are leverage, $S$ is mean absolute deviation divided by a factor 0.6745 to make it an unbiased estimator of standard deviation, and $K$ is a tuning constant whose default value of 4.685 provides for 95% asymptotic efficiency as the ordinary least squares assuming the Gaussian distribution (Holland and Welsch, 1977). Observations assigned zero weights in any iteration are regarded as outliers and removed from further computation.

Fig. 3 shows apparent rates of sea level change at tide gauge stations in group 1B up until 2004. The reason for not including post-2004 data in the analysis is substantiated in Section 4. The determined rates are not consistent with the fact that the area covered by their extent is small, which implies that sea level change should be comparable at each of them. The rate differences have to be explained by vertical motions unrelated to the actual sea state in the study area. Crustal deformation is a major source of spatial variability in tide gauge records (Gornitz, 1995). Deformation caused by Global Isostatic Adjustment (GIA) alone cannot explain the differences. GIA is a very long wavelength phenomenon and its magnitudes in the study area as provided by the ICE-5G model in Peltier (2004) only slightly increase from +0.50 to +0.65 mm/yr depending on latitude going northward in the Gulf. Vertical crustal motions that produce rate variations in group 1B stations must be more local and have a smaller spatial scale. The differences of apparent rates thus point to contamination of sea level readings by tectonically-induced motion, details of which are dealt with in the next section.

## 3. Vertical land motion from precise GPS measurements

Geodetic measurements that may be useful in determining vertical motions in the vicinity of tide gauge stations do exist, but only came to the attention of the research community after the tragic 2004 Sumatra-Andaman mega-earthquake and the devastating Indian

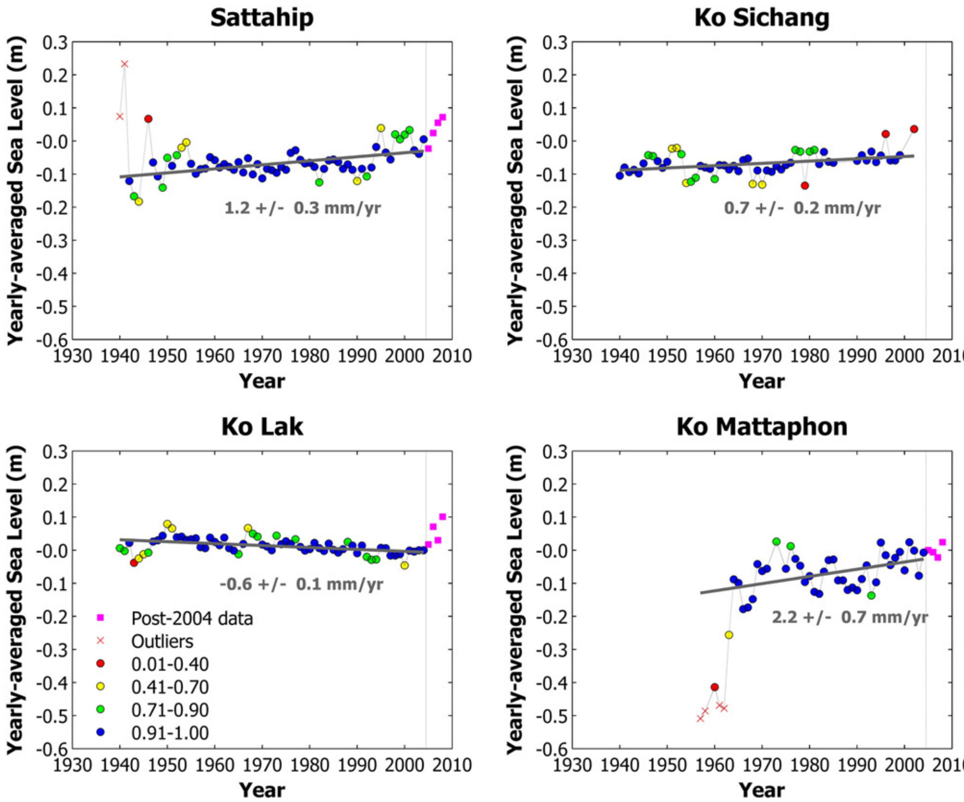


**Fig. 3.** Long-term apparent sea level rate of group 1B tidal stations. The Ko Sichang time series ended in 2002 because the station was closed down and operations moved to a new tide gauge at Laem Chabang deep-sea port. Dotted vertical lines in the right of all sub-figures mark the time when the Sumatra-Andaman earthquake occurred on 26 December 2004. Observations have been color-coded according to their final weight in the robust fit (weights of outliers are zero).

Ocean tsunami that followed. Vigny et al. (2005) mention 7 GPS campaign sites in Thailand of which two are close to Sattahip, Ko Sichang and Ko Mattaphon. These stations are CHON and BANH (see also Fig. 1), which are part of the so-called GEODYSSEA/THAICA network dedicated to crustal motion studies. The network encompasses the major plate tectonic zones in Southeast Asia. Earliest data of precise GPS measurements go back to November 1994 and the last campaign in Thailand before the Mw 9.2 earthquake was in late October 2004. Several more campaigns with a higher repetition rate followed, in order to capture the post-seismic signals. Details of these GPS campaigns at CHON and BANH are given in Table 2.

The distance between BANH and Ko Mattaphon is 27.0 km whereas the distances from CHON to Ko Sichang and Sattahip are 26.1 km and 55.6 km respectively. CHON is one of ~40 GPS campaign sites (located on bedrock) that make up the GEODYSSEA network in Southeast Asia. This network was designed to accurately determine the Sundaland plate motion and plate boundaries and verify whether it currently is moving independently from the Eurasian plate (Wilson et al., 1998). The GEODYSSEA GPS campaign measurements in Thailand were initially processed to obtain accurate 3D coordinates in the ITRF97 global reference frame (Becker et al., 2000). BANH is one of the concurrently observed Thai GPS points of the THAICA zero-order network (Royal Thai Survey Department, 2003). In order to derive a coherent and accurate velocity field in the ITRF2000 Reference Frame (IERS), we use the dual frequency GPS data from the full network (GEODYSSEA, THAICA and other continuous GPS (CGPS) stations in SE Asia), and adopt the absolute GPS positioning technique, also referred to as Precise Point Positioning (PPP) technique, in our study. With this technique a daily repeatability of a few millimetres can be expected horizontally and about a centimetre vertically, for data from a static site occupied by a geodetic-quality receiver (Zumberge et al., 1997). All dual frequency GPS data have been uniformly processed with the GIPSY-OASIS II software developed by the Jet Propulsion Laboratory (JPL).

We processed the GPS data in daily batches. Each point position was based on the ionosphere-free combination of the zero-differenced GPS carrier phase and pseudorange observations at 5-minute intervals, with a cut-off elevation angle of 15°. Tropospheric delays and gradients were stochastically estimated at each time interval. Ocean loading effects were modelled with the GOT00.2 model (Scherneck and Bos, 2009). To account for different GPS antennas, relative antenna phase center corrections from the U.S. National Geodetic Survey (NGS) were applied (NGS, 2009).

The individual point positions were merged into daily full-network solutions. Due to the nature of PPP processing, the different station positions are modelled as uncorrelated. Nevertheless the phase ambiguities can still be fixed to improve the position in the east–west direction. The daily ambiguity-fixed solutions were combined into 7-day campaign averaged solutions using 7-parameter Helmert transformations. In order to condense the results and to facilitate the detection and down weighting of outliers, the overall repeatability weighted root mean square (WRMS) statistics of the 7-day combination solution were used to scale the formal errors in their variance–covariance matrices. Next, the absolute median algorithm (Rousseeuw, 1998) was applied to detect and remove outliers prior to the computation of final coordinate repeatabilities. These values are direct indicators for the internal precision of each station. In general, the GPS points CHON and BANH perform very well, with daily coordinate repeatabilities (1994–2009) typically ranging from 1 to 5 mm for the horizontal components and from 3 to 15 mm for the vertical component.

