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RESEARCH ARTICLE

Geodetic Science

Sea level variability at Colombo, Sri Lanka, inferred from the conflation of satellite altimetry and tide gauge measurements

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Abstract: Accurate long-term measurements of sea level are fundamental to evaluating coastal risks, such as the impact of sea-level rise on near-shore ecosystems, groundwater dynamics, and coastal flooding. This study examines sea-level variability at Colombo, Sri Lanka using satellite altimetry, tide gauge measurements separately and their conflated solution under a single model. Modelling of conflated satellite altimetry and tide gauge measurements shows a geocentric (absolute) local sea-level rise of 3.56 ± 0.32 mm/y without any signature of a uniform acceleration since 1981 at this locality. The measurements disclosed statistically significant periodic changes in sea level of luni-solar origin. The conflated model solution enabled the estimation of a statistically significant in-situ vertical land motion (0.58 ± 0.19 mm/yr) without the aid of global positioning measurements. The conflation model explains 98% of the sea-level variability, which makes it suitable for accurate seal level predictions for coastal risk assessments in Colombo, Sri Lanka.

Keywords: Colombo Sri Lanka tide gauge, satellite altimetry, sea-level rise, sea-level trend and acceleration, vertical land motion.

INTRODUCTION

Located in the Indian Ocean, off the Southeast Coast of India, Sri Lanka is a small island with diverse geography and a tropical climate. Its 1,700 km of coastline sounds highly vulnerable to the impact of climate change. This sounds alarming when considering the fact that roughly 50% of its inhabitants live in coastal areas on the West. Therefore, evaluating past and current sea-level changes is essential in this region for coastal risk assessment.

There have not been many studies that rigorously assess the sea-level variability in Sri Lanka. Wijeratne *et al*. (2008) analysed seasonal sea-level variability in this region using altimetric, meteorological and hydrographic information, including results from numerical modelling, to understand the main factors which contribute to the observed Mean Sea Level (MSL) changes. Gunathilaka *et al*. (2017) has estimated the sea-level trend at Colombo Port using 20 years of satellite altimetry (SA) data and tide gauge (TG) data from 1993 to 2012. Their estimated absolute sea-level trend in Colombo was around 2.50 ± 0.53 mm/y. Previous studies of sea-level fluctuations in different regions have confirmed that the sea level has increased during the 20th century and still escalating at a global scale of the absolute sea-level trend of about 3.2 ± 0.4 mm/y (Unnikrishnan *et al*., 2015). A recent study by Palamakumbure *et al*. (2020) investigated risk assessment of sea-level inundation along the south and southwest coasts of Sri Lanka using two tide gauges, together with Digital Elevation Models (DEMs). The time span of their local data was markedly short (2006–2017) to capture sea-level variability in this locality to be useful for reliable predictions. Their study was extensive, but the effect of the vertical land motion (VLM) in this region was not taken into account as a correction. Therefore, the results refer to relative sea-level changes, which are of limited use for coastal risk assessments. More importantly, their investigation was based on tide gauge (TG) data that were not corrected for the effect of the atmospheric pressure (Inverted Barometer, IB) effect, which is markedly noisy at this station.

In this study, we address all these issues which were not considered in the previous studies and deploy not only longer TG data (1981–2018) corrected for the IB, but also incorporate SA data (1992–2018) and take into

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consideration the effect of the VLM at the Colombo TG station. We rigorously evaluate sea-level variability at the Colombo TG station records and estimate sea-level rise using TG data and the SA in combination under a single model for optimal assessment of the results. The mathematical and statistical models used in this study permit concurrent estimation of absolute and relative sea-level trend and acceleration, low-frequency sea-level variations, including periodic annual and semi-annual sea-level changes together with VLM without Global navigation satellite system (GNSS) measurements.

In the following sections, we provide information on monthly SA, TG and GNSS data nearby Colombo, Sri Lanka TG station. Then we calculate separately the relative and absolute sea-level trend and acceleration using monthly TG and SA data, respectively. The discrepancy between the calculated relative and absolute sea-level trends provides an estimate of the linear rate of VLM experienced at the TG station. These findings will serve as a benchmark for evaluating the conflated model solution estimations. The model parameters mentioned above estimated simultaneously using restricted (constrained) least squares (Iz *et al*., 2020). Finally, the concurrently estimated VLM rate of the conflation model is compared with the VLM rate estimated from the GNSS data observed in the vicinity of the tide gauge station. The latter data is from the GNSS solution 'NGL14' produced by the Nevada Geodetic Laboratory (NGL) using a precise point positioning daily position time series for over 17,000 globally distributed stations.

