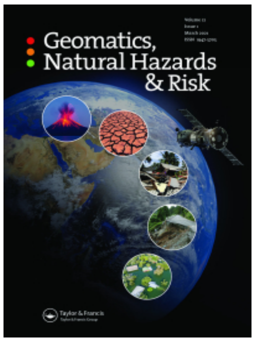

Geomatics, Natural Hazards and Risk

ISSN: 1947-5705 (Print) 1947-5713 (Online) Journal homepage: www.tandfonline.com/journals/tgnh20

Estimating vertical land motion-adjusted sea level rise in a data-sparse and vulnerable coastal region

Ashraf Dewan, Hardik Jain , Md Alamgir Hossain , Mohammed Sarfaraz Gani Adnan & Md Redowan Mahmud

To cite this article: Ashraf Dewan, Hardik Jain , Md Alamgir Hossain , Mohammed Sarfaraz Gani Adnan & Md Redowan Mahmud (2025) Estimating vertical land motion-adjusted sea level rise in a data-sparse and vulnerable coastal region, Geomatics, Natural Hazards and Risk, 16:1, 2545375, DOI: 10.1080/19475705.2025.2545375

To link to this article: https://doi.org/10.1080/19475705.2025.2545375

GEOMATICS, NATURAL HAZARDS AND RISK
2025, VOL. 16, NO. 1, 2545375
https://doi.org/10.1080/19475705.2025.2545375

Taylor & Francis
Taylor & Francis Group

OPEN ACCESS Check for updates

Estimating vertical land motion-adjusted sea level rise in a data-sparse and vulnerable coastal region

Ashraf Dewan[a], Hardik Jain[b], Md Alamgir Hossain[c], Mohammed Sarfaraz Gani Adnan[d] and Md Redowan Mahmud[b]

[a]School of Earth and Planetary Sciences, Curtin University, Perth, Australia; [b]School of Electrical Engineering, Computing and Mathematical Sciences, Curtin University, Perth, Australia; [c]Economic Relations Division, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh; [d]Department of Civil and Environmental Engineering, Brunel University of London, Uxbridge, UK

ABSTRACT

Sea level rise (SLR), driven by global warming, threatens coastal Bangladesh through inundation, land loss, and displacement. However, SLR estimates are often inconsistent or overestimated due to limited data and inadequate correction for vertical land motion (VLM). This study presents an integrated approach to accurately assess SLR by combining multi-station tide gauge (TG) records with satellite altimetry (SA) and interferometric synthetic aperture radar (InSAR) data across Bangladesh's coastline. Relative SLR (RSLR) rates were derived from TGs, absolute SLR (ASLR) from SA, and InSAR-derived VLM trends were used to correct TG-based estimates. Results revealed strong seasonal variations, with sea levels peaking in April and lowest in September. Decadal trends indicated alternating phases of rise and fall. Annual SLR rates averaged 5.40 mm/year from TGs and 4.94 mm/year from SA, with notable spatial variations. VLM analysis showed subsidence at five TG sites and uplift at six. After VLM adjustments, all stations exhibited positive ASLR trends, averaging 4.58 mm/year. This study demonstrates that incorporating VLM and corrections of TG records significantly improves SLR estimation. The findings provided critical insights into the spatial and temporal dynamics of sea level change and provide a scientific basis for climate adaptation and infrastructure planning in Bangladesh's vulnerable coastal zone.

ARTICLE HISTORY
Received 18 March 2025
Accepted 4 August 2025

KEYWORDS
Sea level rise; tide gauge; altimetry; InSAR; vertical land motion

1. Introduction

Rising global temperatures have accelerated the melting of glaciers and ice sheets, contributing significantly to sea level rise (SLR). The global mean sea level (GMSL) is not only increasing but has also shown signs of acceleration in recent decades. According to the Intergovernmental Panel on Climate Change (IPCC), the rate of GMSL rise increased from 1.4 mm/year between 1901 and 1990 to 3.6 mm/year during 1993–2015, primarily due to anthropogenic factors (Pörtner et al. 2019). Using integrated multi-mission ocean altimeter data, Hamlington et al. (2024) reported that the global SLR rate has accelerated from 2.1 mm/year in 1992 to 4.5 mm/year in 2024. However, SLR trends vary considerably across regions and time periods (Church et al. 2007; Han et al. 2010), posing distinct threats to low-lying and densely populated coastal areas. Despite ongoing uncertainties in magnitude, deltaic regions remain particularly vulnerable to the impacts of rising seas (Nicholls and Cazenave 2010).

SLR estimates derived from tide gauge (TG) records reflect relative sea level rise (RSLR), which combines ocean height changes and vertical land motion (VLM). To obtain absolute sea level rise (ASLR), it is necessary to correct TG records using VLM estimates from satellite altimetry (SA) (Qiao et al. 2023), global navigation satellite systems (GNSS) (Bruni et al. 2022; Zhou et al. 2022), and

CONTACT Mohammed Sarfaraz Gani Adnan sarfaraz.adnan@brunel.ac.uk
Supplemental data for this article can be accessed online at https://doi.org/10.1080/19475705.2025.2545375.

interferometric synthetic aperture radar (InSAR) (Aobpaet et al. 2013; Kleinherenbrink et al. 2018). Robust SLR assessments also require accounting for atmospheric pressure effects (Zou et al. 2021) and tidal variations induced by celestial mechanics (Cartwright, 2000; Beenstock et al. 2015; Hagen et al. 2021). Recent studies have demonstrated the feasibility of using GNSS to correct TG data for VLM (Zhou et al. 2022; Haodong et al. 2024), offering reliable ground benchmarks.

Bangladesh, with its low-lying topography and high population density, is one of the most vulnerable countries to GMSL rise. Various anthropogenic and natural factors, including reduced freshwater discharge (Sherin et al. 2020), rapid land use changes (Abdullah et al. 2019), and frequent natural hazards (Karim and Mimura 2008), exacerbate this vulnerability. Projections suggest that large portions of the coastal region may be submerged due to ongoing SLR (Carvalho and Wang 2019), leading to land loss (Ericson et al. 2006), displacement (Bell et al. 2021), reduced agricultural yields (Ministry of Environment Forest and Climate Change (MoEFC) 2022), and enhanced threats to critical infrastructure (Adshead et al. 2024). Additionally, ground deformation from urbanization, groundwater extraction, mining, and tectonic activity further complicates sea level assessments (Steckler et al. 2016).

Accurately estimating SLR along the Bangladesh coast is challenging but remains vital. Previous studies on SLR in this region fall into three broad categories: (i) those using single- or multi-station TG records (Khan et al. 2000; Singh 2002; Lee 2013; Climate Change Cell (CCC) 2016; Carvalho and Wang 2019; Anwar et al. 2022; Rose and Bhaskaran 2022), (ii) those relying on satellite altimetry (Cheng et al. 2013; Kusche et al. 2016; Ghosh et al. 2018; Akhter et al. 2021), and (iii) those integrating tidal and inland water records (Becker et al. 2020; Feist et al. 2021). A few studies have addressed effective sea level rise (ESLR), incorporating sedimentation processes (Pethick and Orford 2013). A more recent work by Amin and Hasan (2024) introduced non-linear SLR trends across the Bangladesh coast.

Despite such efforts, inconsistencies and overestimations in SLR rates remain (Brammer 2014; Islam 2022; Steckler et al. 2022). These arise from three major issues. First, many studies neglect VLM, a key factor in accurate SLR estimation. When VLM is considered (Pethick and Orford 2013; Becker et al. 2020), regional values are often used instead of site-specific data, which may misrepresent local trends (Tay et al. 2022). Second, TG records in Bangladesh are frequently affected by inconsistencies like offsets and noise. Rigorous quality control and homogenization are crucial to ensure reliable trend estimates (Becker et al. 2019; Hague et al. 2022). Third, several studies are based on short TG records, which limits capturing long-term trends (Khan et al. 2000; Lee 2013; Akhter et al. 2021; Rose and Bhaskaran 2022). Moreover, due to the Bay of Bengal's (BoB) sensitivity to monsoonal systems (Wahid et al. 2007), accurate SLR estimation must correct for regional ocean and atmospheric signals (Zou et al. 2021).

Other complicating factors include ocean warming (Kumar et al. 2016), increased coastal salinity (Sherin et al. 2020), anthropogenic modifications like the construction of polders, which influence hydrodynamic processes (Pethick and Orford 2013; Islam 2022). Integrated analyses that combine TGs, SA, and InSAR remain limited. A comprehensive assessment of both marine (ASLR) and crustal (RSLR) components of SLR is needed (Pfeffer and Allemand 2016) to understanding the true extent of sea level dynamics. This integrated approach can inform climate adaptation planning in a region where millions of people are at risk.

This study aims to provide a robust spatiotemporal assessment of coastal sea-level variability by integrating long-term TG records, SA data and InSAR-derived VLM estimates across the entire coastal region of Bangladesh.