The campaign fiducial-free network solutions were transformed into the global International Terrestrial Reference Frame (ITRF) solution of 2005 (Altamimi et al., 2006) using the coordinates and velocities of a subset of well-determined regional and global

**Table 2**
GPS campaigns at CHON and BANH. Antenna type names are according the IGS naming convention. Four types of receivers were used: (1) Trimble 4000SSi (with the TRM14523.00, TRM334280.00+GP and TRM22020.00+GP antennae), (2) Trimble 4800 (with the TRM4800 antenna), (3) Trimble R7/5700 (with the TRM41249.00 and TRM39105.00 antenna) and (4) Leica SR520/5320 (with the LEIAT502 antenna). The GPS points were continuously observed (in 24 h sessions) in campaign-mode for typically 5 to 7 days (shorter observation periods were due to equipment problems). The GPS point at CHON was established in 1994 and is located on bedrock with a specially designed GEODYSSEA (screw-on type) marker yielding a re-centering accuracy of 0.2 mm (Simons et al., 1999). Therefore the antenna setup always has the same vertical height above the marker. Since 2004 this point was almost always re-observed with the same antenna type. BANH was built in 1994 and is part of the zero-order Thai GPS network and is equipped with a geodetic (metal disk) survey marker on top of a (0.4 × 0.4 × 1.0 m) concrete monument that lies about 0.15 m above the ground. Qualified surveyors of RTSD have observed this point with a tripod. Hereby the antenna is centered optically and verified with a plumb. Both antenna (height) setups are carefully registered on log sheets and accompanied with photos (since 2004 in digital format) to verify the antenna height measurements.

| Campaign# | CHON | | | BANH | | |
|---|---|---|---|---|---|---|
| | Fixed GEODYSSEA marker setup | | | Tripod above zero-order monument | | |
| | # of days | Days | Antenna | # of days | Days | Antenna |
| 1994 (Nov) | 5 | 332–336 | TRM14532.00 | 4 | 324–327 | TRM14532.00 |
| 1996 (Apr) | 5 | 109–113 | TRM14532.00 | 5 | 109–113 | TRM22020.00+GP |
| 1998 (Nov) | 5 | 323–327 | TRM33429.00+GP | – | – | – |
| 2000 (Oct) | 5 | 284–288 | TRM22020.00+GP | – | – | – |
| 2001 (Oct) | 5 | 282–286 | TRM22020.00+GP | 5 | 282–286 | TRM22020.00+GP |
| 2002 (Oct) | 7 | 279–285 | TRM4800 | 7 | 279–286 | TRM39105.00 |
| 2004 (Oct) | 7 | 299–305 | LEIAT502 | 7 | 299–305 | TRM4800 |
| 2005.1 (Feb) | 5 | 041–045 | LEIAT502 | 5 | 041–045 | TRM4800 |
| 2005.2 (Jul) | 3 | 182–185 | LEIAT502 | 4 | 185–188 | LEIAT502 |
| 2005.3 (Oct) | 7 | 282–288 | LEIAT502 | 7 | 282–288 | TRM22020.00+GP |
| 2006.1 (Apr) | 5 | 093–097 | LEIAT502 | 5 | 093–097 | LEIAT502 |
| 2006.2 (Jul) | 5 | 191–195 | LEIAT502 | 5 | 191–195 | TRM4800 |
| 2006.3 (Nov) | 7 | 307–313 | LEIAT502 | 7 | 307–313 | TRM22020.00+GP |
| 2007.1 (May) | 7 | 131–137 | LEIAT502 | 7 | 131–137 | TRM4800 |
| 2007.2 (Nov) | 7 | 324–330 | TRM41249.00 | 7 | 324–330 | TRM4800 |
| 2008 (Nov) | 7 | 312–318 | LEIAT502 | 7 | 312–318 | TRM22020.00+GP |

International GNSS Service (IGS) stations to estimate 7-parameter Helmert transformations. Previous experience with mapping local networks in SE Asia (*e.g.* Wilson et al., 1998; Simons et al., 1999) into ITRF has shown that if only regional IGS stations are selected the mapping may not always be optimal, and position and velocity errors may occur. Moreover, some stations may have been affected by nearby earthquakes, and hence they do not always fit the linear velocity trend given by ITRF2005. To avoid the above-mentioned mapping problems, up to 31 IGS stations were included in the data processing. This was done to establish an un-deformed reference solution, which is not affected by episodic jumps in the time series of some of the IGS stations. In total, IGS data from up to 31 stations were retrieved for each campaign period from the IGS databases. Typically, 10–20 IGS stations were used in the mapping of each weekly averaged solution. They were selected (when available) on basis of best performance in the weekly-combination repeatability test (Simons et al., 2007). The root mean square (RMS) values obtained from the mapping process were found to be of the order of 1–3 mm and 10 mm respectively for the horizontal and vertical components.

From 1994 onwards, the CHON and BANH position solutions resulted in up to 10 year long position time series in ITRF2005. The 1994–2004 station velocities were extracted by linear regression, which implies steady-state motion (which of course is no longer a valid assumption after the 2004 Mw 9.2 earthquake). This was verified by analyzing the misfits with respect to the linear trends. Mostly small offsets were observed, and overall the 3D RMS values are 3, 4 and 5–13 mm in north, east and up, respectively.

### 3.1. Pre-2005 uplifts

The vertical component of the 3D coordinate time series of CHON and BANH are shown in Fig. 4, along with the estimated linear height trend before and after the earthquake. Before the earthquake we do not have continuous GPS near both stations. For this we are forced to use the available GPS campaign data. As the measurements do not exactly span the same period of the year, they could be biased from a seasonal effect (likely of atmospheric origin). The seasonal cycles were estimated from post-earthquake data of nearby CGPSs assuming that the behaviour remained the same. A robust regression fit with IRLS, which was modified to model the vertical land motion as a combination of a linear trend, an annual and a semi-annual cycle, was applied to simultaneously solve these parameters for the time series (early 2005–end of 2009) of the weekly GPS solutions of RYNG (established in early 2005, 39.4 km from CHON). Plots of the weekly solutions and annual cycles can be found in the electronic supplement. The same procedure was applied to the time series of CPNT CGPS (beginning of 2005–end of 2009, 33.1 km from BANH), The amplitudes of the annual cycle are 12.0 mm and 11.0 mm for RYNG and CPNT respectively, with their positive peaks at 140 and 147 days after January 1st. The height coordinates of CHON and BANH were then compensated for these annual cycles.

At both stations, the pre-2005 height coordinates were then analyzed for the linear trends which represent inter-seismic uplifts. In the determination of these motions, we opted for ordinary regression instead of IRLS, which was used in other trend analyses in this study. This is because the IRLS technique requires a substantial number of observations to be able to interpret where the trend line lies for the majority. A limited number of GPS measurements in this case does not provide this consensus information. Ordinary weighted least square regression was therefore applied to obtain pre-earthquake vertical motion which is the sum of GIA and inter-seismic deformation. Observations having residuals greater than 2-sigma from the residual mean are considered outliers and all observations pass the criteria. The detected uplift rates are $3.8 \pm 1.3$ mm/yr at CHON and $2.2 \pm 0.8$ mm/yr at BANH. The uncertainties in vertical velocities were obtained by increasing the formal errors of the velocity estimates by individual factors determined from the weighted root mean square (WRMS) that represents the actual scatter in each time series and the total observation period (T) using the 2WRMS/T algorithm as discussed in Simons et al. (2007).

We tested the sensitivity of the pre-2005 vertical motions by recursively removing from the time series one pre-earthquake measurement at a time and re-fitting the linear trend to the rest. At both CHON and BANH, removing any single measurement from the height time series of BANH does not corrupt the uplift trend. Further, the BANH height time series is very consistent with that of CHON. If

