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Article

A Reanalysis of Vertical Land Motion at Tide Gauge Stations in Thailand Utilizing GNSS Continuous Operating Reference Stations

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Abstract. Sea level monitoring is critical for coastal management, water resource planning, and climate change studies, particularly in Thailand, where agriculture forms the backbone of the economy. In Thailand, sea level observations primarily rely on tide gauge stations. However, tide gauge measurements are often influenced by vertical land motion (VLM), including land subsidence or uplift. To address this, the Global Navigation Satellite System (GNSS) offers a reliable solution for determining VLM. This study leverages the established network of Continuous Operating Reference Stations (CORS) in Thailand, utilizing co-located GNSS CORS with tide gauge stations in the Gulf of Thailand to quantify VLM at tide gauge stations. The VLM corrections were applied to tide gauge data to refine sea level estimates and provide insights into long-term sea level changes. The findings reveal that sea level changes corrected for VLM demonstrate discrepancies of approximately 4–5 millimeters when compared to sea level changes derived from satellite altimetry. This indicates that GNSS-derived VLM from the CORS network in Thailand is influenced by additional factors that may introduce biases in corrected sea level measurements. These results highlight the importance of addressing these influences to improve the accuracy of sea level monitoring and contribute to more reliable climate and coastal management strategies.

Keywords: Sea level monitoring, tide gauges, vertical land motion, GNSS, continuous operating reference stations.

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1. Introduction

Sea level is a critical information for understanding the impacts of climate change, coastal management, and infrastructure planning. Tide gauge (TG) measures local sea levels, but their observations are influenced by both geocentric sea level variations and vertical land motion (VLM). Correcting for VLM at TG is essential to transform observed sea levels into the geocentric reference frame used by satellite altimeters. Furthermore, VLM corrections are necessary for TG employed in sea level reconstructions. It is noteworthy that the average VLM at TG often differs from that of the surrounding basin, necessitating localized determination to accurately estimate sea level change. While models addressing large-scale VLM phenomena, such as glacial isostatic adjustment (GIA) and the Earth's elastic response to contemporary mass redistribution, have improved in accuracy, TG corrections typically account only for GIA, which can reach magnitudes of approximately 10 mm/year [1]. However, other factors, including water storage changes, post-seismic deformation, and anthropogenic activities, also affect sea level monitoring, especially long-term trends, as measured by TG. These localized processes cannot be fully captured by global models [2]. Therefore, VLM observations at TG are important for understanding regional sea level changes and refining global sea level rise estimates.

In recent decades, the Global Navigation Satellite System (GNSS) has become an indispensable tool for estimating VLM at TG. Continuous Operating Reference Stations (CORS) are strategically installed near TG to monitor local VLM, ensuring accurate sea level change monitoring. The integration of GNSS data with TG observations enables correction of vertical land motion effects on sea level measurements, offering a more precise assessment of sea level trends. To this end, the International GNSS Service (IGS) initiated the Tide Gauge Benchmark Monitoring Pilot Project (TIGA) to provide high-quality VLM estimates by co-locating GNSS stations with TG benchmarks. TIGA supports critical applications such as calibrating satellite altimetry, disentangling crustal movements from sea level changes, and refining GIA models. These contributions are crucial for establishing a globally consistent vertical reference system and enhancing scientific research and climate monitoring efforts [3].