2. Materials and methods

2.1. Study area

The Ganges-Brahmaputra-Meghna (GBM) delta, covering approximately two-thirds of Bangladesh (Becker et al. 2020), is among the most climate-vulnerable regions globally (Syvitski et al. 2009). The coastal zone, located between 21° and 23° N latitude and 89° and 93° E longitude, is bordered by land to the north and the BoB to the south (Figure 1). Elevations range from 1 to 1.5 meters above sea level,

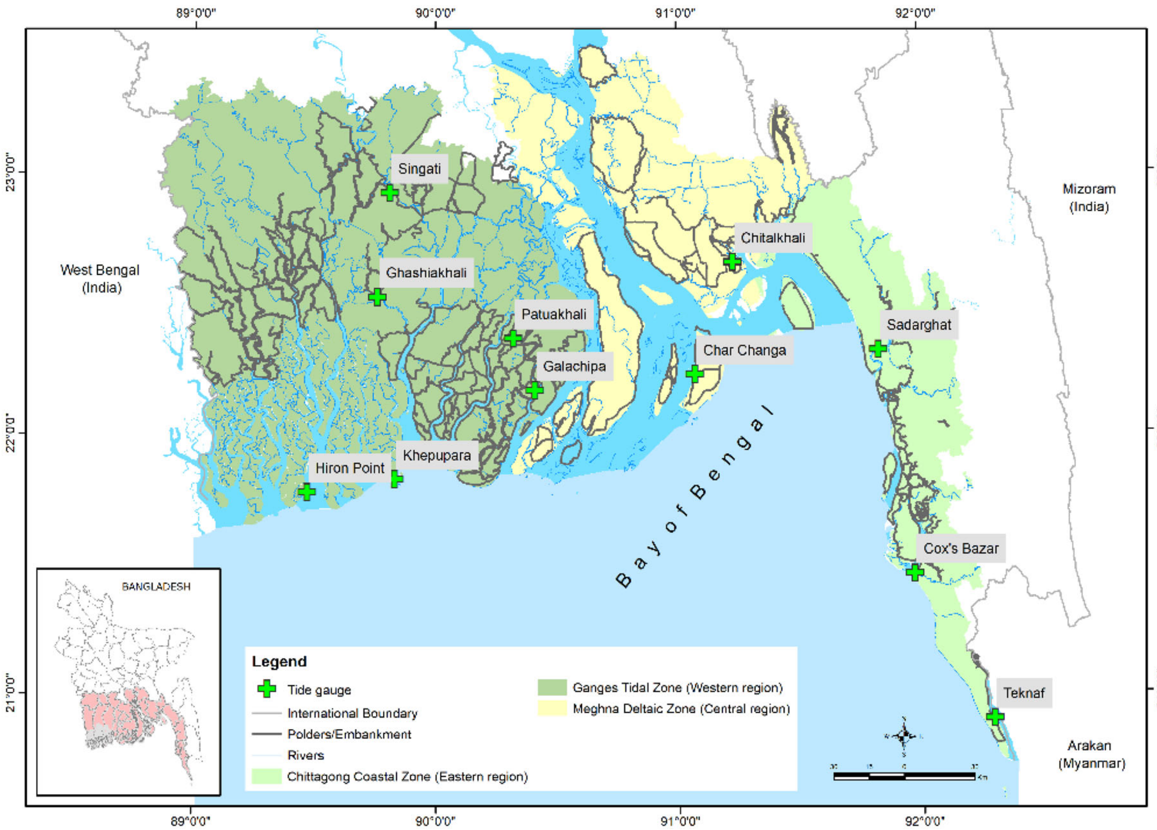

Figure 1. Map of the study area showing the locations of the 11 selected TG stations along the Bangladesh coastline.

making the region extremely susceptible to rising seas. The waters and sediments from the GBM Rivers play a crucial role in maintaining the environmental sustainability of the area.

Bangladesh's coast is typically divided into three geomorphologically distinct regions: western, central, and eastern (Islam 2004). The western zone—also known as the Ganges tidal plain—is characterized by extensive mangrove forest and represents a moribund or mature delta. The central region, dominated by the Meghna estuarine floodplain, is more dynamic due to active delta-building processes. The eastern region, or the Chittagong coastal plain, is marked by wide, flat beaches. According to the 2021 Population and Housing Census, over 43.8 million people reside in the coastal belt, with a density of 972 people/km^2 (BBS 2022).

2.2. TG data and analysis

Water level data in Bangladesh are recorded by two primary agencies: Bangladesh Water Development Board (BWDB) and Bangladesh Inland Water Transport Authority (BIWTA). While BWDB operates approximately 127 tidal and 18 non-tidal coastal stations, BIWTA manages 38 stations (Amin and Hasan 2024). This study initially considered all BIWTA-operated stations. Water levels recorded by BIWTA are referenced to the local mean sea level (MSL) datum. Regarding the geographical distribution, the stations are mostly concentrated in the southwestern coastal region (http://biwta.port-log.net/live/Map.php). A completeness index (CI) was calculated following Fenoglio-Marc et al. (2012), and stations were selected based on two criteria: (i) geographical coverage of the coastal region and (ii) CI $\geq$ 90%. 11 stations met these criteria (Figure 1). Hourly water level data were collected for the period 1977-2023. Nine stations provided a 47-year continuous dataset (1977–2023); one had 45 years (1979–2023), and another 43 years (1982–2023) (Supplementary Table S1). After 2019, most stations shifted to 5-minute recording intervals.

Initial checks were performed to detect offsets, outliers, non-stationary patterns, and data gaps. Outliers were removed using the Isolation Forest (IForest) algorithm with a contamination value of 0.1

(Liu et al. 2008; Zhao et al. 2019). Consistency was verified by comparing cleaned TG data with the Permanent Service for Mean Sea Level (PSMSL) database. Only five stations—Char Changa, Cox's Bazar, Hiron Point, Khepupara, and Sadarghat—were available in the PSMSL archive. High correlations (0.92–0.99, $p < 0.01$) were observed at five matching stations.

Abrupt changes and inhomogeneities were detected using the RHtests (v4) algorithm (Wang et al. 2007; Wang 2008), which was adapted in a Python environment. Although originally developed for precipitation and temperature adjustments, RHtests has also been used for TG data correction (Hague et al. 2022). Quantile-matching (QM) adjustments were used to correct offsets and distributional shifts (Figure 2).

Then missing data was interpolated using cubic spline interpolation (He et al. 2014), which has proven effective for reducing error margins for time series tidal records (Jiang et al. 2018). Stationarity was evaluated using the Augmented Dickey-Fuller (ADF) test (Cheung and Lai 1995) to verify that statistical properties of TG records (e.g. mean, variance) remain constant over time. Autocorrelation (ACF) and partial autocorrelation (PACF) analyses confirmed the statistical reliability of the cleaned dataset.

The TG records were then corrected for ocean tides. Harmonic tidal analysis was conducted to isolate and remove high-frequency tidal constituents, as well as ensure that long-term sea level trends are not biased by short-term fluctuations. Without nodal correction, mean sea level estimation can be biased (due to decadal variations), particularly in shallow water areas where friction plays a significant role (Zou et al. 2021). An 18.61-year nodal tide correction was applied to mitigate biases in decadal variability.

Regional sea levels can be influenced by atmospheric and oceanic circulation changes (Han et al. 2010). Since the study area experiences pronounced atmospheric pressure variations due to monsoonal systems (Wahid et al. 2007), the inverted barometric (IB) effect was corrected using monthly mean sea surface pressure from the NCEP/NCAR reanalysis dataset (Dickman 1988). The local mean atmospheric pressure was computed for each station using bilinear interpolation. For the BoB region, surface gravity was set to $9.84\,\mathrm{m/s^2}$ (https://www.sensorsone.com/local-gravity-calculator/), and ocean water density was assumed to be $1020\,\mathrm{kg/m^3}$, resulting in $1/\rho g = 99.71 \times 10^{-6}$ m/Pa (La Violette 1967). Figure 3 illustrates raw and corrected data for Patuakhali TG site.

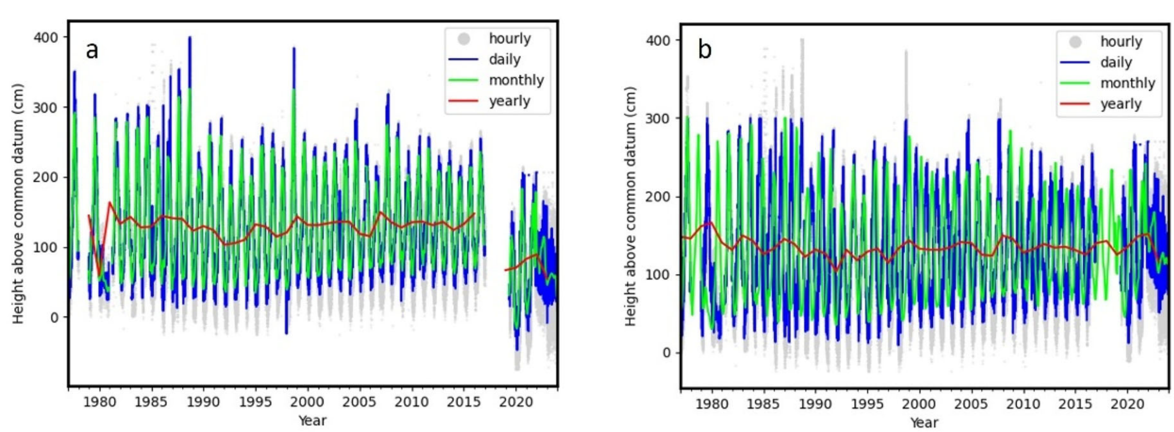

Figure 2. Data processing at TGs. This figure shows (a) outlier removed and (b) QM-adjusted TG records for the Singati site.