MATERIALS AND METHODS

Tide gauge and satellite altimetry records at Colombo, Sri Lanka

The Colombo Port floating-type TG records span from 1981 to 2018 (Figure 1). Originally, this was an hourly data set and converted to the daily mean and then into monthly mean values to comply with the SA data. This TG time series are referenced to the Low Water Ordinary Spring Tide (LWOST) datum, which is close to the Lowest Astronomical Tide (LAT), and the difference between the observed MSL and the LWOST datum at the TG station is around 0.4 m (Prasanna *et al*., 2021). These TG time series records refer to relative sea-level changes since the corrections for the VLM have not been applied. The TG time series were corrected for the IB effect (Figure 2) using a near-real-time update of the Mean Sea-level Pressure (MSLP) data set, HadSLP2r, of the Met Office Hadley Centre. This data set is a unique combination of monthly globally complete fields of land and marine pressure observations on a 5-degree geographic grid from 1850 to 2019 (Allan & Ansell, 2006).

Among the various SA products that are available at this location, for our study region, we used SA sea-level anomaly data produced by NASA in its MEaSUR (Making Earth Science Data Records for Use in Research Environments) program, downloaded in July 2021 for the period from October 1992 to June 2019 (Figure 3). These are fully corrected gridded Sea Surface Height Anomalies (SSHA) above a mean sea surface on a 1/6th degree grid every 5 days. The gridded data are derived from the SSHA data of TOPEX/Poseidon, Jason-1, Jason-2 and Jason-3 as reference data from the level 2 swath data found (Zlotnicki *et al*., 2019).

Figure 1: Tide gauge location at Colombo in Sri Lanka (Google Maps, 2021).

RESULTS AND DISCUSSION

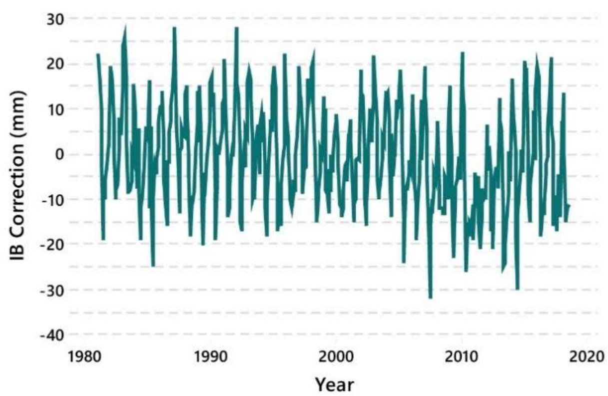

Figure 2: Inverted barometer correction (IB) for the TG records.

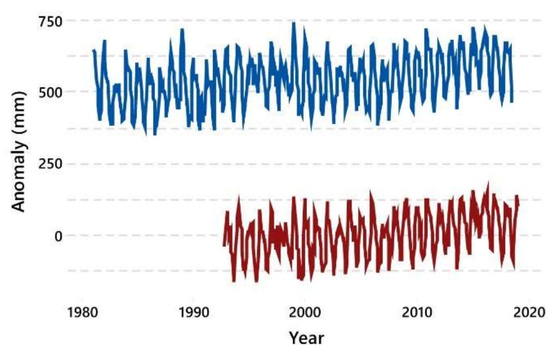

Figure 3: Monthly SA (red) and TG (blue) sea-level measurements at Colombo, Sri Lanka. The time series of the data refer to their own datum. TG time series are corrected for the IB effect.

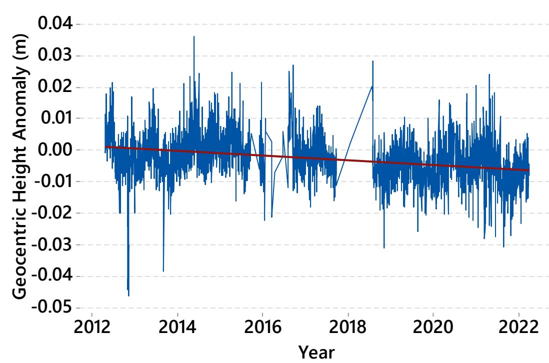

Figure 4: Daily averaged GPS measurements during 2012–2022 at the station SGOC, Narahenpita, Sri Lanka. The estimated linear trend (red line), the rate of VLM, is -0.82 ± 0.08 mm/y. Note that downloaded NSL records reported a trend of -0.19 ± 0.89 mm/y.