The benefits of integrating GNSS and TG data are particularly evident in data-sparse regions. For example, studies in coastal Chile and the Antarctic Peninsula have demonstrated how GNSS data can quantify nonlinear VLM, as well as co-seismic and post-seismic subsidence, which are undetectable using TG alone [4]. Similarly, [5] analyzed data from seven TG and GNSS station pairs around the Chesapeake Bay (CB), the largest estuary in the United States, to investigate relative sea level rise (RSLR) since the 20th century. Their study accounted for the combined effects of GNSS-derived land subsidence (LS) and absolute sea level rise (ASLR) across various geological zones—pre-Cretaceous (pre-C), Cretaceous (C), Tertiary (T), and Quaternary (Q). They observed progressively increasing LS rates from the pre-C to Q zones, except at Yorktown, where subsidence is influenced by a 35-million-year-old bolide impact crater. Estimated ASLR rates before 1992 ranged from 1.10 to 1.15 mm/year after removing LS from RSLR measurements. These findings underscore the importance of geological variability in influencing RSLR and provide valuable insights for coastal management and climate adaptation strategies in the CB region. Similarly, [6] estimated VLM and ASLR at three TG stations with co-located GNSS stations in French Polynesia for the period 2007–2020. Their methodology, validated through modeling vertical motion at the IGS THTI station on Tahiti Island, significantly agreed with previous studies. The study provided VLM estimates of -0.92 ± 0.17 mm/year at Tubuai Island, -0.49 ± 0.39 mm/year at Vairao Village, and -0.43 ± 0.17 mm/year at Rikitea. Corresponding ASLR rates were 5.25 ± 0.60 mm/year, 3.62 ± 0.52 mm/year, and 1.52 ± 0.23 mm/year, respectively. These results offer a comprehensive understanding of sea level activities and VLM in French Polynesia.

Accurate estimation of vertical land motion relies significantly on the precision of GNSS-derived station vertical positions and velocities. A robust approach to achieving this is the implementation of a homogeneous processing strategy for GNSS observations. For example, the ULR-repro3 reanalysis conducted by the University of La Rochelle offers enhanced VLM estimates at tide gauge stations by leveraging a larger network of GNSS stations and extending the observation period by approximately seven years. This reanalysis incorporates advanced modeling and correction techniques, significantly reducing uncertainties in vertical velocity estimates to a median value of 0.25 mm per year. These refined time series and velocity estimates are critical for accurately assessing sea level changes and their impacts on coastal regions, complementing satellite altimetry and tide gauge observations [7].

In the past decades, GNSS observations have been utilized to correct VLM at tide gauge stations in Thailand, yielding valuable insights into regional sea level trends. For instance, [8] analyzed sea level changes in the Gulf of Thailand using GPS-corrected tide gauge data and multi-satellite altimetry. The findings indicated that sea levels in the region are rising at a rate significantly faster than the global average, with long-term trends of 5.0 ± 1.3 mm per year at Sattahip and $4.5 \pm$

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1.3 mm per year at Ko Sichang. VLMs were derived from the GPS campaign conducted for only one week per year from 1994 to 2008, focusing on two stations: Sattahip and Ko Mattaphon, which are in close proximity to the tide gauge stations. The authors emphasized the impact of the 2004 Mw 9.2 Sumatra-Andaman earthquake on post-seismic land motions, as indicated by the GPS-derived VLM, which caused a transition from uplift to subsidence. This resulted in downward motions of −3.9 mm/yr at Sattahip and Ko Sichang, and −12.7 mm/yr at Ko Mattaphon. The study hilights the vulnerability of coastal areas, particularly Bangkok, to flooding due to rapid sea level rise and crustal deformation. Additionally, [9] investigated VLM on Phuket Island, Thailand, in the aftermath of the 2004 Sumatra-Andaman earthquake, which had significant implications for sea level change estimates. Their study utilized data from two continuous GNSS stations installed to monitor VLM since 1994, alongside satellite altimetry observations dating back to 1992. Before the earthquake, sea level rise was estimated at 1.0 ± 0.7 mm per year; however, post-earthquake VLM induced substantial subsidence, contributing to a cumulative sea level rise of up to 16 cm by 2020. This study underscored the role of post-seismic subsidence in exacerbating coastal erosion along the Andaman Sea coastline and highlighted the need for adaptive coastal management strategies in response to these dynamic changes.

Despite significant achievement, many TG stations in Thailand remain uncorrected for vertical land motion. In recent years, organizations such as the Royal Thai Survey Department (RTSD) and the Department of Land (DOL) have established a network of GNSS CORS across the country, with several stations located near TG [10]. This development provides an opportunity to derive precise VLM estimates at TG using GNSS CORS data. As previously mentioned, adopting a homogeneous processing strategy and extending GNSS observation records are essential for improving the accuracy of GNSS-derived VLM estimates at TG.