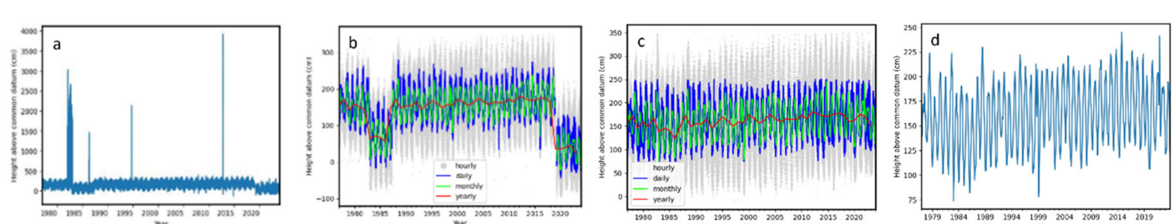

Figure 3. TG records for the Patuakhali station showing the data processing steps: (a) raw observations, (b) outlier-removed data with visible offsets, (c) homogenised time series, and (d) final dataset after ocean signal and atmospheric pressure corrections.

Daily TG data were aggregated to monthly, annual, and decadal time scales, from which monthly, decadal and annual RSRL were estimated. Piecewise linear regressions were employed to detect decadal trends, whereas linear trends were used for annual series. Incomplete decadal records (e.g. 1977–1979, 2021–2023) were excluded. The monthly analysis represented the mean trend. The tidal range (TR), defined as the difference between daily low and high tides, was also computed. To assess uncertainty in the estimated trends, the standard error for the slope was calculated. This was done by evaluating the differences between observed and predicted values, considering the number of data points and the spread of the predictor variable.

2.3. Altimetric data and analysis

Multi-temporal sea surface height anomaly (SSHA) data for the BoB were acquired using the EarthAccess toolbox (https://github.com/nsidc/earthaccess). SSHA values provided height anomalies above a reference mean sea surface on a 1/6° grid at five-day intervals. Data points within a 1/4° radius around each TG site were extracted and resampled to monthly intervals, taking the mean of the available time points to maintain consistency with the monthly TG records. The annual rate was then determined using linear regression. To assess decadal trends, the dataset was segmented into decadal intervals and analyzed. Additionally, monthly variability was examined by grouping data according to monthly distributions.

2.4. Interferometric synthetic aperture radar (InSAR)

Single look complex (SLC) Sentinel-1 synthetic aperture radar (SAR) data in interferometric wide (IW) mode with vertical-vertical (VV) polarisation, from April 2014 to December 2024, was used to estimate VLM at each TG site. A total of 3490 scenes were obtained from the Alaska Satellite Facility (ASF) (https://search.asf.alaska.edu/). Only highly coherent scenes from ascending orbits during dry winter months (December-February) were selected to ensure optimal interferometric conditions (Higgins et al. 2014).

Data were processed using the pyGMTSAR library, which facilitates the use of the GMTSAR InSAR toolbox. Topographic corrections were conducted using a Shuttle Radar Topographic Mission (SRTM) digital elevation model (DEM). For each TG site, interferometric pairs were formed under constraints: a perpendicular baseline <150 m and a temporal baseline <60 days. Most optimal pairs had 12-day intervals. A relatively low correlation threshold of 0.15 was used due to low coherence in flat, vegetated areas.

Interferograms were unwrapped and detrended to eliminate large-scale biases. A Gaussian filter was applied to remove effects from solid Earth tides and the ionosphere. Vertical displacement was estimated using coherence-weighted least squares and converted from phase (rad) to displacement (mm). VLM was computed using the small baseline subset (SBAS) method for a 0.09-degree radius (approximately 10 km) surrounding each TG site (coordinates were from BIWTA). The vertical displacements were used to determine VLM velocity *via* linear regression.

3. Results

3.1. Seasonal and decadal variability in sea level

The analysis of TG data revealed pronounced seasonal patterns in sea level across the Bangladesh coast. Sea levels typically peaked in April and reached their lowest levels in September. This seasonal variation was particularly strong at stations such as Cox's Bazar, Sadarghat, and Patuakhali, whereas relatively muted fluctuations were observed at Hiron Point and Ghashiakhali. Figure 4a, b illustrates these seasonal dynamics for Hiron Point, while Supplementary Figures S1–S2 present comparable trends across all TG stations and SA data.

Decadal trends showed substantial variation over time. In the 1980s, relatively high sea level trends were recorded at all TG sites, ranging from 0.12 ± 24.36 mm/year to 90.24 ± 12.35 mm/year (Table 1).

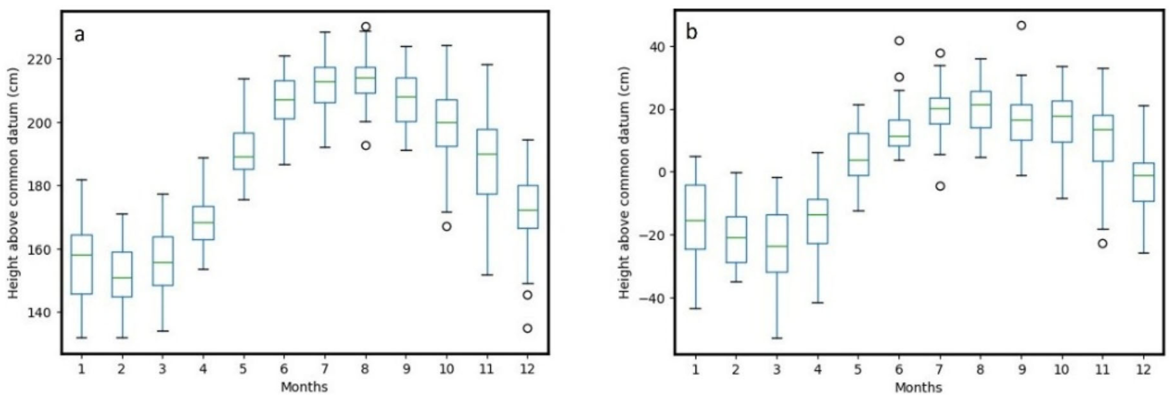

Figure 4. Monthly SLR variations at Hiron Point based on (a) TG observations and (b) SA data.

Table 1. Decadal SLR trends (mm/year) derived from TG records.

TGs	1980–1989	1990–1999	2000–2009	2010–2019
Char Changa	24.42 ± 10.78	21.14 ± 12.15	12.50 ± 10.66	10.66 ± 10.40
Chitalkhali	39.70 ± 16.97	40.22 ± 19.70	31.19 ± 19.70	−16.69 ± 16.28
Cox's Bazar	10.12 ± 8.85	−3.90 ± 9.23	15.96 ± 8.87	−14.50 ± 7.95
Galachipa	26.21 ± 9.70	−6.18 ± 9.78	3.30 ± 9.81	−11.80 ± 9.26
Ghashiakhali	90.24 ± 12.35	−7.03 ± 10.21	−0.5 ± 9.73	69.27 ± 11.25
Hiron Point	11.59 ± 8.29	3.16 ± 8.07	−0.53 ± 7.62	12.06 ± 6.95
Khepupara	14.02 ± 8.88	10.10 ± 10.74	−8.53 ± 9.00	−22.18 ± 7.28
Patuakhali	3.46 ± 11.77	8.40 ± 10.79	0.81 ± 10.17	−1.20 ± 10.74
Sadarghat	31.55 ± 11.56	3.02 ± 11.05	−8.39 ± 10.53	31.86 ± 9.87
Singati	0.12 ± 24.35	−5.43 ± 21.25	7.93 ± 19.87	−1.83 ± 16.16
Teknaf	53.08 ± 17.80	11.83 ± 8.74	−20.40 ± 9.09	−17.93 ± 6.98

Table 2. RSLR rates (mm/year) based on homogenised TG data corrected for ocean tide and IB effects.

TGs	Period	Homogenised	Ocean-tide correction	Ocean-tide + IB corrections
Char Changa	1979–2023	9.88 ± 1.12	9.82 ± 1.25	9.87 ± 1.33
Chitalkhali	1978–2023	14.78 ± 1.82	15.08 ± 2.14	15.09 ± 2.22
Cox's Bazar	1977–2023	3.42 ± 0.90	3.67 ± 1.66	3.70 ± 1.78
Galachipa	1977–2023	8.00 ± 0.94	8.32 ± 1.52	8.41 ± 1.48
Ghashiakhali	1977–2023	22.38 ± 1.08	22.39 ± 1.10	22.47 ± 1.11
Hiron Point	1977–2023	4.01 ± 0.75	3.75 ± 0.33	3.86 ± 0.35
Khepupara	1977–2023	−4.65 ± 0.89	−5.00 ± 1.17	−4.93 ± 1.28
Patuakhali	1977–2023	4.96 ± 1.05	5.06 ± 2.56	5.14 ± 2.39
Sadarghat	1977–2023	3.45 ± 1.03	3.18 ± 1.74	3.22 ± 1.60
Singati	1977–2023	2.04 ± 1.99	2.07 ± 2.92	2.13 ± 2.80
Teknaf	1982–2023	−9.52 ± 1.05	−9.55 ± 2.00	−9.48 ± 2.15

However, a declining trend in SLR was evident in the subsequent decades. SA data (Supplementary Table S2) corroborated this pattern, with only Cox's Bazar showing a decrease during the 2000–2009 period, and eight out of eleven stations registering declining trends during 2010–2019. Basin-wide analysis for the BoB based on SA showed a declining progression of decadal rates, from 8.67 ± 2.65 mm/year (1990–1999) to 2.68 ± 1.32 mm/year (2000–2009), and 1.57 ± 1.33 mm/year (2010–2019).