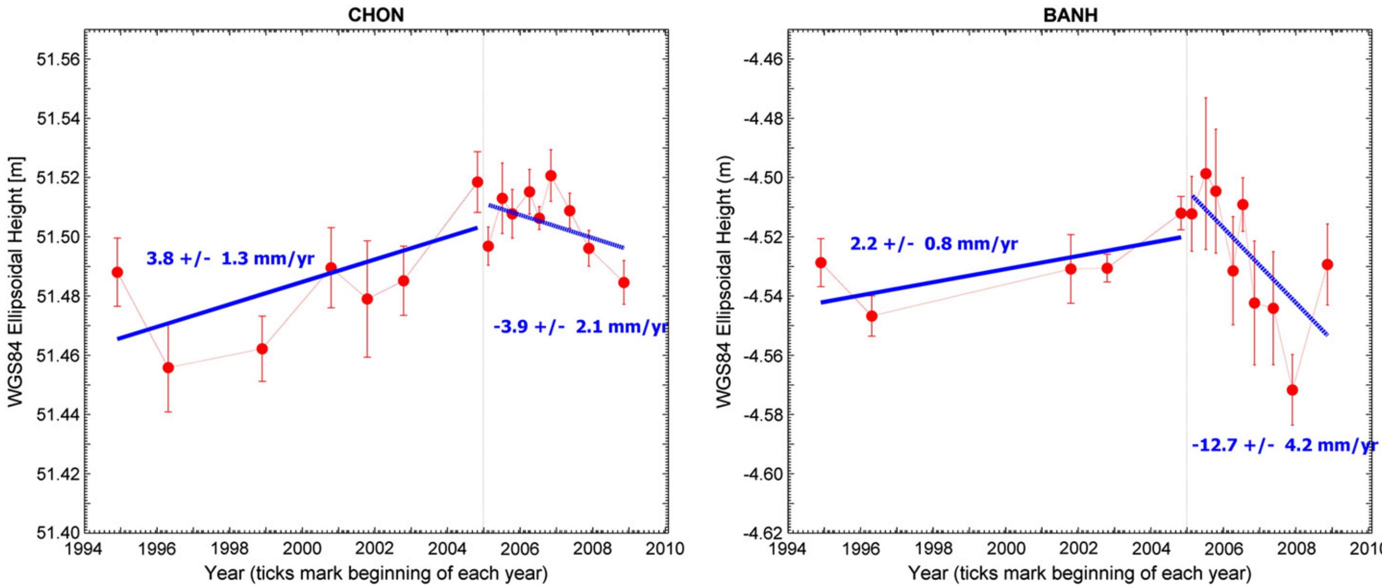


**Fig. 4.** Vertical land motions at CHON and BANH. Precise GPS height coordinates of both stations were corrected for seasonal variations estimated from 2005–2009 CGPS data at RYNG (collocation distance 39.4 km with CHON) and CPNT near BANH (33.1 km collocation with BANH). Plots of GPS height time series, since the first campaign in November 1994 until October 2004, reveal a combined inter-seismic and GIA uplift at both locations. Also shown are post-seismic height time series at both sites (at the right of dotted vertical lines marking the earthquake time). All GPS campaigns were conducted by the Royal Thai Survey Department and analyzed in cooperation with DEOS (Simons et al., 2007). Details on the computational process and the (verified) 1-sigma error bars are given in Simons et al. (2007). The post-seismic phase error bars at BANH are noticeably higher since they take into account (remaining) height offsets between the 5 different GPS antennas used (although antenna phase offset correction tables are used in the GPS processing). Still, the post-2004 downward trend of height is detected as in the case of CHON where almost always the same GPS antenna type (and setup) was employed.

measurements in Nov-1998 and Oct-2000, are removed from CHON time series, its up–down pattern is the same as depicted by that of BANH. This similarity is not repeated after the earthquake, when non-steady motion is expected even though measurements and processing were carried out in the same fashion as in the pre-earthquake period. This suggests that the pre-2005 similarity between CHON and BANH did not result from any systematic effects of GPS, but rather from the tectonic signal. Altogether, this confirms the presence of pre-earthquake uplift that was captured by GPS despite the noisy appearance of the data.

The uplift shown by the trend lines are consistent with an elastic loading/slip dislocation model which predicts that during the inter-seismic (loading) period the portion of the upper plate (Sundaland block) overlying the locked subduction interface is gradually depressed, while the region landward of the locked fault zone bows slightly upward (Meltzner et al., 2006). Land uplift means that tide gauge readings are lower than actual (absolute) and the apparent rates of sea level change need to be compensated by adding the uplift rates. After the earthquake, the behaviour at CHON and BANH is completely different: we notice an abrupt change in trend: from a gradual rise to a sharp decline, suggesting a strong downward motion. The combination of landfall and sea level rise worsens the situation for low-lying urban areas around the western and northern parts of the Gulf, and this situation is probably even worse for regions located closer to the 2004 Sumatra-Andaman earthquake epicentre.

### 3.2. Co-seismic displacements of the Sumatra-Andaman earthquake

The Sumatra-Andaman earthquake completely changed the crustal motion pattern in Thailand, in both the horizontal and vertical directions. GPS data from campaigns and fixed (continuous) sites in Indonesia, Malaysia and Thailand show that the Sundaland block, on which all tidal stations in Thailand are situated, was considerably deformed (Vigny et al., 2005). Horizontally, the direction of motion changed abruptly from mainly eastward (~30 mm/yr) towards the earthquake epicentre in the southwest. Small, but significant, co-seismic jumps between 5 and 10 mm were detected even at stations more than 3000 km away from the earthquake epicentre. In the vertical direction, ground displacements in the near field (close to the earthquake epicentre), determined from various techniques, show a characteristic pattern: a region of (co-seismic) uplift near the Sumatra trench and a region of subsidence away from it (Subarya et al., 2006). Evidence of 1500 mm uplift near the epicentre of the earthquake was shown in Sieh (2005) in the form of emerged coral reefs. In the far field the elastic dislocation slip model (Meltzner et al., 2006) predicts co-seismic subsidence that decreases when moving further away from the Sumatra trench, where the earthquake epicentre is located.

Data from yearly GPS campaigns (unlike continuous GPS) after the earthquake are less suitable for the accurate detection of vertical co-seismic displacements, since they typically have noisier position estimates, and also are affected by a strong post-seismic signal. This makes the use of GPS data from post-2004 campaigns at BANH and CHON less reliable and measurements from CGPS are more appropriate. Most of the CGPS sites are in Malaysia (Vigny et al., 2005). Fig. 1 shows the 4 CGPS nearest to the tidal stations. Co-seismic vertical displacements at these locations, determined from GPS processing (the difference between the first weekly averaged static solution after and before the earthquake), are PHKT ($20.4 \pm 14.5$ mm), NTUS ($-8.1 \pm 5.2$ mm), ARAU ($12.1 \pm 13.0$ mm) and BNKK ($-5.9 \pm 9.2$ mm). These co-seismic rates are derived from a data set, of which the horizontal component is analyzed and presented in Satirapod et al. (2011). Both uplift and subsidence are present at PHKT and NTUS, contradicting the model that predicts only subsidence in the far field. At BNKK and ARAU, standard deviations are too large to be useful for co-seismic corrections. Besides, none is close enough to any group 1B tide gauges. Vertical co-seismic displacement is comparable to a shift of reference and could cause a bias in the determined trend. The unavailability of reliable co-seismic magnitudes is a reason for us to exclude post-2004 data from the analysis.

### 3.3. Post-seismic velocities

As mentioned earlier, GPS campaigns were carried out more frequently from 2005 onwards at all GEODYSSEA/THAICA GPS points in Thailand, to capture the 3D post-seismic signals. Although the campaign-derived heights in the post-seismic time series remain noisy (Fig. 4, data points right of the dashed vertical line) they do indicate downward motion ($-3.9\pm2.1$ mm/yr at CHON and $-12.7\pm4.2$ mm/yr at BANH, assuming a linear trend at both sites). At CHON, almost all (8/9) re-measurements were made using an identical antenna setup and the linear vertical trend for the post-seismic (2005–2008) period does indicate significant downward motion. Although the BANH re-measurements were carried out with multiple antenna types (possibly introducing artificial vertical position shifts due to different antenna phase centre behaviours) downward vertical motion here also seems to initiate after December 2004.

Post-seismic effects from past mega-thrust earthquakes are evident even several decades after the event as demonstrated from GPS velocity observation in the regions of the Mw 9.5 1960 Chile earthquake and Mw 9.2 Alaska earthquake (Pollitz et al., 2006). As part of an effort to better determine post-seismic motion, two collocated CGPS receivers were installed at Sattahip (STSH, collocation distance to the tide gauge 12 m) in January 2008, and in Ko Mattaphon (MATP, 5 m collocation) in March 2009. Initial assessment of weekly averaged height time series obtained from precise point positioning computation of 30 s interval observations indicates a substantial downward trend. However, since post-seismic motions are not steady, correction of tide gauge data after the earthquake is not as straightforward as in the pre-earthquake period and longer time series are required before more reliable post-seismic velocities can be obtained. While the availability of post-seismic motion corrections is not of paramount importance in our study as the number of years after the earthquake is still much shorter than the total years of the record, in the longer run the cumulative effect of post-seismic tectonic plate subsidence will make it imperative for sea level change study to know subsidence rates.