This research aims to reanalyze long-term GNSS observations from CORS co-located with TG stations in Thailand. Through a time series analysis of reprocessed GNSS-derived vertical positions, VLM models at TG stations are determined, enabling the correction of VLM effects at these stations. Section 2 outlines the current status of TG stations in Thailand, their co-located GNSS CORS, and the selection criteria for this study. The GNSS data processing methodology, including the derivation of vertical positions and the modeling of VLM, is described in Section 3. Section 4 demonstrates the results of sea level changes obtained from TG stations in Thailand, both before and after applying VLM corrections derived from co-located GNSS CORS, and provides a discussion of the findings. Finally, the conclusions and outlooks of this study are summarized in Section 5.

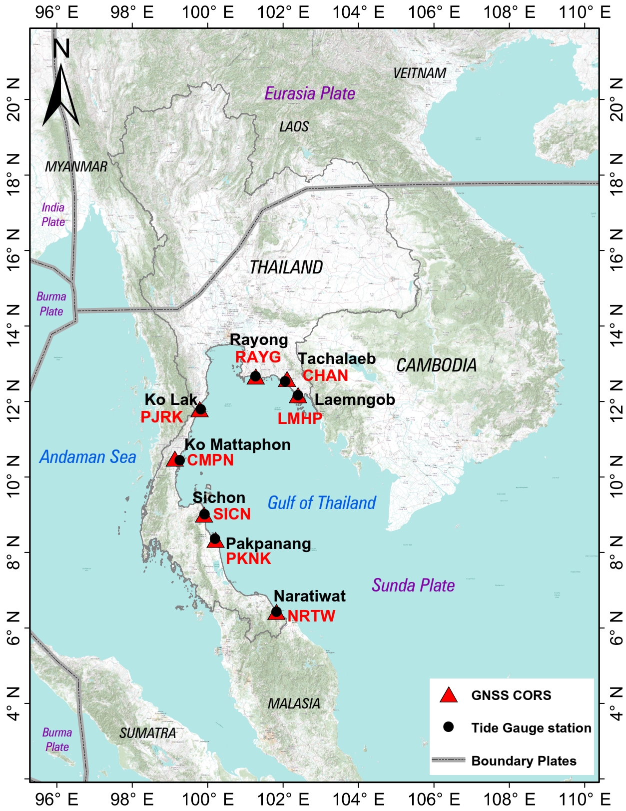

Fig. 1. The locations of selected TG and co-located GNSS CORS in the Gulf of Thailand.

Table 1. The inter-distance between selected tide gauge and co-located GNSS stations in the Gulf of Thailand.

TG stations	GNSS Stations	Distance (km)
KO LAK	PJRK	2.533
KO MATTAPHON	CMPN	14.735
LAEMNGOB	LMHP	0.302
NARATIWAT	NRTW	0.452
PAKPANANG	PKNK	2.371
RAYONG	RAYG	0.955
SICHON	SICN	1.800
TACHALAEB	CHAN	9.458

2. Tide Gauge Stations and Co-located GNSS CORS in Thailand

This study utilized GNSS observations from CORS established by various governmental organizations, including the Department of Lands (DOL) and Department of Public Works and Town and Country Planning (DPT). Sea level observations were acquired from tide gauges managed by the Marine Department of Thailand, with the TG located primarily within the Gulf of Thailand (see Figure 1). However, in this study, GNSS CORS co-located with TG were not precisely established at the same sites as the TG. To address this, we selected GNSS CORS within a 15 km radius of the TG, ensuring that neither the TG nor the GNSS CORS were situated across active fault lines. Table 1 lists the TG and their corresponding GNSS CORS, along with the inter-site distances between each TG and its co-located GNSS CORS.

3. Data Analysis

This section details the time-series analysis of sea level changes obtained from the selected TG, including the methodologies for outlier detection and the functional model employed in this study. Additionally, the GNSS data processing is outlined, with particular emphasis on the procedure used to extract VLM from the GNSS station position time-series. This VLM information was subsequently applied to correct the sea level observations derived from the TG. Furthermore, the analysis includes a comparison between the VLM-corrected sea level changes and the sea level changes obtained from satellite altimetry data.