3.2. Relative and absolute sea level trends

Table 2 summarizes the estimated rates of RSLR at the 11 TG sites. Ocean tide corrections impacted SLR estimates by 0.02 to 0.4 mm/year, with the change observed at Khepupara (0.36 mm/year). After applying corrections for both ocean tide and the IB effect, the long-term RSLR rate at Khepupara was −4.93 mm/year over the 1977–2023 period. Similarly, Hiron Point exhibited the largest IB correction effect of 0.12 mm/year, amounting to about 3% of its corrected RSLR rate (4.00 mm/year). These adjustments underscore the importance of applying both tidal and atmospheric corrections, even for long-term records.

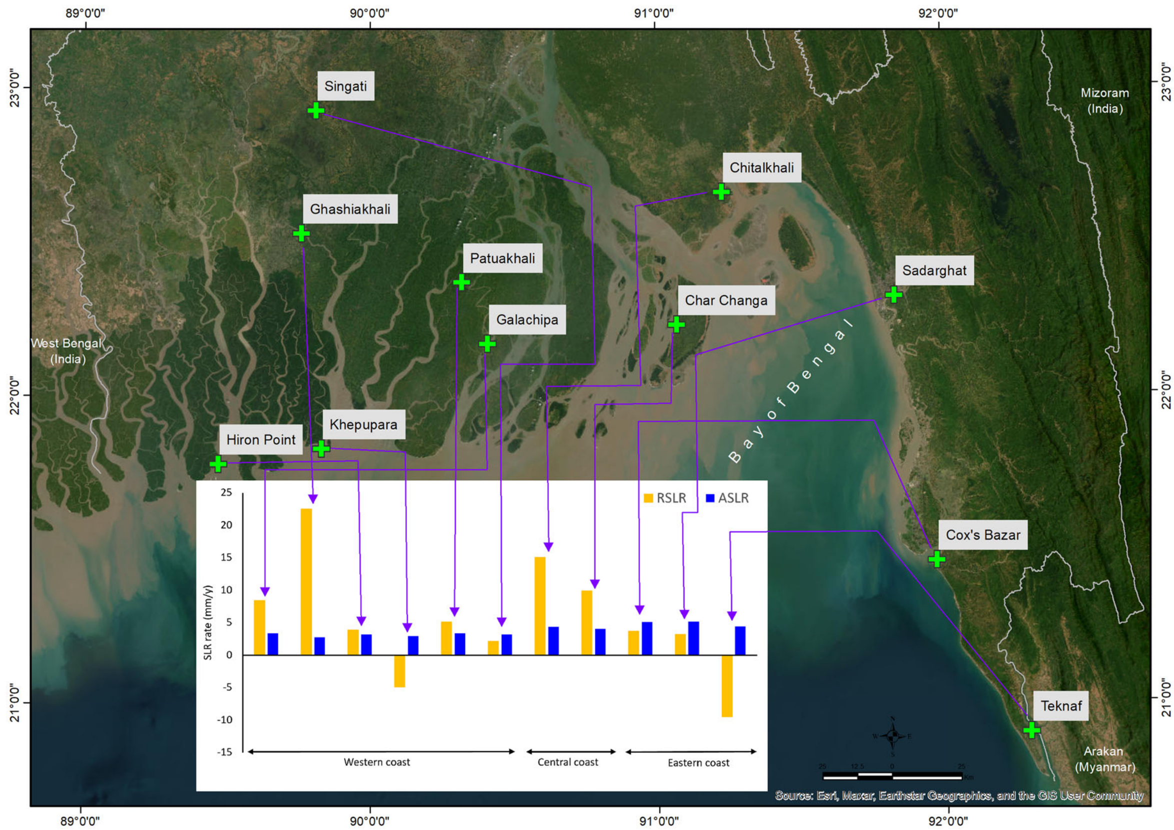

Figure 5. Spatial distribution of annual RSLR and ASLR rates across coastal Bangladesh.

Table 3. InSAR-derived VLM trend at TGs.

TG	Vertical land motion rate (mm/y)
Char Changa	−8.70 ± 0.23
Chitalkhali	−9.38 ± 0.33
Cox's Bazar	0.85 ± 0.11
Galachipa	−3.22 ± 0.06
Ghashiakhali	−19.46 ± 0.31
Hiron Point	3.68 ± 0.46
Khepupara	11.78 ± 0.12
Patuakhali	−4.43 ± 0.14
Sadarghat	4.64 ± 0.10
Singati	0.76 ± 0.04
Teknaf	14.28 ± 0.24

The spatial distribution of annual RSLR and ASLR rates is presented in Figure 5. Two TG sites—Khepupara and Teknaf—exhibited negative RSLR trends, whereas all other stations showed positive ASLR rates when estimated from SA. Overall, the mean annual RSLR rate derived from TG records was 5.40 mm/year, while the ASLR rate estimated from SA was 4.94 mm/year across the BoB. This general agreement in magnitude, despite methodological differences, highlights the effectiveness of cross-platform validation in sea level research.

3.3. VLM-adjusted SLR

VLM trends derived from InSAR data are summarized in Table 3, with sample displacement trends for three representative TG sites shown in Figure 6a–c. The analysis revealed land subsidence at five TG stations and uplift at six, indicating spatial heterogeneity in land deformation along the coast. Such variability in VLM has significant implications for local RSLR, and must be accounted for when interpreting long-term sea level trends.

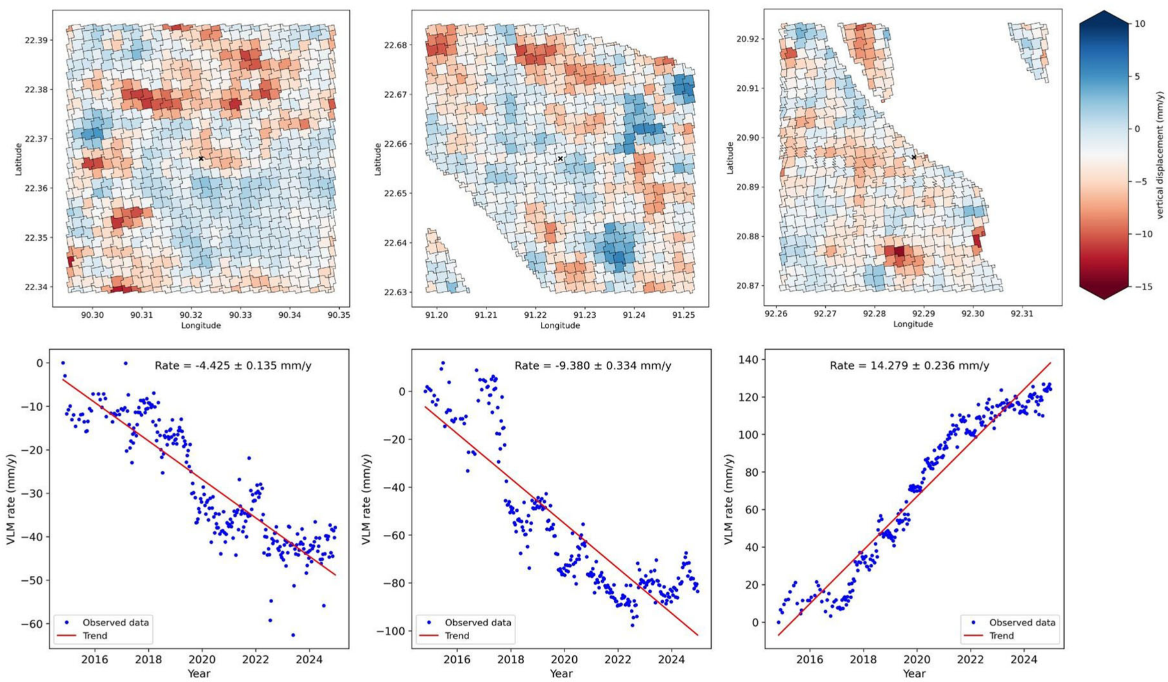

Figure 6. InSAR-derived VLM trends at three representative TG stations: (a) Patuakhali (western coast), (b) Chitalkhali (central coast), and (c) Teknaf (eastern coast). For some stations, InSAR coordinates correspond to a nearby pixel (~500 m from the TG location) due to low coherence at the exact TG site. The symbol '×' denotes the TG location.

Figure 7 shows the spatial distribution of VLM-adjusted ASLR, which incorporates TG measurements corrected using InSAR-derived VLM data. All TG stations exhibited positive ASLR rates after VLM adjustment. However, the magnitude varied across sites due to differences in vertical displacement. The highest VLM-adjusted ASLR rates were observed between 91.0° and 92.0°E longitude. On average, the VLM-adjusted ASLR across the study area was 4.58 mm/year, slightly lower than the uncorrected RSLR but closely aligned with the SA-derived ASLR value of 4.94 mm/year.

3.4. Consistency across methods and uncertainty analysis

To evaluate the consistency of different sea level estimation methods, this study analyzed overlapping records from TG, SA, and VLM-adjusted TG data (TG+InSAR) for the period 2014–2023. As shown in Figure 8, SLR estimates from TG+InSAR and SA agreed at 9 out of 11 stations, even when uncertainties were accounted for. A relative sensitivity analysis indicated that tidal signal variability contributed a median of 21.51% to the overall SLR variability at TG sites.

Further assessment of time series agreement was conducted using cross-correlation analysis between TG+InSAR and SA records, accounting for potential time lags (0 to 44 days). The analysis yielded a root mean squared error (RMSE) of 41.72 cm, a root mean square of the differences (RMSD) of 41.29 cm, and a coefficient of determination (R^2) of 0.33. Despite these relatively large error margins, the *p*-values ranged from $1e^{-13}$ to $1e^{-2}$ at a 95% confidence level, indicating that the correlations were statistically significant, albeit affected by temporal and spatial variability in the datasets.