## 4. Absolute sea level change of the period 1940–2004

The evolution of the crustal deformation pattern in this region can be demarcated by the 2004 Sumatra-Andaman mega-earthquake into two episodes, *i.e.* pre- and post-earthquake. Sea level data of each period can then be accordingly corrected for vertical land motion. For the determination of absolute sea level change rate of the pre-earthquake period, we compensate the apparent rates from the tide gauges with inter-seismic motions. For the post-earthquake period this is more problematic because of the lack of reliable co- and post-seismic land velocities near the tide gauges. Alternatively, one could adopt large standard deviations to account for the large uncertainties of the co- and post-seismic motion estimates. Nevertheless, for the time being we believe this is not necessary; with the post-earthquake period covering only a few years, it is not anticipated that the absolute long-term rates of the complete record will be significantly different from those determined from the 60 years of pre-earthquake tidal data.

A question in the determination of 1940–2004 absolute rates of sea level change is whether a single decade of GPS-derived vertical land motion rates can be extrapolated back in time with impunity to correct the multi-decade tidal rates. In 3D tectonic-induced deformation, determining the vertical movement is difficult because its magnitude is small and the height component of the GPS coordinates is not as accurate as the horizontal components. Nevertheless, a linear trend can still be inferred from pre-earthquake GPS data at both CHON and BANH. Unfortunately, no geodetic measurements are available in the preceding decades, so we do not have direct evidence that in the Sumatra subduction zone the rate has been linear for a sustained period. We therefore seek analogy with another subduction zone *i.e.* the Nankai in southwest Japan. The Nankai subduction zone is one of the particularly appropriate examples because it has a short recurrence period (100–150 years) and a geodetic/seismological data set spanning almost a complete earthquake cycle (Tabei et al., 2007). Using tide gauges as indirect geodetic observations of interseismic deformation, Savage and Thatcher (1992) reported an interseismic vertical deformation that can be characterized by an exponential decaying function for the decade after large earthquakes (Tonankai in December 1944, Ms = 8.0; and Nankaido in December 1946, Ms = 8.2) and a steady uplift rate over the 1956–1985 interval, which is also assumed for the remaining period of this earthquake cycle. Based on the motion behaviour described by this geophysical subduction-context model, a steady motion over a long interseismic period (550–700 years as estimated in Jankaew et al., 2008 and 600 years in Monecke et al., 2008) of the Sumatra trench is also expected. We thus assume a steady upward motion at both GPS stations for the whole 1940–2004 period.

The elastic dislocation model for subduction-zone interseismic deformation predicts a peak rate of vertical motion at a certain distance from the earthquake epicenter or convergent boundaries, and then tapers off smoothly. Sieh et al. (1999) constructed a suite of three such models that fit equally well with the vertical motion rates derived from the analysis of coral ring data collected in west Sumatra. All models depict a peak rate at about 150 km from the trench, and rates that flatten to near-zero at around 400 km distance. These predictions may not be realistic in a region several hundreds of kilometres away, like Thailand, as no data from this region were used to constrain the model. However, they clearly suggest a gradual decrease of vertical velocity in the far field. In the Nankai subduction zone, Tabei et al. (2007) used data from an array of CGPS to generate a vertical velocity field of the crustal deformation. The distribution shows that as distance from the trough increases, the rates of vertical motion become less varied. Although 27.0 km apart, the radial distances from the epicenter of Sumatra-Andaman earthquake to BANH and Ko Mattaphon are almost equal (8.2 km longer to BANH). Likewise, the difference between the distances from CHON and Ko Sichang to the epicenter is only 9.1 km. A change in the vertical velocity would not be observable for such a small distance in this far-field region. Radial separation of 54.7 km between CHON and Sattahip is greater, but based on the above-mentioned studies, the rate difference could be well within the error margin of the GPS heights.

As vertical motion from both GIA and interseismic deformation are steady over the entire period, the detected uplift rate of CHON is added to the apparent rates of Sattahip and Ko Sichang to obtain the absolute sea level change rates. Uplift at BANH is used to correct the apparent tidal rate at Ko Mattaphon. There is no GEODYSSEA/THAICA network point close enough to allow for correction at Ko Lak. However, the relationship between tidal data, land motions and altimetry measurements will prove to be vital for the determination of vertical movements at Ko Lak, details of which will be discussed in Section 5.4. From the combination with altimetry we found for Ko Lak an (indirect) uplift estimate of $3.6\pm1.5$ mm/yr. The resulting absolute rates of sea level rise at group 1B station are summarized in Table 3.

## 5. Sea level change and vertical land motion from satellite altimetry

For the study of recent sea level change from satellite altimetry we employ the TUDelft/NOAA Radar Altimeter Database System RADS (Naeije et al., 2008; http://rads.tudelft.nl). RADS provides a continuous and consistent observing system and has the complete backlog of all available satellite altimeter observations (Naeije et al., 2007). Space-borne altimeters emit sequences of short pulses at microwave frequency and then measure the return times to obtain the instrument-to-sea surface distance. Knowledge of the exact position of the satellite provides then a means to deduce the sea level independently, unaffected by land motion. The practice is somewhat more complex: one has to account for instrument design, calibration and validation results, media (atmospheric) corrections, geophysical adjustments like tides, inverse barometer, and sea state, reference

**Table 3**
Long-term absolute rates of sea level rise at four tide gauges in the Gulf of Thailand. The vertical land motions at these tidal stations are derived from a) campaign GPS data at CHON, b) campaign GPS data at BANH, and c) difference of sea level change rates detected by satellite altimetry and tidal data (see Section 5.4).

| Tidal stations | Apparent SLR rates (mm/yr) | Vertical land motions (mm/yr) | Absolute SLR rates (mm/yr) |
|---|---|---|---|
| Sattahip (1940–2004) | 1.2 ± 0.3 | 3.8 ± 1.3[a] | 5.0 ± 1.3 |
| Ko Sichang (1940–1999) | 0.7 ± 0.2 | 3.8 ± 1.3[a] | 4.5 ± 1.3 |
| Ko Lak (1940–2004) | −0.6 ± 0.1 | 3.6 ± 1.5[b] | 3.0 ± 1.5 |
| Ko Mattaphon (1964–2004) | 2.2 ± 0.7 | 2.2 ± 0.8[c] | 4.4 ± 1.1 |

system, precise orbits (satellite height), sampling characteristics, and so on. This is largely taken care of within RADS, but detailed inspection is still needed because we are analyzing data close to the coast. Table 4 presents a summary of the chosen models and corrections to infer sea level anomaly from the altimeter record.

### 5.1. Altimetry processing strategy and corrections of altimetry data

We use altimetry data of ERS-1, ERS-2, Envisat, TOPEX, POSEIDON, Jason-1, and Jason-2 from 1 January 1993 up to and including 31 December 2009 from the RADS database. To be able to merge data from different satellite platforms we apply the reference frame biases between the different satellite missions that reflect the differences in the orbits, as well as some other geographical differences in the altimeter-dependent models (*e.g.* sea state bias). Here we start from the NASA Goddard consistently reprocessed TOPEX/Jason reference frame and orbits (Beckley et al., 2007), already incorporated in RADS. For the estimation of all the other satellite altimeter biases with respect to the TOPEX reference we adopted a global analysis in which the difference with respect to the TOPEX reference frame is modelled by 5 spherical harmonic coefficients constituting a constant bias, shifts in Z, X, and Y directions and a difference in flattening based on as much coincident data as possible (Remko Scharroo, personal communication). For the small area we are considering, these modelled biases amount to an almost constant bias (given in Table 4).