3.1. Apparent Sea Level Change Analysis from Tide Gauge Stations

In this study, we analyzed long-term sea level trends using hourly sea level records from tide gauges operated by the Marine Department of Thailand (see Table 1) for the period 2005–2023. In addition, the TG observations at KO LAK station were obtained from the Permanent Service for Mean Sea Level (PSMSL) [11, 12]. Data points exceeding 3-sigma thresholds were identified as outliers and excluded from the analysis. To mitigate noise and eliminate micro-scale effects in the time series, which could introduce bias into the long-term trend estimation, the hourly sea level data were resampled to a monthly interval.

The time-series analysis was based on a mathematical model for long-term observations [13], as expressed in Eq. 1.

3.2. GNSS Data Analysis and Vertical Land Motion Extraction

Regarding GNSS data analysis, daily GNSS observations spanning five years (2019–2023) were obtained from the CORS stations listed in Table 1. The GNSS observations were processed using the Bernese GNSS Software version 5.4 [14] to derive precise station coordinates. In this study, the Precise Point Positioning (PPP) technique was employed. The CODE repro3 satellite orbits and clock products, provided by the Center for Orbit Determination in Europe (CODE) [15], were used. These products are part of the reprocessing campaign for the determination of the International Terrestrial Reference Frame 2020 (ITRF2020) [16]. Dual-frequency GPS and GLONASS observations were utilized to form an ionosphere-free linear combination, which was subsequently used to estimate daily station coordinates and hourly tropospheric parameters. Corrections for satellite and receiver phase center offsets and variations (PCO and PCV) were applied using the IGS14R3 ANTEX file [17]. Furthermore, all processing adhered to the IERS Conventions 2010 [18], which provide the essential models and corrections required for high-accuracy GNSS data analysis. A summary of the models used in this study is provided in Table 2.

$$Y(t) = a + b \cdot t + A_1 \cdot \sin(2\pi f_1 t) + B_1 \cdot \cos(2\pi f_1 t) + A_2 \cdot \sin(2\pi f_2 t) + B_2 \cdot \cos(2\pi f_2 t) + U(t) \quad (1)$$

where a represents the offset component of the time series, and b denotes the linear trend. $A_{1,2}$ and $B_{1,2}$ are the coefficients for the seasonal components, with frequencies of f_1 and f_2 corresponding to the annual and semi-annual cycles, respectively. $U(t)$ denotes a normal-distributed error. The seasonal component amplitude, $C_{1,2}$, are determined by $C_{1,2} = \sqrt{A_{1,2}^2 + B_{1,2}^2}$

The station position models were derived by applying the functional model described in Eq. 1 to the GNSS-derived daily station position time series for each station. The vertical component of the station position model, representing VLM, was subsequently incorporated into the sea level time series obtained from the selected TG in this study.

3.3. Absolute Sea Level Change Analysis

After extracting GNSS-derived vertical land motion for each selected tide gauge, these corrections, computed using the functional model described in Section 3.2, were applied to the apparent sea level (APSL) observations from the TG to derive the absolute sea level (ABSL). The resulting ABSL time-series were analyzed using the functional model presented in Eq. 1 to determine sea level trends and assess changes in sea levels in the Gulf of Thailand.

This study also includes a comparison of apparent and absolute sea level changes and evaluates the consistency between TG-derived ABSL and satellite altimetry observations. Satellite altimetry-derived sea levels (SASL) were sourced from the Global Ocean Gridded L4 Sea Surface Heights and Derived Variables Reprocessed (1993–Ongoing) dataset provided by the E.U.

Table 2. Summary of used model for GNSS data processing in this study.