4. Discussion

Understanding the complexity of sea level dynamics requires not only accurate measurement but also careful correction of geophysical and non-geophysical influences. This study integrated TG records, SA, and InSAR data to assess SLR across coastal Bangladesh, one of the world's most climate-vulnerable regions.

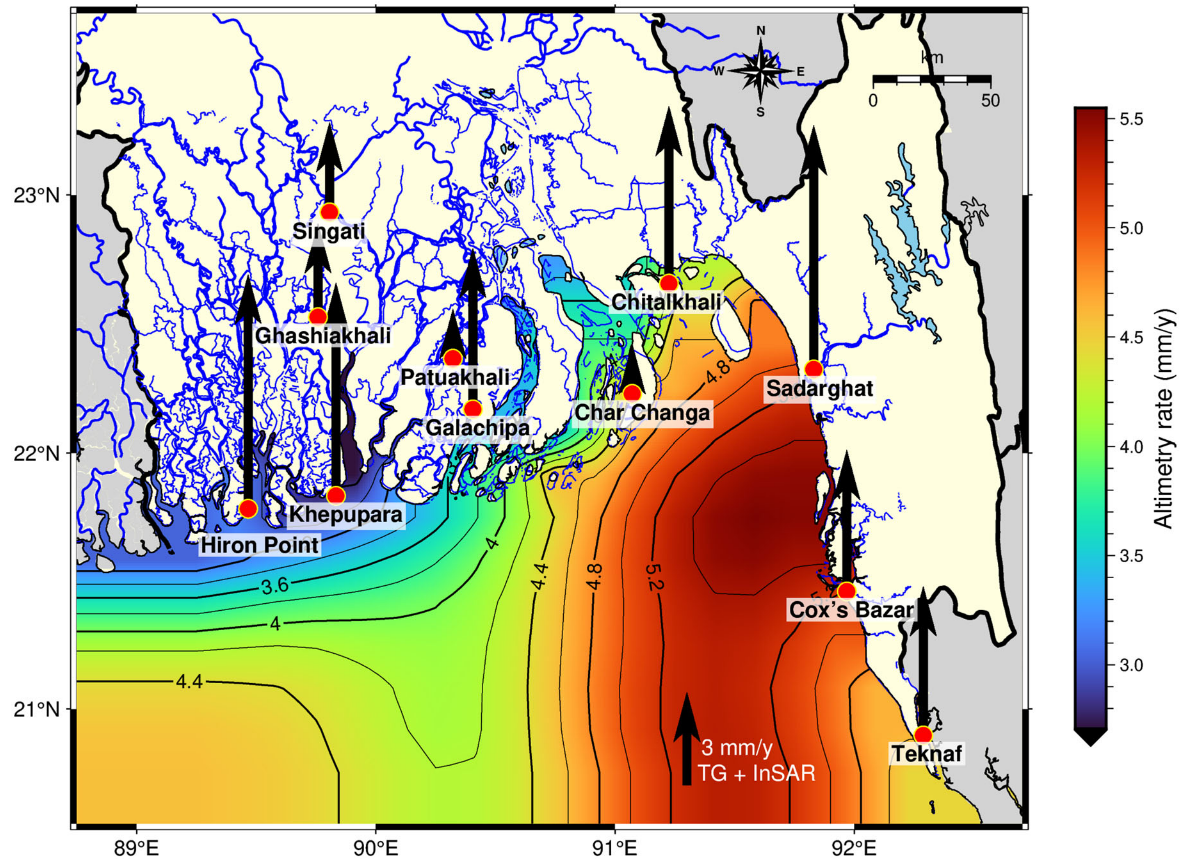

Figure 7. The rate of ASLR from SA and TG+InSAR estimates. Vertical quivers represent VLM-adjusted ASLR rates at TG locations, superimposed on the gridded SA data. Contours indicate ASLR rates (in mm/year) with an interval of 0.4 mm/year.

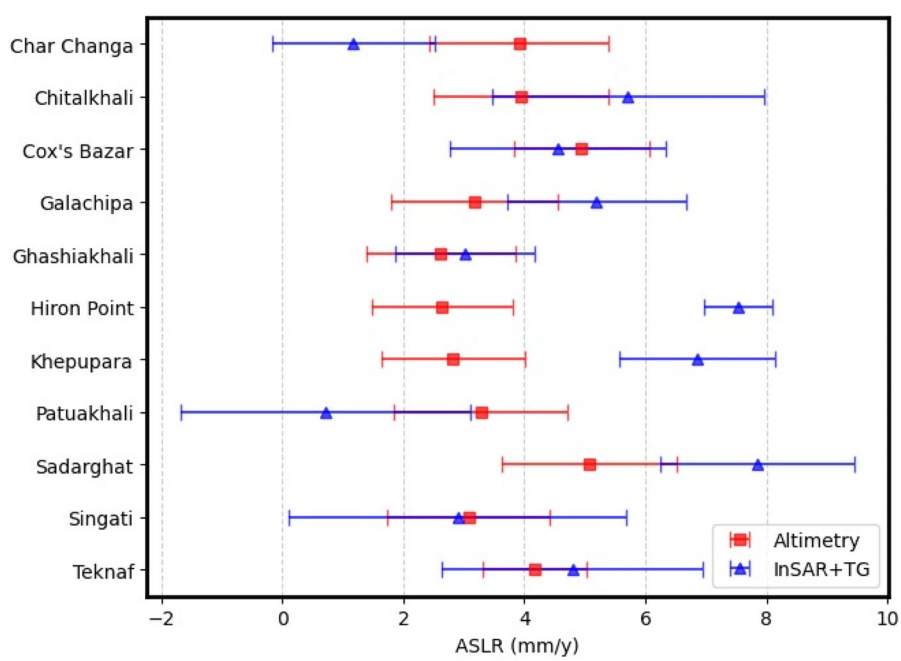

Figure 8. Comparison of ASLR estimates derived from TG records corrected with InSAR-based VLM and those obtained from SA across coastal Bangladesh.

The corrected TG records showed that most stations exhibited increasing RSLR trends, except for Khepupara and Teknaf, where negative rates persisted even after applying corrections such as IB, tidal constituents, and VLM. These findings highlight the importance of applying such corrections to derive physically meaningful sea level estimates (Han et al. 2010; Zou et al. 2021). As Wahid et al. (2007) noted, a 15 mb change in atmospheric pressure could result in a sea level change up to 15 cm along the Bangladesh coast, emphasising the significance of incorporating atmospheric influences (Adebisi et al. 2021).

Monthly analyses revealed a consistent seasonal cycle in sea level, with peak levels observed in April and the lowest levels in September, a pattern that agrees with Ghosh et al. (2018). This seasonal variation is likely linked to the semi-diurnal lunar tide (M2), whose amplitude has reportedly changed since 1993 (Tazkia et al. 2017; Rose and Bhaskaran 2022). In the absence of comparable high-resolution monthly studies in this region, our results offer new insights into seasonal sea level variability and provide a valuable reference for future research.

Decadal analyses revealed non-monotonic trends, with alternating periods of rising and falling sea levels—a characteristic that aligns with earlier observations by Srinivasu et al. (2017). These fluctuations suggest the influence of both climatic factors (e.g. ocean-atmosphere interactions; Becker et al. 2019) and non-climatic processes (e.g. land use change, polder construction) (Pethick and Orford 2013). The observed variations in high tide, low tide, and TR, as shown in Supplementary Table S3, further substantiate the spatial and temporal diversity in sea level dynamics across the region. In the western region, for example, high tide trends ranged from $+30.78 \pm 1.02$ mm/year (Ghashiakhali) to -4.87 ± 1.20 mm/year (Khepupara), while the eastern stations showed mixed results, including a negative trend at Teknaf. The central region displayed relatively uniform trends (>10 mm/year). Given that multiple factors influence tides in Bangladesh and other coastal areas (Ericson et al. 2006; Cao et al. 2020), further investigation is warranted.

The analysis for TR trends revealed amplification at seven of the eleven TG sites, though the magnitude of change varied. While Pethick and Orford (2013) linked tidal amplification to heightened RSLR variability in the western coast, this study showed more nuanced perspective. Three western TGs—Patuakhali, Khepupara, and Galachipa—revealed negative TR trends, while others in the same zone exhibited positive ones. In contrast, central region stations showed consistent TR amplification, while two of the three eastern stations also experienced significant increase. These results align partly with Pickering et al. (2017), who demonstrated the regional dependency of tidal amplification in deltas. Overall, tidal amplification was most pronounced in the eastern region (6.23 mm/y), followed by the western (2.4 mm/y) and central (1.49 mm/y) zones. This suggests that regional drivers such as seabed topography and frictional effects play a substantial role in shaping local tidal dynamics (Khan et al. 2020).

The impact of anthropogenic modifications also varies across regions. For instance, polders are predominantly found in the western region, while embankments and flood control infrastructure are commonly found in the central and eastern zones (Auerbach et al. 2015; Adnan et al. 2020). These structural interventions, in combination with natural factors such as sediment supply and tectonic activity, influence both tidal propagation and sea level variability. The western region, particularly, has been affected by upstream freshwater withdrawal, reducing sediment delivery and altering hydrodynamic processes (Sarwar 2013).