There is no co-located GNSS station to monitor VLM at this TG station. The nearest site is 5 km away, located at Surveyor General's Office Colombo (SGOC), Narahenpita, Sri Lanka. GNSS measurements are maintained by German Research Centre for Geosciences (GFZ), and processed time series are available from the University of Nevada at Reno (NGL), which are shown in Figure 4. The station is identified as Site ID: SGOC # DOMES: 23501M003, and the VLM data shown were downloaded from NGL in May 2022. The sporadic measurement span was carried out during 2012–2022 with an approximately two-year gap. The reported VLM -0.19 ± 0.89 mm/y recorded in the download GNSS NGL differed significantly from the estimated trend -0.82 ± 0.08 mm/y using weighted least squares (WLS); here weights are assigned to be the inverse of the squared standard deviations of the daily measurements in this study. The standard error of the estimated linear rate was also corrected for the AR(1) effect in this analysis.

In the following section, sea-level anomalies monitored by these two diverse technologies (TG and SA) are modelled and analysed separately.

Individual kinematic model solutions for satellite altimetry and tide gauge records

Sea-level variations were customarily modelled using quadratics, and this research goes back over three decades (Douglas, 1992). However, it must be noted that the quadratic model is ambiguous. The underlying physics of a quadratic model is kinematics, which describes the motion of objects without reference to the forces which cause the motion. The quadratic model is also misleading. It hides important issues for its implication of the uniformity of the acceleration and dependency of the trend estimate on the initial epoch when there is a uniform acceleration and unified datum definition. The quadratic representation of the sea-level variations is equivalent to the following basic kinematic model,

$$h_t = h_{t_0} + v_{t_0}(t - t_0) + \frac{a}{2}(t - t_0)^2 + u_t, \qquad ...(01)$$

and

$$v_t = v_{t_0} + a(t - t_0)t, \text{if } a \neq 0 \qquad ...(02)$$

where, h_t refers to the monthly averaged tide gauge data observed and v_t is the velocity at an epoch *t*. To improve the numerical stability of the solution, the epochs of the measurements are moved to the middle of the series t_0. The unknown sea-level reference height is defined at t_0 and denoted by h_{t_0}. The uniform acceleration/deceleration in sea level and the initial velocity are denoted as a and v_{t_0} respectively. When there is no acceleration $v_t = v = constant$. If the observations are referenced to the TG records, the initial velocity would be a relative trend. If the observations are from the nearby SA, they are inherently geocentric. The assumed statistical properties of the random variable are *assumed* to be $u_t \sim iid(0, \sigma_u^2)$, where σ_u^2 is the variance of the random variable.

We used this model, given by equations (1) and (2), to represent and estimate the trends and uniform accelerations for SA and TG time series using Ordinary Least Squares (OLS) procedure. The solutions serve as baselines to compare the conflation model presented in the following sections conjured to be an improvement over the individual models.

Table 1 shows the estimated relative and absolute sea-level trends, their standard errors, SE, and adjusted R^2 values. Sea-level trends are statistically significant at a 95% confidence level (CL) for solutions of both TG and SA models, but the estimated acceleration parameters are both rejected at 95% CL for the TG and SA measurements. Therefore, the estimated trends/velocities are constant.

The difference between the relative TG and absolute SA trends is an estimate of the VLM experienced at this station. The magnitude of this estimated VLM rate is large, but it is not statistically significant (-0.68 ± 0.63), i.e., the null hypothesis $H_0: v_{VLM} = v_{SA} - v_{TG} = 0$ cannot be rejected (Table 1). Nonetheless, the GNSS measurements carried out at 5 km away from the TG station indicate a statistically significant VLM (-0.82 ± 0.08 mm/y). Although the magnitudes of the VLM from two different sources agree, it is not conclusive because v_{VLM} estimate is noisy.

The solution statistics and the display of the residuals show that this model is inappropriate for representing the sea-level variations at this locality. The residuals exhibit unmodeled systematic variations, and their non-random behaviour is supported by their histograms (Figure 5a and Figure 5b). The adjusted R^2 values explain only 13% and 11% of the anomalies in TG and SA measurements, respectively. Some of the reasons for the poor performance of these basic kinematic models are the topics of the following sections.

A confluence model for the SA and TG measurements and its solution

One of the reasons for the failure of the above basic kinematic model is the unmodelled effect of low-frequency sea-level variations, as evidenced in the residuals (Figure 5a, Figure 5b). Iz (2014; 2015) identified and developed an improved kinematic model consisting of a linear velocity, uniform acceleration, and statistically significant and globally prevalent specific low frequency sea-level variations. Their origins are luni-solar forcings impacting sea-level variations with periods of 18.6 years for the lunar node changes and 11.1 years for solar variation (ibid.). Inspired by the findings of the study of Wijeratne *et al.* (2008), representations for annual and semi-annual periodic sea-level variations are also incorporated into the model.