Modeling and a-priori information	
Observations	Ionosphere-linear combination formed by undifferenced GNSS observations
A priori products	Orbits, clock corrections, Earth rotation parameters from CODE repro3 solution [15]
Tropospheric correction	Troposphere delays computed with Saastamoinen, mapped with VMF3 [19]
Ionospheric correction	1st order effect considered with ionosphere-free linear combination, 2nd order correction applied
Antenna phase center	Corrections from dedicated repro3 ANTEX applied (IGS14R3.atx) [17]
Solid Earth tides	According to IERS 2010 Conventions [18]
Permanent tide	Conventional tide free
Ocean loading	FES2014b [20]
Atmospheric loading	S1 and S2 tidal corrections [21]
High-frequent EOP model	Desai-Sibois model [22]
Mean pole tide	According to IERS 2010 Conventions [18]

Copernicus Marine Service Information [23]. To account for coastal altimetry uncertainties, satellite data within a 15 km radius of each TG station were considered for a comparison. Daily SASL data at the TG locations were resampled to monthly intervals for the 2005–2023 period and analyzed using the same functional model applied to TG-derived sea levels. The TG-derived ABSL changes were then compared with the satellite altimetry-derived sea level changes to assess their agreement.

4. Results and Discussions

The APSL analysis conducted in this study identifies a rising trend in sea levels across the Gulf of Thailand. For instance, Fig. 2 illustrates the APSL time series at the PAKPANANG tide gauge, which demonstrates an annual increase. Similarly, Fig. 3 shows a comparable positive trend at the SICHON tide gauge. Other tide gauges in the region display consistent patterns of increasing APSL, supporting the conclusion that sea level rise in the Gulf of Thailand is in agreement with global mean sea level trends [24]. However, the rates of APSL change vary by several millimeters per year across the TG network. Table 3 summarizes the computed sea level change rates derived using the methodology outlined in Section 3. The highest rate, 14.6 mm/year, is observed at the PAKPANANG station, while the lowest, 3.7 mm/year, is observed at the SICHON station. Despite their geographic proximity, these TG demonstrate significant disparities in APSL change rates, primarily attributable to vertical land motion at the TG sites, as identified in previous studies by [8].

To quantify VLM, observations from co-located GNSS CORS (see Table 1) were employed, as described in Section 3.2. Figure 2 shows the vertical position time series at the PKNK station, indicating a subsidence trend. A similar pattern is observed at the SICN station (see Fig. 3). Other co-located GNSS CORS in this study demonstrate comparable trends, consistent with the findings at PKNK and SICN. Table 3 presents the long-term trends of GNSS-derived VLM estimated from these stations. These trends align with the APSL changes observed at the TG but with opposite signs, confirming that APSL variations are significantly influenced by VLM.

After determining GNSS-derived VLM corrections for each selected TG, these corrections were applied to APSL measurements to compute absolute sea level changes. Table 3 provides the corrected ABSL change rates for the selected TGs. The application of GNSS-derived VLM corrections substantially mitigated the impact of land motion, reducing sea level change rates from several millimeters per year to a few millimeters per year for most TGs. For example, the sea level change rate at PAKPANANG was reduced from 14.6 mm/year to 0.6 mm/year. Furthermore, the ABSL change rates were compared with SASL trends. The results show significant discrepancies of 4–5 mm/year between ABSL changes derived from TG and those obtained from SASL, except at the TACHALAEB station, where the difference is only 1 mm/year. Notably, the ABSL changes derived from TG remain inconsistent across the Gulf of Thailand, whereas the SASL data demonstrates uniform ABSL changes for all selected locations. These discrepancies suggest that GNSS-derived VLM estimates are influenced by systematic biases at the selected CORS. One major factor is the differing foundation types of TG and GNSS CORS. The inter-station distances between the TG and their co-located GNSS CORS can extend up to several kilometers, as shown in Table 1, introducing potential spatial inconsistencies. Additionally, the GNSS CORS analyzed in this study are installed on soil layers (DOL, personal communication, 2024), unlike the TG, which are typically anchored to bedrock. For example, Fig. 4 shows the site of GNSS CORS at SICN station that was installed on soil layers. Soil layers are more susceptible to subsidence caused by rainfall and anthropogenic activities such as groundwater extraction [25]. These factors introduce biases in the