When examining long-term trends, the results revealed spatial variability in annual RSLR, with rates ranging from -9.52 ± 1.05 mm/year at Teknaf to $+22.38 \pm 1.08$ mm/year at Ghashiakhali. These findings are consistent with previous studies (e.g. Sarwar 2013; Kusche et al. 2016; Becker et al. 2020; Islam 2022). For instance, Islam (2022) reported SLR rates of 2.1–25 mm/year at different coastal stations, while Sarwar (2013) found −8.33 mm/year at Teknaf and 38.88 mm/year in the Lower Meghna region. In contrast, Mörner (2010) claimed sea level stability in western Bangladesh, which the findings of the present study do not support. Discrepancies between studies may be due to differing record lengths used, data quality, and methods of analysis (Feist et al. 2021). The ASLR rate estimated from SA (4.94 mm/year) is in line with previous altimetric studies by Kusche et al. (2016), who reported a rate of 6.1 mm/year for 2002–2014. The observed difference of 0.46 mm/year between TG- and SA-based could be attributed to the differences in spatial coverage, measurement resolution, and land-sea interface complexities, especially given the number of islands and narrow channels along the Bangladesh coast (Vinogradov and Ponte 2010; Adebisi et al. 2021). Moreover, altimetric precision can be degraded in near-shore zones due to hardware limitations and wave interference (Zhou et al. 2022).

VLM is a crucial factor influencing sea level estimates, yet site-specific VLM data are often lacking. Many previous studies have used generalized regional values or proxy techniques such as ALT-TG (e.g. Carvalho and Wang 2019; Becker et al. 2020), which can underestimate local conditions (Watson 2019; Woodworth et al. 2019). By incorporating InSAR-derived VLM at each TG site, this study offers a more accurate representation of ASLR. The VLM estimates in this study generally align with earlier findings by Syvitski et al. (2009) and Higgins et al. (2014), though they diverge from GNSS-based estimates reported by Reitz et al. (2015), who found subsidence rates of 3–8 mm/year from 2003 to 2013.

Notably, this study also observed uplift at six TG sites (Table 3), a relatively underreported phenomenon. At Hiron Point, for example, the uplift rate of 3.67 mm/year corresponds closely with the 3.56 mm/year reported by Ostanciaux et al. (2012) for the western Ganges delta. Geological core analysis by Haque et al. (2022) further supports this observation. Conversely, subsidence was detected in several stations in the western and central regions, consistent with studies by Grall et al. (2018) and Singh (2002).

The VLM-adjusted ASLR rates derived in this study ranged from 7.86 ± 1.60 mm/year to 0.716 ± 2.398 mm/year, with an average of 4.58 mm/year across the coast (Figure 7). This is slightly lower than the SA-based rate (4.94 mm/year), but the similarity underscores the reliability of the integrated TG+InSAR approach. Analysis of coastal SA grids produced an ASLR rate of 4.59 mm/year (Figure 9), nearly identical to the TG+InSAR estimate. When compared to the GMSL rate of 3.3 mm/year, the observed RSLR in Bangladesh is approximately 2.1 mm/year higher indicating the combined effects of rising ocean levels and local land deformation (Syvitski et al. 2009).

This study also examined the consistency between ASLR rates derived from SA and those obtained *via* TG+InSAR. The findings confirmed agreement in nine of the eleven stations, a result that aligns with earlier work by Tsimplis and Woodworth (1994), who explored consistency between coastal altimetry and tide gauge data in the Mediterranean. Notably, VLM accounted for a median of 22% of the observed SLR rate in Bangladesh, highlighting the importance of localized vertical land processes—particularly those driven by anthropogenic activity (e.g. groundwater extraction, infrastructure loading) (Feist et al. 2021; Steckler et al. 2022).

Together, these findings emphasise that SLR along the Bangladesh coast is shaped by the interaction of global ocean dynamics, regional atmospheric variability, and local geophysical processes. A comprehensive understanding of these intertwined factors is essential for developing effective adaptation

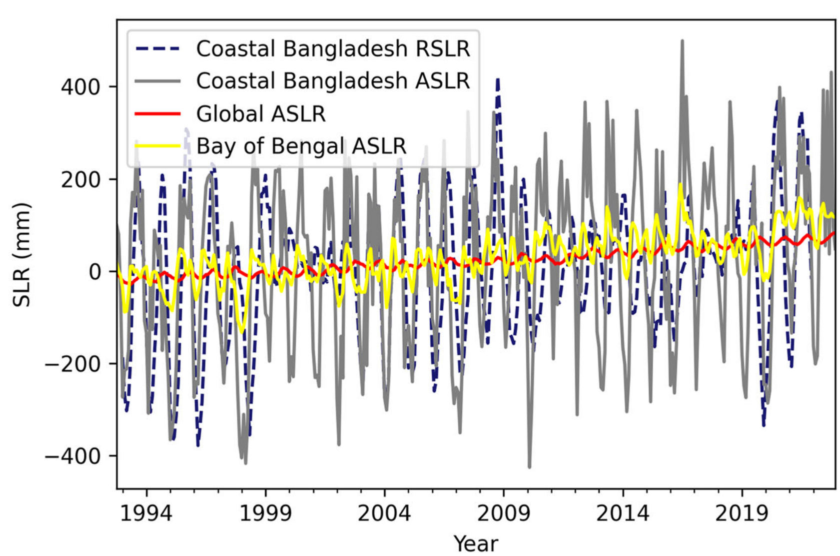

Figure 9. Comparison of the SLR rates between the coastal Bangladesh and the GMSL. The Bay of Bengal region is defined by the longitude range [89°, 92.5°E] and latitude range [20°, 23.5°N], while the coastal region includes areas within 50 km of the shoreline.

strategies and making informed investment decisions in this densely populated and environmentally sensitive region.

5. Conclusion

This study aimed to estimate both relative and absolute SLR rates along the Bangladesh coast, one of the world's most climate-vulnerable and densely populated low-lying regions. By integrating long-term records from TGs, SA, and VLM data derived from InSAR, this study provided a comprehensive assessment of sea level dynamics across the entire coastal zone.

The results demonstrate considerable temporal variability in sea level, with a strong seasonal cycle characterised by peak sea levels in April and lows in September, as well as distinct decadal patterns showing alternating phases of rising and falling sea levels. Spatial variability was equally evident, with SLR rates varying significantly among the three coastal zones—higher in the east (4.73 mm/year), moderate in the west (3.66 mm/year), and lowest in the central region (2.4 mm/year). These findings underscored the importance of localised sea level assessments, especially in deltaic environments where complex hydro-morphological processes interact with climate-induced changes.

Crucially, the incorporation of VLM data corrected for local land deformation, allowing for more accurate ASLR estimates. The VLM-adjusted ASLR rate, averaging 4.58 mm/year, closely matched the SA-derived ASLR rate of 4.94 mm/year. This alignment validates the integrated approach used in this study and demonstrates the importance of correcting for vertical land motion, particularly in subsiding or uplifting regions. Furthermore, the difference between the observed RSLR and GMSL rate—approximately 2.1 mm/year—highlights the additive effect of land movement on perceived SLR along the coast.

By capturing these spatial and temporal complexities, the study contributes to a more nuanced understanding of coastal vulnerability in Bangladesh. The integrated methodological framework also helps address previous limitations in SLR estimation, such as inconsistent station selection, short record lengths, and inadequate correction for non-geophysical influences.

Nevertheless, several limitations remain. Measurement noise, datum offsets, and uncertainties in VLM estimation—particularly distinguishing between tectonic uplift and sediment compaction—could introduce errors. The use of C-band InSAR, while effective, is limited by its inability to penetrate dense vegetation. Further missions such as NASA-ISRO's NISAR, which will utilise L-band radar, are expected to provide improved estimates. Additionally, the uneven distribution of long-term TG records across regions may influence the spatial representativeness of trends.

However, the novelty of this study lies in its integration of multi-source datasets—TGs, SA, and InSAR—to derive site-specific, VLM-adjusted ASLR estimates for the entire Bangladesh coastline. This is the first study of its kind in the region to offer such a comprehensive, corrected, and cross-validated assessment. The findings not only advance scientific understanding of sea level dynamics in deltaic environments but also provide essential inputs for climate adaptation planning, coastal infrastructure development, and disaster risk reduction in a region acutely exposed to the consequences of sea level rise.

Authors' contributions

CRediT: **Ashraf Dewan**: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing; **Hardik Jain**: Formal analysis, Methodology, Software, Visualization, Writing – original draft, Writing – review & editing; **Alamgir Hossain**: Data curation, Investigation, Resources, Validation, Writing – review & editing; **Mohammed Sarfaraz Gani Adnan**: Funding acquisition, Investigation, Project administration, Resources, Writing – review & editing; **Redowan Mahmud**: Conceptualization, Investigation, Resources, Validation, Writing – review & editing.

Disclosure statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Funding

The authors would like to acknowledge the School of Earth and Planetary Sciences at Curtin University for providing research support grants. MSGA received support from the Leverhulme Trust through an Early Career Fellowship [grant reference ECF-2023-074].

ORCID

Ashraf Dewan http://orcid.org/0000-0001-5594-5464
Mohammed Sarfaraz Gani Adnan http://orcid.org/0000-0002-7276-1891

Data availability statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Abdullah AYM, Masrur A, Adnan MSG, Baky M, Hassan QK, Dewan A. 2019. Spatio-temporal patterns of land use/land cover change in the Heterogeneous Coastal Region of Bangladesh between 1990 and 2017. Remote Sens. 11(7):790. doi: 10.3390/rs11070790.

Adebisi N, Balogun AL, Min TH, Tella A. 2021. Advances in estimating sea level rise: a review of tide gauge, satellite altimetry and spatial data science approaches. Ocean Coast Manag. 208:105632. doi: 10.1016/j.ocecoaman.2021.105632.