As the quality of the radial accuracy of the orbits of the TOPEX-class satellites (TOPEX, POSEIDON and JASON) outperforms the accuracy of the orbits of the ERS-class satellites (ERS and ENVISAT) we performed a so-called dual-crossover minimization analysis (Schrama, 1989) in which the orbit of the TOPEX-class satellites is held fixed and those of the ERS-class satellites are adjusted simultaneously. In this we consider only crossovers between ERS-class and TOPEX-class satellites and not those between themselves. The area used for the crossover minimization is much larger than the area under investigation to have sufficient crossover information to estimate the smooth (1 cycle per orbital revolution) orbit error function fits. The timeframe covered by individual crossovers is limited to 18 days to reduce the risk of eliminating real oceanic signal and, with that, sea level trend. We applied the orbit error estimate to the ERS-class satellites and put a tight constraint on the resulting sea level anomaly (<1 m difference from mean sea surface reference), which resulted in an outlier-free data set. Then ERS-class and TOPEX-class data were merged and gridded to sea level anomaly grids on a daily basis. Our study area is 5°–14° North, and 99°–105° East. Gridding involved both temporal and spatial weighing. We choose a rectangular mesh with block size 0.25° and an e-folding of 0.75° and cut-off at 1.5° (space) and of 9 days and cut-off at 18 days (time), based on the average track spacing and the repeat time of the ERS-class type coverage (35 days, 501 rev, 0.72° spacing). This ensures focus on data in the vicinity of mesh points, but also allows for occasional data gaps. Subsequently the daily solutions are collected per month and a monthly average is calculated. This method aims to (more or less) equalize the final monthly altimeter solution with the monthly tide gauge solution: a monthly tide gauge solution is based on continuous measurements at one location, whereas the altimeter, in a best case scenario, revisits the tide gauge only 3 times in a month, and in worst-case scenario only once, giving rise to more fluctuations in the altimetry when compared to the tide gauge. It appeared that this methodology (daily to monthly altimeter results) improves the root mean square of the difference (designated as RMSE in the remaining of the paper) between monthly-solutions of altimeter and tide gauge, and also the correlation between the two.

Standard environmental corrections have been applied including the correction by the MOG2D model (Carrére and Lyard, 2003), which corrects for the effect of atmospheric pressure on sea level. This effect is of a high-frequency nature (hours) and aliases into the altimeter

**Table 4**
Corrections and models for the RADS altimeter analysis.

| Correction/model | Editing (m) | | Description | Source |
|---|---|---|---|---|
| | Min | Max | | |
| Orbit/gravity field | | | All satellites: EIGEN GL04C | Förste et al. (2008) |
| | | | | Beckley et al. (2007) |
| | | | ERS: DGM-E04/D-PAF | Scharroo and Visser (1998) |
| Dry troposphere | −2.4 | −2.1 | All satellites: atmospheric pressure grids | ECMWF |
| Wet troposphere | −0.6 | 0.0 | Radiometer measurement | On-board satellite |
| Ionosphere | −0.4 | 0.04 | All satellites: altimeter dual frequency, smoothed | On-board satellite |
| | | | ERS/POSEIDON: NIC08 (GPS-based) | Scharroo et al. (2008) |
| Dynamic atmosphere | −1.0 | 1.0 | High frequency MOG2D + ECMWF inv. baro | Carrrère and Lyard (2003) |
| Ocean tide | −5.0 | 5.0 | GOT4.7 model (update from GOT99.2) | Ray (1999) |
| Load tide | −0.5 | 0.5 | GOT4.7 model (update from GOT99.2) | Ray (1999) |
| Solid earth tide | −1.0 | 1.0 | Elastic response to tidal potential | Cartwright and Tayler (1971) |
| | | | | Cartwright and Edden (1973) |
| Pole tide | −0.1 | 0.1 | Tide produced by polar wobble | Wahr (1985) |
| Sea state bias | −1.0 | 1.0 | All satellites: CLS non parametric | Tran et al. (2010) |
| | | | ERS/POSEIDON: BM3/BM4 parametric | Labroue et al. (2006) |
| Reference | −1.0 | 1.0 | DNSC08 mean sea surface | Andersen and Knudsen (2009) |
| Engineering flag | | | Only altimeter land flag based on 2′ × 2′ mask | ETOPO1 (NOAA) |
| Applied reference frame biases (cm) | | | ERS-1 = + 3.4, ERS-2 = + 7.3, ENVISAT = + 5.2, JASON-1 = −4.8, JASON-2 = + 15.9, POSEIDON = −1.5 | Global analyses of differences with TOPEX reference frame (adapted WGS84) |

data at much lower frequencies due to under-sampling (Fenoglio-Marc et al., 2004). It will therefore not be averaged out in altimetry monthly means, and has to be corrected. In contrast the high (over) sampling rate of tide gauges can capture the entire atmospheric signal, which will average out when taking the monthly average, and a correction is not needed.

### 5.2. Sea level change from altimetry

Taking the monthly mesh solutions we determined sea level trend on a mesh point to mesh point basis. For each mesh point the complete time series for that location was subjected to a robust regression analysis using IRLS, similar to the estimation of sea level trends mentioned in Section 2.2. Fig. 5 presents the geographical distribution of the 1993–2004 and the 1993–2009 altimetry-determined sea level change rate. We consider the 1993–2009 solution to be more representative for the long-term absolute sea level change but we need the 1993–2004 solution for a direct and fair comparison with the tide gauges in order to be able to extract the inter-seismic vertical land motion (which in turn will be compared with the earlier GPS results).

The geographical patterns for the shorter-term and long-term altimetry solutions are quite similar and suggest increasing values going from the southeastern part of the Gulf (connection with the open boundary with the South China Sea) inward the Gulf, especially near the discharge of large rivers like the Chao Phraya River and the Koh Kong River, possibly indicating an increasing supply of water. Though the patterns look similar the actual values differ significantly for the two timespans. We believe that this should be addressed to an 18.6 yr cycle due to lunar nutation (Loder and Garrett, 1978). To fully eliminate this contribution from the 1993–2009 altimetry-determined sea level change, a period of at least 18.6 years would be needed, *i.e.*, 1.6 additional years of altimetry or proper modelling of this effect. However, for the 17-year (1993–2009) period, the effect is small. Given a worst-case scenario of 2 cm amplitude of nodal tide (as suggested by the Gulf's long-term tide gauge records we investigated), the missing 1.6 years account for only 0.5 mm/yr. Clearly this will not significantly change the pattern of sea level rise in the Gulf of Thailand shown in Fig. 5 (right) as the detected rates are significantly larger.

The lunar nodal tide effect can be considerably larger though, for a period much shorter than 18.6 years, *e.g.* the 11-year (1993–2004) period. However, this signature is witnessed in both the altimetry AND the tide gauges. As a result these data are affected in the same manner. When subtracting tidal solutions of sea level from the altimetry solutions over the same time span, regardless of how long the records are, this lunar node effect will cancel out.

### 5.3. Validation of altimetry results

We validate the altimetry rate of sea level change against the sea level trend from the 9 tide gauges of group 1B and group 2 listed in Table 1. For this, the monthly 1993–2004 altimeter time series corresponding to each tide gauge is considered (bilinear interpolation from 4 nearest surrounding mesh points) and compared directly with the tide gauge time series of sea level. The reason for using only the 1993–2004 period for the comparison is twofold. First, tidal data are available to our study only up to 2008, and the records of three stations, Laem Singh, Ko Sichang and Songkhla end in 2006, 2002 and 2005 respectively, for various reasons as explained in Table 1. Second, our altimetry record starts in 1993, and the tide gauge recordings include inter-seismic motion only up to the 26th December 2004 Sumatra-Andaman earthquake; we need this information to determine the inter-seismic vertical land motion, particularly at Ko Lak where we do not have GPS data.