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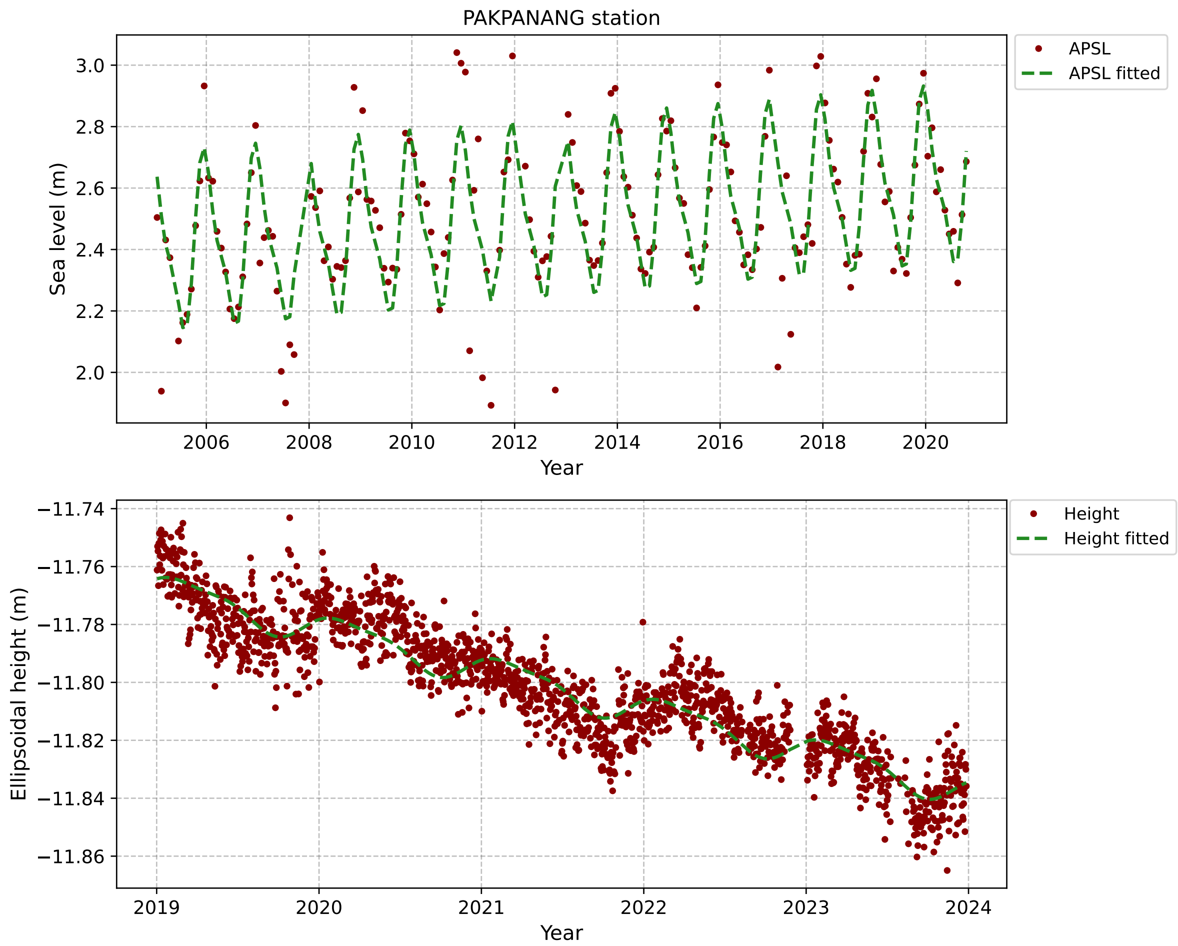

Fig. 2. Time series of APSL changes derived from tide gauge stations (top panel) and VLM inferred from GNSS vertical component of station position time series (bottom panel) at PAKPANANG station. The APSL time series includes seasonal variations and long-term trends, with a fitted model capturing both periodic signal and linear component. The GNSS time series depicts vertical land motion, with the fitted model accounting for secular trends and seasonal signals.