Adnan MSG, Abdullah AYM, Dewan A, Hall JW. 2020. The effects of changing land use and flood hazard on poverty in coastal Bangladesh. Land Use Policy. 99:104868. doi: 10.1016/j.landusepol.2020.104868.

Adshead D, Paszkowski A, Gall SS, Peard AM, Adnan MSG, Verschuur J, Hall JW. 2024. Climate threats to coastal infrastructure and sustainable development outcomes. Nat Clim Chang. 14(4):344–352. doi: 10.1038/s41558-024-01950-2.

Akhter S, Qiao F, Wu K, Yin X, Chowdhury KMA, Chowdhury NUMK. 2021. Seasonal and long-term sea-level variations and their forcing factors in the northern Bay of Bengal: a statistical analysis. Dyn Atmos Oceans. 95:101239.

Amin MK, Hasan GJ. 2024. Linear and non-linear trends of sea level from tide gauges along the coastline of Bangladesh. Reg Stud Mar Sci. 73:103508. doi: 10.1016/j.rsma.2024.103508.

Anwar MS, Rahman K, Bhuiyan MAE, Saha R. 2022. Assessment of sea level and morphological changes along the eastern coast of Bangladesh. JMSE. 10(4):527. doi: 10.3390/jmse10040527.

Aobpaet A, Cuenca MC, Hooper A, Trisirisatayawong I. 2013. InSAR time-series analysis of land subsidence in Bangkok, Thailand. Int J Remote Sens. 34(8):2969–2982. doi: 10.1080/01431161.2012.756596.

Auerbach LW, Goodbred SL, Jr Mondal DR, Wilson CA, Ahmed KR, Roy K, Steckler MS, Small C, Gilligan JM, Ackerly BA. 2015. Flood risk of natural and embanked landscapes on the Ganges–Brahmaputra tidal delta plain. Nature Clim Change. 5(2):153–157. doi: 10.1038/nclimate2472.

BBS. 2022. Population & Housing Census 2022: Preliminary Report. Dhaka, Bangladesh: Bangladesh Bureau of Statistics (BBS). Available from: https://bbs.portal.gov.bd/sites/default/files/files/bbs.portal.gov.bd/page/b343a8b4_956b_45ca_872f_4cf9b2f1a6e0/2023-09-27-09-50-a3672cdf61961a45347ab8660a3109b6.pdf.

Becker M, Karpytchev M, Papa F. 2019. Hotspots of relative sea level rise in the tropics. In: Tropical extremes, Elsevier. pp. 203–262.

Becker M, Papa F, Karpytchev M, Delebecque C, Krien Y, Khan JU, Ballu V, Durand F, Cozannet GL, Islam AKMS, et al. 2020. Water level changes, subsidence, and sea level rise in the Ganges–Brahmaputra–Meghna delta. Proc Natl Acad Sci U S A. 117(4):1867–1876. doi: 10.1073/pnas.1912921117.

Beenstock M, Felsenstein D, Frank E, Reingewertz Y. 2015. Tide gauge location and the measurement of global sea level rise. Environ Ecol Stat. 22(1):179–206. doi: 10.1007/s10651-014-0293-4.

Bell AR, Wrathall DJ, Mueller V, Chen J, Oppenheimer M, Hauer M, Adams H, Kulp S, Clark PU, Fussell E, et al. 2021. Migration towards Bangladesh coastlines projected to increase with sea-level rise through 2100. Environ Res Lett. 16(2):024045. doi: 10.1088/1748-9326/abdc5b.

Brammer H. 2014. Bangladesh's dynamic coastal regions and sea-level rise. Clim Risk Manag. 1:51–62. doi: 10.1016/j.crm.2013.10.001.

Bruni S, Fenoglio L, Raicich F, Zerbini S. 2022. On the consistency of coastal sea-level measurements in the Mediterranean Sea from tide gauges and satellite radar altimetry. J Geod. 96(6):41. doi: 10.1007/s00190-022-01626-9.

Cao Y, Zhang W, Zhu Y, Ji X, Xu Y, Wu Y, Hoitink AJF. 2020. Impact of trends in river discharge and ocean tides on water level dynamics in the Pearl River Delta. Coast Eng. 157:103634. doi: 10.1016/j.coastaleng.2020.103634.
Cartwright D. 2000.Tides: a scientific history. Cambridge University Press.
Carvalho KS, Wang S. 2019. Characterizing the Indian Ocean sea level changes and potential coastal flooding impacts under global warming. J Hydrol. 569:373–386. doi: 10.1016/j.jhydrol.2018.11.072.
Cheng X, Xie SP, McCreary JP, Qi Y, Du Y. 2013. Intraseasonal variability of sea surface height in the Bay of Bengal. JGR Oceans. 118(2):816–830. doi: 10.1002/jgrc.20075.
Cheung YW, Lai KS. 1995. Lag order and critical values of the augmented Dickey–Fuller test. J Bus Econ Stat. 13(3):277–280. doi: 10.2307/1392187.
Church J, Wilson S, Woodworth P, Aarup T. 2007. Understanding sea level rise and variability. EoS Trans. 88(4): 43–43. doi: 10.1029/2007EO040008.
Climate Change Cell (CCC). 2016. Assessment of sea level rise in Bangladesh coast through trend analysis. Dhaka (Bangladesh): Department of Environment, Ministry of Environment and Forests.
Dickman SR. 1988. Theoretical investigation of the oceanic inverted barometer response. J Geophys Res. 93(B12): 14941–14946. doi: 10.1029/JB093iB12p14941.
Ericson JP, Vörösmarty CJ, Dingman SL, Ward LG, Meybeck M. 2006. Effective sea-level rise and deltas: causes of change and human dimension implications. Glob Planet Change. 50:63–82.
Feist SE, Hoque MA, Islam MA, Ahmed KM, Fowler M. 2021. Recent trends in inland water level change in coastal Bangladesh–implications of sea level rise in low-lying deltas. Glob Planet Change. 206:103639. doi: 10.1016/j.gloplacha.2021.103639.
Fenoglio-Marc L, Schöne T, Illigner J, Becker M, Manurung P, Khafid. 2012. Sea level change and vertical motion from satellite altimetry, tide gauges and GPS in the Indonesian region. Mar Geod. 35(sup1):137–150. doi: 10.1080/01490419.2012.718682.
Ghosh S, Hazra S, Nandy S, Mondal PP, Watham T, Kushwaha SPS. 2018. Trends of sea level in the Bay of Bengal using altimetry and other complementary techniques. J Spat Sci. 63(1):49–62. doi: 10.1080/14498596.2017.1348309.
Grall C, Steckler MS, Pickering JL, Goodbred S, Sincavage R, Paola C, Akhter SH, Spiess V. 2018. A base-level stratigraphic approach to determining Holocene subsidence of the Ganges–Meghna–Brahmaputra Delta plain. Earth Planet Sci Lett. 499:23–36. doi: 10.1016/j.epsl.2018.07.008.
Hagen R, Plüß A, Jänicke L, Freund J, Jensen J, Kösters F. 2021. A combined modeling and measurement approach to assess the nodal tide modulation in the North Sea. J Geophys Res Oceans. 126: e2020JC016364.
Hague BS, Jones DA, Trewin B, Jakob D, Murphy BF, Martin DJ, Braganza K. 2022. ANCHORS: a multi-decadal tide gauge dataset to monitor Australian relative sea level changes. Geosci Data J. 9(2):256–272. doi: 10.1002/gdj3.136.
Hamlington BD, Bellas-Manley A, Willis JK, Fournier S, Vinogradova N, Nerem RS, Piecuch CG, Thompson PR, Kopp R. 2024. The rate of global sea level rise doubled during the past three decades. Commun Earth Environ. 5(1):601. doi: 10.1038/s43247-024-01761-5.
Han W, Meehl GA, Rajagopalan B, Fasullo JT, Hu A, Lin J, Large WG, Wang J-w, Quan X-W, Trenary LL, et al. 2010. Patterns of Indian Ocean sea-level change in a warming climate. Nature Geosci. 3(8):546–550. doi: 10.1038/ngeo901.
Haodong LIU, Xiaoxing HE, Shengbo YANG, Jie WANG, Xiang LIU, Abbasi R. 2024. Feasibility analysis of utility satellite altimetry and tide gauges for vertical land motion estimation along the coastline of Australia. Acta Geodyn Geomater. 21(4):329–342.
Haque MM, Ghosh MK, Hoyanagi K. 2022. Coastal development in southwestern Bangladesh: understanding the interplay between storms and sea level rise. Prog Phys Geogr Earth Environ. 46(3):331–356. doi: 10.1177/03091333211046189.
He L, Li G, Li K, Shu Y. 2014. Estimation of regional sea level change in the Pearl River Delta from tide gauge and satellite altimetry data. Estuar Coast Shelf Sci. 141:69–77. doi: 10.1016/j.ecss.2014.02.005.
Higgins SA, Overeem I, Steckler MS, Syvitski JPM, Seeber L, Akhter SH. 2014. InSAR measurements of compaction and subsidence in the Ganges-Brahmaputra Delta, Bangladesh. JGR Earth Surface. 119(8):1768–1781. doi: 10.1002/2014JF003117.
Islam MR, editor. 2004. Where land meets the sea: a profile of the coastal zone of Bangladesh. Dhaka (Bangladesh): The University Press Limited.
Islam MS. 2022. Sea-level changes along Bangladesh coast: how much do we know about it?. In Applied geomorphology and contemporary issues. Cham (Switzerland): Springer. p. 611–633.
Jiang D, Chen H, Jin G, Lv X. 2018. Estimating smoothly varying open boundary conditions for a 3D internal tidal model with an improved independent point scheme. J Atmos Ocean Technol. 35(6):1299–1311. doi: 10.1175/JTECH-D-17-0155.1.
Karim MF, Mimura N. 2008. Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh. Glob Environ Change. 18:490–500.