The following model accounts for the effects of low-frequency changes in the extended kinematic model and can be used in the analyses of both SA and TG records,

$$h_t = h_{t_0} + v_{t_0}(t - t_0) + \frac{a}{2}(t - t_0)^2 + \sum_{k=1}^{4}\left\{\alpha_k \sin\left[\left(\frac{2\pi}{P_k}\right)(t - t_0)\right] + \gamma_k \cos\left[\left(\frac{2\pi}{P_k}\right)(t - t_0)\right]\right\} + \varepsilon_t \qquad ...(03)$$

$$v_t = v_{t_0} + a(t - t_0)t, \text{ if } a \neq 0 \qquad ...(04)$$

The unknown parameters α_k " and " γ_k in the above model are the components of the periods P_k to be estimated and used in computing the amplitudes and the phase angles of the luni-solar periodicities and the annual and semi-annual variations for eight additional parameters.

Note that the variable ε_t that represents the disturbance is different from u_t of the basic kinematic model. It refers to a first order autoregressive process, AR(1), and other random effects, including instrument errors in sea-level changes. This property of the disturbances is not recognized by the basic kinematic model given by equation (1), which is another source of inaccuracy in the separate model solutions. The AR(1) error ε_t is represented as,

$$\varepsilon_t = \rho\varepsilon_{t-1} + u_t \qquad t = \cdots, -2, -1, 0, 1, 2, \ldots \qquad ...(05)$$

where, $-1 \leq \rho \leq 1$ is the unknown autocorrelation coefficient of AR(1) process. Like before, the properties of the random noise u_t, is $u_t \sim iid(0, \sigma_u^2)$.

The estimated AR(1) correlation coefficients for the SA and TG records are $\hat{\rho}_{SA} = 0.15$ and $\hat{\rho}_{TG} = 0.20$. They reduce the effective time span of the SA records from 27 to 20 years and TG records from 37 to 25 years, resulting in an artificial overestimation of the SE of the parameters.

This model can now be used to *conflate* records of SA and TG measurements under a single model, namely, the confluence model, which was introduced by Iz *et al.* (2020). The following confluence model represents absolute and relative linear sea-level trends in SA, TG and VLM together with the periodic sea level changes. The model is expressed as,

$$h_t^{TG} = h_{t_0}^{TG} \pm v^{VLM}(t^{TG} - t_0^{TG}) + v^{SA}(t^{TG} - t_0^{TG}) + \sum_{k=1}^{m}\left\{\begin{matrix}\alpha_k \sin\left[\left(\frac{2\pi}{P_k}\right)(t^{TG} - t_0^{TG})\right] + \\ +\gamma_k \cos\left[\left(\frac{2\pi}{P_k}\right)(t^{TG} - t_0^{TG})\right]\end{matrix}\right\} + \varepsilon_t^{TG} \qquad ...(06)$$

$$h_t^{SA} = h_{t_0}^{SA} \pm v^{VLM}(t^{SA} - t_0^{TG}) + v^{TG}(t^{SA} - t_0^{TG}) + \sum_{k=0}^{m} \begin{Bmatrix} \alpha_k \sin\left[\left(\frac{2\pi}{P_k}\right)(t^{SA} - t_0^{TG})\right] + \\ +\gamma_k \cos\left[\left(\frac{2\pi}{P_k}\right)(t^{SA} - t_0^{TG})\right] \end{Bmatrix} + \varepsilon_t^{SA} \quad ...(07)$$

$$\varepsilon_t^{TG} = \rho_{TG}\varepsilon_{t-1}^{TG} + u_t^{TG} 0 \leq |\rho_{TG}| < 1, \quad u_t^{TG} \sim iid\left(0, \sigma_{u^{TG}}^2\right) \quad ...(08)$$

$$\varepsilon_t^{SA} = \rho_{SA}\varepsilon_{t-1}^{SA} + u_t^{SA} 0 \leq |\rho_{SA}| < 1, \; u_t^{SA} \sim iid\left(0, \sigma_{u^{SA}}^2\right) \quad ...(09)$$

The superscripts SA and TG identify the origin of the measurements in the observation equations. The sign of the v^{VLM} is decided depending on the nature of the VLM being a subsidence or an uplift. Because the estimated uniform accelerations were not statistically significant in SA and TG records, the trends or velocities are constant; hence they are no longer part of the confluence model.