Table 3. Annual rates of absolute and relative sea level changes at selected TG stations in the Gulf of Thailand. The table presents the APSL change rate derived from TG observations, VLM obtained from co-located GNSS CORS, and the ABSL change rate. The ABSL rate and its associated uncertainties are re-estimated using APSL, corrected for VLM, and subsequently computed with the functional model in Eq. 1. Additionally, SASL annual rates are provided for comparison. Uncertainties are provided at the 1-sigma confidence level.

Tide gauge stations	APSL (mm/year)	VLM (mm/year)	ABSL (mm/year)	SASL (mm/year)
KO LAK	9.4 ± 0.6	-7.7 ± 0.03	1.7 ± 0.6	5.3 ± 0.5
KO MATTAPHON	5.7 ± 0.7	-4.9 ± 0.02	0.8 ± 0.7	6.2 ± 0.5
LAEMNGOB	6.6 ± 0.5	-3.9 ± 0.15	2.7 ± 0.5	5.4 ± 0.5
NARATIWAT	6.8 ± 0.6	-3.2 ± 0.14	3.7 ± 0.6	5.7 ± 0.5
PAKPANANG	14.6 ± 1.5	-14.0 ± 0.03	0.6 ± 1.5	4.7 ± 0.6
RAYONG	4.3 ± 0.8	-4.1 ± 0.12	0.2 ± 0.8	5.1 ± 0.5
SICHON	3.7 ± 0.9	-4.0 ± 0.13	-0.3 ± 0.9	4.9 ± 0.6
TACHALAEB	12.1 ± 0.8	-5.8 ± 0.04	6.4 ± 0.8	5.4 ± 0.5

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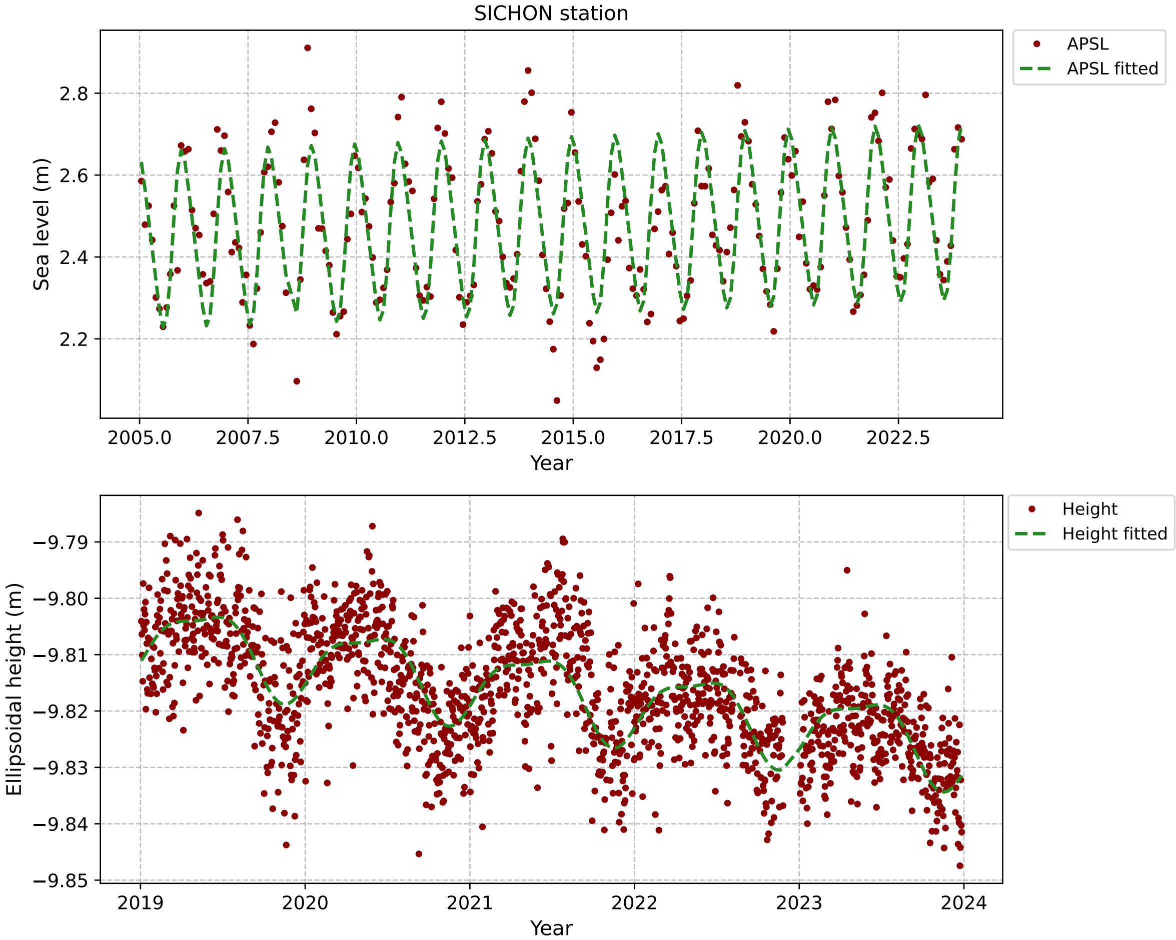