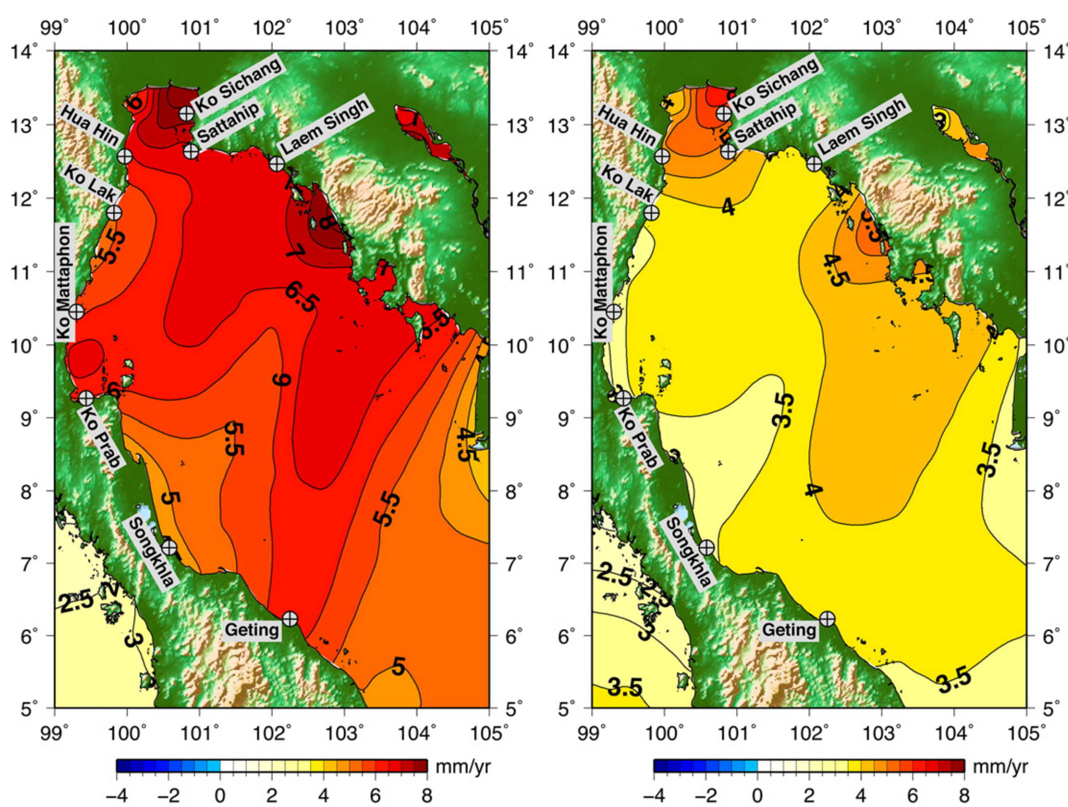


**Fig. 5.** Geographical distribution of sea level trend derived from 1993–2004 (left) and 1993–2009 (right) multi-satellite altimetry. A simultaneous fit of linear trend, annual and semi-annual cycles with IRLS scheme was applied to the altimetry monthly-solution at each grid point.

Fig. 6 shows plots of monthly-averaged sea level from altimetry and tide gauges. Simultaneous fitting of a linear trend and annual/semi-annual cycle with IRLS, as was used for analysis of long-term sea level change described in Section 2.2, is applied to both altimetry and tidal data for each location. At all stations, the phases of the annual cycle detected by both methods correspond very well, resulting in high correlations around 0.9 or higher, except at Ko Sichang and Hua Hin. The agreement is especially good when TOPEX-class altimetry is in the vicinity of the tide gauge, as shown by low RMSE at Ko Lak and Geting, where the nearest TOPEX/Jason ground track is only around 10 km away, and also at Sattahip and Laem Singh, both of which are within 100 km from a TOPEX-class satellite ground track. In cases when the ground tracks are more than 100 km away from the tide gauges, the influence of TOPEX/Jason weakens rapidly though picked up partly by ERS/Envisat, resulting in smaller amplitude of altimetry time series witnessed at Hua Hin, Ko Mattaphon, Ko Prab and Songkhla.

The in-phase annual cycle also compares to that from multi-mission altimetry-observed sea level in South China Sea, as depicted in Rong et al. (2007), although the amplitude in the Gulf is smaller and delayed. Interannual sea level variability linked to oceanic phenomena such as El Niño could be responsible for part of this observed variability (Fenoglio-Marc and Tel, 2010). The sea level change patterns and values from our 1993–2004 altimetry analysis, as shown in Fig. 5, also match with the results reported by Cheng and Qi (2007) covering the western part of the South China Sea from 1993 to 2001. However, the large sea level fall during a very strong 1997–1998 El Niño reported in an altimetry study of the South China Sea by Cheng and Qi (2007) is not directly observed in either tide gauge or altimetry data in the Gulf of Thailand.

### 5.4. Estimate of vertical land motion from altimetry and tidal measurements

Assuming that both tide gauges and altimetry capture the same oceanic signals, these signals are cancelled when the tidal rate trend is subtracted from the corresponding altimetry rate. Hence, only vertical land motion remains, as it is registered by the tide gauge but not by the altimeter. The assumption is valid only if a good match between altimetry and tide gauge time series can be achieved, as determined by correlation and especially RMSE. Past studies, *e.g.* Cazenave et al. (1999), Nerem and Mitchum (2002) and Fenoglio-Marc et al. (2004) demonstrated the usefulness of this basic idea. The results have been collected in Table 5.

The lack of geodetic data at most tidal stations prohibits direct validation of the vertical motions presented in Table 5, except at Sattahip, Ko Mattaphon and Geting. The detected downward motion at Laem Singh and Songkhla can be confidently attributed to heavy sedimentation that has led to the end of operation of both tide gauges. At Hua Hin, we notice an abnormal low reading in mid-1998 and a

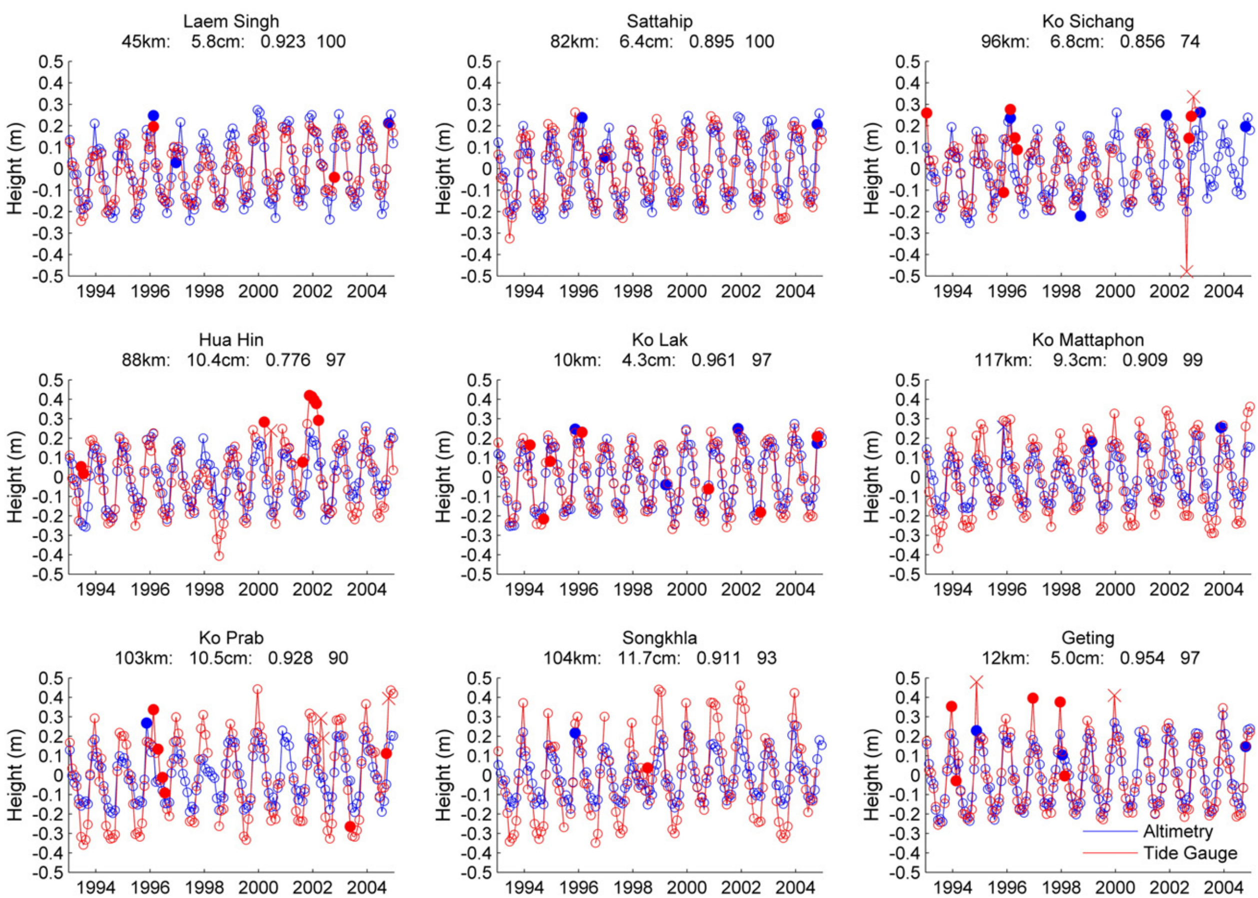


**Fig. 6.** Comparison plots between tide gauge monthly-average time series and those from altimetry. At each tidal station the (arbitrary) mean of altimetry time series is shifted to coincide with mean of tide gauge time series. Solid circles represent observations having final weights less than 0.5 and the crosses mark the outliers (weights equal 0). Details of weighting scheme and outlier detection are given in Section 2.2. Values below each tidal station name represent respectively distance from the station to the closest TOPEX-class satellite ground track, RMSE, correlation, and percentage of valid (excluding outliers) per total observations in the 12-year time series. For consistency, Ko Sichang is also included, although the absence of tidal data since the beginning of 2003, ten missing months in 2000 and 2001, and two outliers mean that the total number of observations of this station is significantly less than the others.