Khan MJU, Durand F, Testut L, Krien Y, Islam AS. 2020. Sea level rise inducing tidal modulation along the coasts of Bengal delta. Cont Shelf Res. 211:104289. doi: 10.1016/j.csr.2020.104289.
Khan TMA, Singh OP, Rahman MS. 2000. Recent sea level and sea surface temperature trends along the Bangladesh coast in relation to the frequency of intense cyclones. Mar Geod. 23:103–116.
Kleinherenbrink M, Riva R, Frederikse T. 2018. A comparison of methods to estimate vertical land motion trends from GNSS and altimetry at tide gauge stations. Ocean Sci. 14(2):187–204. doi: 10.5194/os-14-187-2018.
Kumar PD, Paul YS, Muraleedharan KR, et al. 2016. Comparison of long-term variability of sea surface temperature in the Arabian Sea and Bay of Bengal. Reg Stud Mar Sci. 3:67–75.
Kusche J, Uebbing B, Rietbroek R, Shum CK, Khan ZH. 2016. Sea level budget in the Bay of Bengal (2002–2014) from GRACE and altimetry. JGR Oceans. 121(2):1194–1217. doi: 10.1002/2015JC011471.
La Violette PE. 1967. Temperature, salinity, and density of the world's seas: Bay of Bengal and Andaman Sea. Washington (DC): Naval Oceanographic Office. Report No. 67-88.
Lee HS. 2013. Estimation of extreme sea levels along the Bangladesh coast due to storm surge and sea level rise using EEMD and EVA. JGR Oceans. 118(9):4273–4285. doi: 10.1002/jgrc.20310.
Liu FT, Ting KM, Zhou ZH. 2008. Isolation forest. In Proceedings of the 2008 Eighth IEEE International Conference on Data Mining. IEEE. p. 413–422.
Ministry of Environment Forest and Climate Change (MoEFC). 2022. Climate change initiatives of Bangladesh achieving climate resilience. Dhaka (Bangladesh): MoEFC.
Mörner NA. 2010. Sea level changes in Bangladesh: new observational facts. Energy Environ. 21(3):235–249. doi: 10.1260/0958-305X.21.3.235.
Nicholls RJ, Cazenave A. 2010. Sea-level rise and its impact on coastal zones. Science. 328(5985):1517–1520. doi: 10.1126/science.1185782.
Ostanciaux E, Husson L, Choblet G, Robin C, Pedoja K. 2012. Present-day trends of vertical ground motion along the coastlines. Earth Sci Rev. 110(1–4):74–92. doi: 10.1016/j.earscirev.2011.10.004.
Pethick J, Orford JD. 2013. Rapid rise in effective sea-level in southwest Bangladesh: its causes and contemporary rates. Glob Planet Change. 111:237–245. doi: 10.1016/j.gloplacha.2013.09.019.
Pfeffer J, Allemand P. 2016. The key role of vertical land motions in coastal sea level variations: a global synthesis of multisatellite altimetry, tide gauge data and GPS measurements. Earth Planet Sci Lett. 439:39–47. doi: 10.1016/j.epsl.2016.01.027.
Pickering MD, Horsburgh KJ, Blundell JR, Hirschi JJ-M, Nicholls RJ, Verlaan M, Wells NC.,. 2017. The impact of future sea-level rise on the global tides. Cont Shelf Res. 142:50–68. doi: 10.1016/j.csr.2017.02.004.
Pörtner HO, Roberts DC, Masson-Delmotte V, et al. 2019. The ocean and cryosphere in a changing climate. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. p. 1155.
Qiao X, Chu T, Tissot P, Ali I, Ahmed M. 2023. Vertical land motion monitored with satellite radar altimetry and tide gauge along the Texas coastline, USA, between 1993 and 2020. Int J Appl Earth Obs Geoinf. 117:103222.
Reitz MD, Pickering JL, Goodbred SL, Paola C, Steckler MS, Seeber L, Akhter SH. 2015. Effects of tectonic deformation and sea level on river path selection: theory and application to the Ganges-Brahmaputra-Meghna River Delta. J Geophys Res Earth Surf. 120(4):671–689. doi: 10.1002/2014JF003202.
Rose L, Bhaskaran PK. 2022. Tidal variations associated with sea level changes in the Northern Bay of Bengal. Estuar Coast Shelf Sci. 272:107881. doi: 10.1016/j.ecss.2022.107881.
Sarwar MGM. 2013. Sea-level rise along the coast of Bangladesh. In: shaw R, Mallick F, Islam A, editors. Disaster risk reduction approaches in bangladesh. Tokyo (Japan): Springer. p. 55–75.
Sherin VR, Durand F, Papa F, Islam AS, Gopalakrishna VV, Khaki M, Suneel V. 2020. Recent salinity intrusion in the Bengal delta: observations and possible causes. Cont Shelf Res. 202:104142. doi: 10.1016/j.csr.2020.104142.
Singh OP. 2002. Spatial variation of sea level trend along the Bangladesh Coast. Mar Geod. 25(3):205–212. doi: 10.1080/01490410290051536.
Srinivasu U, Ravichandran M, Han W, Sivareddy S, Rahman H, Li Y, Nayak S. 2017. Causes for the reversal of North Indian Ocean decadal sea level trend in recent two decades. Clim Dyn. 49(11-12):3887–3904. doi: 10.1007/s00382-017-3551-y.
Steckler MS, Mondal DR, Akhter SH, Seeber L, Feng L, Gale J, Hill EM, Howe M. 2016. Locked and loading megathrust linked to active subduction beneath the Indo-Burman Ranges. Nature Geosci. 9(8):615–618. doi: 10.1038/ngeo2760.
Steckler MS, Oryan B, Wilson CA, Grall C, Nooner SL, Mondal DR, Akhter SH, DeWolf S, Goodbred SL. 2022. Synthesis of the distribution of subsidence of the lower Ganges-Brahmaputra Delta, Bangladesh. Earth Sci Rev. 224:103887. doi: 10.1016/j.earscirev.2021.103887.
Syvitski JPM, Kettner AJ, Overeem I, Hutton EWH, Hannon MT, Brakenridge GR, Day J, Vörösmarty C, Saito Y, Giosan L, et al. 2009. Sinking deltas due to human activities. Nature Geosci. 2(10):681–686. doi: 10.1038/ngeo629.
Tay C, Lindsey EO, Chin ST, McCaughey JW, Bekaert D, Nguyen M, Hua H, Manipon G, Karim M, Horton BP, et al. 2022. Sea-level rise from land subsidence in major coastal cities. Nat Sustain. 5(12):1049–1057. doi: 10.1038/s41893-022-00947-z.

Tazkia AR, Krien Y, Durand F, Testut L, Islam A, Papa F, Bertin X. 2017. Seasonal modulation of M2 tide in the Northern Bay of Bengal. Cont Shelf Res. 137:154–162. doi: 10.1016/j.csr.2016.12.008.

Tsimplis MN, Woodworth PL. 1994. The global distribution of the seasonal sea level cycle calculated from coastal tide gauge data. J Geophys Res. 99(C8):16031–16039. doi: 10.1029/94JC01115.

Vinogradov SV, Ponte RM. 2010. Annual cycle in coastal sea level from tide gauges and altimetry. J Geophys Res. 115(C4):C04021. doi: 10.1029/2009JC005767.

Wahid SM, Babel MS, Bhuiyan AR. 2007. Hydrologic monitoring and analysis in the Sundarbans mangrove ecosystem, Bangladesh. J Hydrol. 332(3–4):381–395. doi: 10.1016/j.jhydrol.2006.07.016.

Wang XL, Wen QH, Wu Y. 2007. Penalized maximal t test for detecting undocumented mean change in climate data series. J Appl Meteorol Climatol. 46(6):916–931. doi: 10.1175/JAM2504.1.

Wang XL. 2008. Accounting for autocorrelation in detecting mean shifts in climate data series using the penalized maximal t or F test. J Appl Meteorol Climatol. 47(9):2423–2444. doi: 10.1175/2008JAMC1741.1.

Watson PJ. 2019. An assessment of the utility of satellite altimetry and tide gauge data (ALT-TG) as a proxy for estimating vertical land motion. J Coast Res. 35(6):1131–1144. doi: 10.2112/JCOASTRES-D-19-00031.1.

Woodworth PL, Melet A, Marcos M, Ray RD, Wöppelmann G, Sasaki YN, Cirano M, Hibbert A, Huthnance JM, Monserrat S, et al. 2019. Forcing factors affecting sea level changes at the coast. Surv Geophys. 40(6):1351–1397. doi: 10.1007/s10712-019-09531-1.

Zhao Y, Nasrullah Z, Li Z. 2019. PyOD: a python toolbox for scalable outlier detection. J Mach Learn Res. 20:1–7.

Zhou D, Liu Y, Feng Y, Zhang H, Fu Y, Liu Y, Tang Q. 2022. Absolute sea level changes along the coast of China from tide gauges, GNSS, and satellite altimetry. J Geophys Res Oceans. 127: e2022JC018994.

Zou F, Tenzer R, Fok HS, Meng G, Zhao Q. 2021. The sea-level changes in Hong Kong from tide-gauge records and remote sensing observations over the last seven decades. IEEE J Sel Top Appl Earth Observations Remote Sensing. 14:6777–6791. doi: 10.1109/JSTARS.2021.3087263.