Fig. 3. Time series of APSL changes derived from tide gauge stations (top panel) and VLM inferred from GNSS vertical component of station position time series (bottom panel) at SICHON station. The APSL time series includes seasonal variations and long-term trends, with a fitted model capturing both periodic signal and linear component. The GNSS time series depicts vertical land motion, with the fitted model accounting for secular trends and seasonal signals.

GNSS-derived VLM estimates, suggesting the need for careful consideration of local geotechnical conditions in sea level studies.

Fig. 4. The site of GNSS CORS at SICN station.

5. Conclusions and Outlooks

This study assessed the impact of vertical land motion at selected tide gauges in the Gulf of Thailand using co-located GNSS continuously operating reference stations. GNSS-derived VLM were applied as corrections to the sea level measurements obtained from TG. The corrected sea level time series, resulting absolute sea level, were analyzed to estimate sea level trends and compared to those derived from satellite altimetry.

The results reveal significant inconsistencies in the apparent sea level change rates obtained from the selected TG, despite their geographic proximity along the Gulf of Thailand coastline. These inconsistencies are attributed to the influence of site-specific VLM. By applying GNSS-derived VLM corrections, the sea level trends from TG were significantly reduced, enabling the derivation of ABSL changes. However, discrepancies occur between ABSL changes derived from TG and those obtained from satellite altimetry. A primary factor contributing to these discrepancies is the difference in the structural foundations of the GNSS CORS and the TG. Unlike TG, which are typically anchored to solid bedrock, the GNSS CORS in this study are installed on soil layers, making them more sensitive to subsidence induced by geophysical processes and anthropogenic activities. These foundation differences introduce systematic biases into the GNSS-derived VLM estimates and, consequently, into the corrected sea level trends.

This study highlights the critical role of accurately determining GNSS-derived VLM in ensuring reliable ABSL change estimates from TG. To achieve this, it is recommended that GNSS CORS installations adhere to the same geotechnical standards as TG, preferably with GNSS CORS co-located directly at the TG stations. Colocating GNSS CORS at TG station ensures that both instruments are subject to identical VLM due to their shared foundation, thereby improving the precision of VLM corrections in sea level observations. Additionally, the temporal span of GNSS observations employed in this study was constrained to five years. It is crucial that the periods of GNSS observations used for the derivation of VLM align with sea level observations obtained from TG. This limitation stems from the fact that the network of GNSS CORS in Thailand was established only five years ago. Moreover, it is imperative that the appropriate time span for this study includes the duration of the Pacific Decadal Oscillation, which spans approximately 50 years. This extended timeframe is crucial for adequately accounting for the effects of the water cycle, which may introduce biases in the measurement of absolute sea level change. Longer time series of GNSS data would enhance the robustness of VLM estimations, thereby reducing uncertainties in sea level change determinations.

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