**Table 5**
Altimeter based sea level trends in the Gulf of Thailand at group-1B and group-2 tide gauge stations (columns 2 and 3), and tide gauge trends over the same period (column 4). We subtracted the tide solutions from the altimeter solutions for the 1993-2004 period (1993-2002 period for Ko Sichang because tide gauge data terminate here at the end of 2002) to derive the vertical land motion (VLM) at individual tide stations (column 5). This is compared with the VLM based on GPS (rightmost column). See Fig. 4 for details of a) and b). For c), the VLM rate is from supplementary text file of Woppelmann et al (2009).

| Tidal Station | Altimetry trend 1993-2009 (mm/yr) | Altimetry trend 1993-2004 (mm/yr) | Tide gauge trend 1993-2004 (mm/yr) | VLM (alt-tg) 1993-2004 (mm/yr) | VLM (gps) (1994-2004) (mm/yr) |
|---|---|---|---|---|---|
| Laem Singh | $3.6 \pm 0.7$ | $6.6 \pm 1.2$ | $10.5 \pm 1.1$ | $-3.9 \pm 1.6$ | N/A |
| Sattahip | $4.8 \pm 0.7$ | $6.9 \pm 1.1$ | $3.2 \pm 1.6$ | $3.7 \pm 1.9$ | $3.8 \pm 1.3$[a] |
| Ko Sichang | $5.8 \pm 0.8$ | $7.8 \pm 1.3$ | $7.6 \pm 2.0$ | $0.2 \pm 2.4$ | $3.8 \pm 1.3$[a] |
| Hua Hin | $4.8 \pm 0.8$ | $6.4 \pm 1.2$ | $4.8 \pm 2.2$ | $1.6 \pm 2.5$ | N/A |
| Ko Lak | $3.6 \pm 0.7$ | $5.5 \pm 1.0$ | $1.9 \pm 1.1$ | $3.6 \pm 1.5$ | N/A |
| Ko Mattaphon | $3.2 \pm 0.7$ | $5.8 \pm 0.9$ | $5.8 \pm 1.9$ | $0.0 \pm 2.1$ | $2.2 \pm 0.8$[b] |
| Ko Prab | $3.3 \pm 0.6$ | $6.0 \pm 1.0$ | $9.9 \pm 1.9$ | $-3.9 \pm 2.1$ | N/A |
| Songkhla | $3.3 \pm 0.6$ | $4.6 \pm 1.0$ | $13.0 \pm 2.4$ | $-8.4 \pm 2.6$ | N/A |
| Geting | $3.9 \pm 0.6$ | $6.1 \pm 0.8$ | $2.6 \pm 1.2$ | $3.5 \pm 1.4$ | $5.1 \pm 1.0$[c] |

spike in 2002, which is not observed at Ko Lak to the south and Sattahip to the east, indicating problematic tidal data. The correlation coefficient between altimetry and tide gauge at Hua Hin is also much lower than other stations. For Ko Sichang, the total absence of 2003–2004 data, 10 missing months during 2000–2001 and outliers accounting for 26% of the total record significantly reduce the number of useable measurements compared to the other stations. Being situated in the inner Gulf, the altimetry solution for this station also likely suffers from errors in the applied ocean tide model. We therefore exclude Laem Singh, Ko Sichang, Hua Hin and Songkhla from further discussion.

At Sattahip (6.3 cm RMSE), the 1993–2004 altimetry-derived land motion of $3.7 \pm 1.9$ mm/yr is nearly identical with the GPS-derived rate of $3.8 \pm 1.3$ mm/yr rate at CHON. At Geting (5.0 cm RMSE), the detected vertical motion of the same period is $3.5 \pm 1.5$ mm/yr, which deviates from the $5.1 \pm 1.0$ mm/yr GPS result of Woppelmann et al. (2009), but still agrees when taking into account the error margins. It is observed that low RMSE signifies low standard deviation of the derived land motion. We therefore expect that at Ko Lak where the RMSE (4.3 cm) is close to that of Geting and substantially lower than that of Sattahip, the accuracy of the estimate of land motion (based on the altimetry/tide gauge combination) is better than the Sattahip accuracy and comparable to the Geting accuracy. This observation is supported by the Ko Lak VLM standard deviation of 1.5 mm/yr shown in Table 5 (column 5 from left). Therefore, we are confident of the reliability of the derived land uplift of $3.6 \pm 1.5$ mm/yr for the 1993–2004 period. As described in Section 4, a steady motion for the entire interseismic era is assumed and we correct this uplift for Ko Lak's apparent rate $-0.6 \pm 0.1$ mm/yr from the tide gauge data (see also Fig. 3), which results in an absolute long-term rising rate of $3.0 \pm 1.5$ mm/yr for the entire 1940–2004 period (see also Table 3).

It appears that RMSE not only explains amplitude discrepancies between tidal and altimetry observations, but is also a measure of quality of the subsequently derived vertical land movement of the tide gauge. However, RMSE is only available after intensive altimetry and tidal data analysis, so some pre-analysis indicator of RMSE would be useful in practice. Fig. 6 illustrates the strong relationship between RMSE and distance between TOPEX ground tracks and the tide gauge. At almost all stations, smaller ground track/tide gauge distance results in low RMSE, which in turn results in low standard deviation of the vertical land motion. Our altimetry solution is driven by TOPEX/Jason altimetry because its shorter revisit period contributes more measurements. As such, TOPEX ground track/tide gauge distance can be used to predict RMSE. A simple rule can then be derived from our results, when TOPEX-class altimetry measurements within 100 km of a tide gauge are available, a good estimate of vertical land motion can be expected. With this rule of thumb and a regional or global plot showing the TOPEX-class altimetry ground tracks with the locations of tidal stations having no nearby GPS, tide gauges whose vertical motions can potentially be derived, can be identified.

In the case where tidal stations do not have GPS measurements or only have low frequency campaign data, the availability of monthly differences of altimetry-tidal data can be further utilized to visualize the patterns of land motion. Four tidal stations having RMSE less than 10 cm are selected to test this idea. In Fig. 7, the monthly differences are represented by the vertical position points: basically, this results from subtracting the altimetry and tide gauge curves displayed in Fig. 6. The remaining signal appears to be quite noisy. This is because of short-term variations present in the monthly altimetry solutions. A 12-month (1 year) central moving average is applied to smooth the variations. At Ko Lak and Geting, both of which have small ground track/tide gauge distances and very low RMSE, smoothing the monthly altimetry-tidal differences shows near steady inter-seismic uplift, which corresponds well with the seismic cycle. At Sattahip, where the separation and RMSE are larger and the assumption that dominant oceanic signals are registered identically by both tide gauges and altimetry is less valid, larger variations remain after the smoothing process, but a clear uplift trend is still visible. In fact, all these stations depict an uplift trend before the earthquake and post-seismic subsidence, which is predicted by the earthquake cycle model of a subduction zone. At Ko Mattaphon, where tide gauge–altimetry separation is largest (117 km), the derived inter- and post-seismic vertical motions is inconsistent with other stations, suggesting that a maximum separation distance of 100 km between tide gauge and altimetry ground track seems to be a good threshold.

Without the availability of high-frequency geodetic measurements such as CGPS for validation, it is at present debatable whether fluctuations of smoothed vertical points, *e.g.* post-seismic up-down movement, represent actual land motion. For the inter-seismic period, there also seems to be a 2001–2003 surge, as shown by data at all stations, but the rates are far too great from a tectonic point of view. Nevertheless, it is shown here that altimetry-tidal data combination can be utilized not only to determine the rates but also to gain some insight into the patterns of vertical land motion.

## 6. Conclusion

The 60-year (1940–2004) trends of sea level change that we derive from tide gauge sea level and GPS measurements in the northern part of the Gulf of Thailand at Sattahip ($5.0 \pm 1.3$ mm/yr) and Ko Sichang ($4.5 \pm 1.3$ mm/yr), are significantly higher than the global rate from tide gauge data of $1.8 \pm 0.3$ mm/yr over a comparable observation period (1950–2000) as reported by Church et al. (2004). The rates are also higher than the value used in the most recent assessment of climate change impact on the coastal-megacity of Bangkok (World Bank, 2009), which is 3 mm/yr (no error margin given in

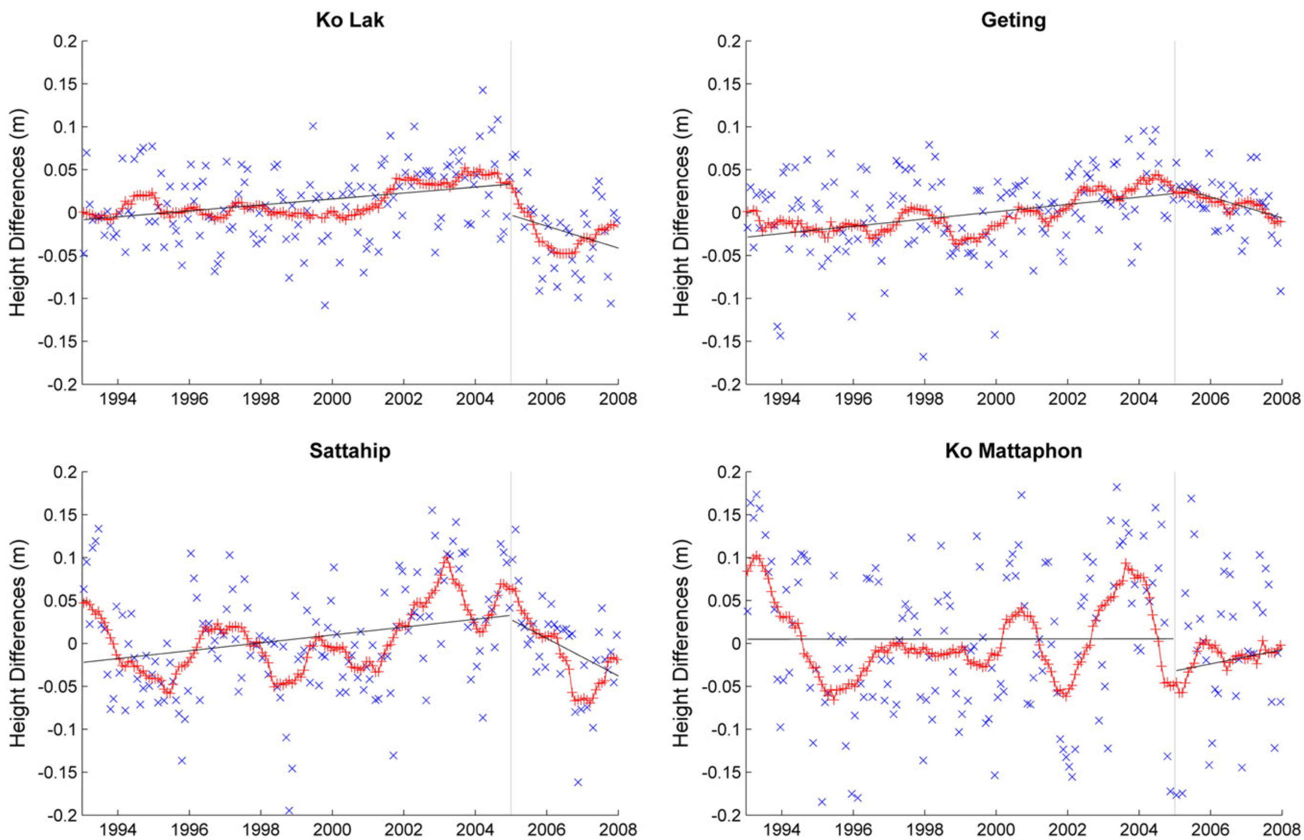


**Fig. 7.** Plots of inter- and post-seismic land motions as derived from the difference between altimetry and tidal data having RMSE values ranging from low (Ko Lak and Geting), moderate (Sattahip) and large (Ko Mattaphon). The blue crosses represent the differences between altimetry and tidal monthly averages. These differences are smoothed by 12-month central moving average shown as red marks. Linear trend lines are fitted to the smoothed values. To avoid mixing inter- and post-seismic signals, data of 6 months before and after the earthquake are not used in the fitting. Except for Ko Mattaphon, the pre-earthquake uplifts are detected at all stations and it can be seen that variations of smoothed monthly differences correlate with RMSE. The post-earthquake downward motions are also detected but the 2005–2008 time series are considered too short to define post-seismic characteristics and so the shown trends should be viewed as only indicative. The contradictory behaviour of Ko Mattaphon with the other stations can be attributed to the large separation between the Topex-class altimetry ground track and the tide gauge (117 km), so the land motion signal is corrupted by oceanic signals registered differently by the tide gauge and the altimeter.

the report). The implication of these fast rising trends is that there is a need for a reassessment of sea level rise impact on low-lying coastal areas north of the Gulf, in particular Bangkok. Somewhat lower rates, yet higher than the global average, are observed at Ko Lak (3.0 ± 1.5 mm/yr) and Ko Mattaphon (4.4 ± 1.1 mm/yr) stations on the western coastal areas. Our analysis of 1993–2009 multi-mission altimetry data exhibits similar rates: *i.e.* Sattahip (4.8 ± 0.7 mm/yr), Ko Sichang (5.8 ± 0.8 mm/yr), Ko Lak (3.6 ± 0.7 mm/yr) and Ko Mattaphon (3.2 ± 0.7 mm/yr). Even higher values can be found near large river deltas.

Recent global studies indicate the presence of sea level acceleration. From the reconstructed global sea level of the period 1870–2004, Church and White (2006) show that the 20th century acceleration of sea level rise is 0.013 mm/yr$^2$. Acceleration of about the same rate that appears to have started at the end of the 18th century is derived in Jevrejeva et al. (2008). However, in our study the 17-year rates of sea level rise from altimetry are larger than multi-decadal tide gauge rates at Ko Sichang and Ko Lak but smaller at Sattahip and Ko Mattaphon. The small differences between the altimetry-based and tide gauge rates can be explained by interannual variations like ENSO and decadal variations due to solar activity and lunar nutation. Nevertheless, the differences are not statistically significant which implies the fast rising rates in the Gulf of Thailand remain largely constant for the last 50–60 years and no acceleration could be detected. Given no conclusive evidence of sea level acceleration in this region, special precaution should be taken in projecting future sea level and impact assessments of sea level rise as in low-lying coastal areas much different flood scenarios could result depending on whether the acceleration is factored in.

A major obstacle preventing the use of complete tide gauge data time series in the determination of long-term sea level trend are the co- and post-seismic motions caused mainly by the 2004 Mw 9.2 Sumatra-Andaman earthquake. Co-seismic vertical land shifts at tide gauges along the coast of Gulf of Thailand are still largely unknown but magnitudes obtained from CGPS at other places in the region show that they are not negligible. Further, magnitudes of non-linear post-seismic motions indicated by GPS measurements near Sattahip and Ko Mattaphon are roughly estimated to be several times larger than rising rates of sea level (on the order of −10 mm/yr). At present, the availability of co- and post-seismic motion corrections are not of paramount importance as the number of years after the earthquake is much shorter than the total years of the record. As a result, no significant change in absolute sea level rates is expected and the 1940–2004 tide gauge relative rates derived in this study were successfully corrected using steady vertical land motions as detected by GPS (1994–2004). In the longer run, impact of co-seismic shifts will decrease but the cumulative effect of post-seismic tectonic plate subsidence, which could last for several decades, will make it imperative for sea level change studies to estimate reliable subsidence rates.

There are many long-record tide gauges in Southeast Asia, but utilizing their sea level measurements has been problematic because of unknown vertical land motion contributions. Our results reinforce the possibility of using near-tide gauge altimetry data as geodetic measurements to capture vertical velocities of the tide gauge, as exemplified by Ko Lak in our case. The derived post-seismic trend of land motion from the altimetry/tide gauge difference at Sattahip confirms the subsidence as detected by GPS. Coupled with downward trends that are also observed at Ko Lak and Geting, this strongly suggests that the extent of downward motion after the Sumatra-Andaman earthquake is region-wide. Our study results lead to an alarming scenario: the impact of a fast rising sea level is now amplified by plate subsidence. The increasing threat of flooding to urban areas around the Gulf of Thailand calls for a re-evaluation of risks, protection and mitigation, particularly for extremely low-lying big cities like Bangkok situated, on average, only 1 m above sea level.

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