The corresponding variance (V) or covariance (C) matrix of the autocorrelated disturbances for any one of the time series can be written as (Kendall, 1968; İz & Chen, 1999),

$$\Sigma = \sigma^2 \cdot \begin{bmatrix} 1 & \rho & \rho^2 & \cdots & \rho^{n-1} \\ \rho & 1 & \cdots & \cdots & \rho^{n-2} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho^{n-1} & \rho^{n-2} & \rho^{n-3} & \cdots & 1 \end{bmatrix} = \sigma^2 \cdot P^{-1} \quad ...(10)$$

where P is the corresponding $n_{TG} \times n_{TG}$ or $n_{SA} \times n_{SA}$ weight matrix depending upon which records are in consideration and σ^2 is the variance of the disturbances, $\boldsymbol{\varepsilon}$. Implicit in this expression is the assumption that measurements are equally spaced in time. The correlation decreases with increasing time lag because $|\rho| < 1$. The above patterned V/C matrix has an analytical inverse and is given by (ibid.),

$$\Sigma^{-1} = \frac{\sigma^{-2}}{1-\rho^2} P = \begin{bmatrix} 1 & -\rho & 0 & \cdots & 0 & 0 \\ -\rho & 1+\rho^2 & -\rho & \cdots & 0 & 0 \\ 0 & -\rho & 1+\rho^2 & \cdots & 0 & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots & \vdots \\ 0 & 0 & 0 & \cdots & 1+\rho^2 & -\rho \\ 0 & 0 & 0 & \cdots & -\rho & 1 \end{bmatrix} \quad ...(11)$$

Assuming SA and TG measurements are uncorrelated, we construct the following V/C matrix for the confluence model,

$$\Sigma^{-1} = \begin{bmatrix} \frac{\sigma_{TG}^{-2}}{1-\rho_{TG}{}^2} P_{TG} & 0 \\ 0 & \frac{\sigma_{SA}^{-2}}{1-\rho_{SA}{}^2} P_{SA} \end{bmatrix} \quad ...(12)$$

At this point, another difficulty arises because, in the above observation, equations of the coefficients of v^{VLM} *and* v^{SA} for SA and v^{VLM} *and* v^{TG} for TG are co-linear. Nonetheless, the following constraint between the relative and absolute velocities, v^{TG} and v^{SA}, and v^{VLM}, enables a unique solution for estimating the confluence model parameters.

$$\pm v^{VLM} + v^{TG} - v^{SA} = 0 \quad ...(13)$$

The confluence model was evaluated using the Restricted (constrained) Least Squares Solution (RLSS) method (Iz *et al*., 2020). The residuals of the solution of the confluence model for the SA and TG records are shown in Figure 5c and Figure 5d. The unknown first-order autoregressive correlation coefficients, AR(1), for the TG and SA, denoted by $\hat{\rho}_{TG} = 0.2$ and $\hat{\rho}_{SA} = 0.15$, respectively, were calculated from the residuals iteratively by evaluating their autocorrelation functions. According to the Durbin-Watson (DW) statistics, the expected value for random distributions is 2. In this solution, the calculated DW for the TG residuals and the SA residuals are 2.1 and 1.85, respectively, which shows that the confluence model removes systematic sea-level variations at this station effectively.

The amplitudes of luni-solar forcing and annual and semi-annual sea-level variations are also statistically significant, as tabulated in Table 2.

VLM estimate using the confluence model is consistent with the one obtained by differencing absolute and relative velocities, namely, -0.58 ± 0.19 mm/y vs -0.68 ± 0.63 mm/y, respectively. Moreover, the null hypothesis for the estimated VLM rate using the confluence model $H_0: VLM_{SA} - VLM_{TG} = 0$ is rejected, i.e., the linear rate of VLM is statistically significant. The VLM trend estimated from the conflation model is also compared to the one obtained from daily GNSS measurements. They agree in magnitude, -0.58 ± 0.19 mm/y vs -0.82 ± 0.08 mm/y, and both estimates are statistically significant ($\alpha = 0.05\%$). Their difference, $H_0: VLM_{SA} - VLM_{TG} = 0$, can no longer be rejected.

Table 1: Comparison of individual solution statistics using TG and SA records to those using the conflated model. The SE of the estimates are 1σ. Note that the subsidence rate estimated in this study is significantly different from the reported rate, -0.19±0.89 mm/y in the downloaded file. N/A Not Applicable.

Solution	SA records	TG records	Conflated SA & TG records		GNSS
$\boldsymbol{\nu}$ (mm/yr.)	3.50 ± 0.53	2.82 ± 0.34	3.56 ± 0.32	2.98 ± 0.19	N/A
SE (mm)	71.6	77.6	37.2		1.5
Adj. R^2%	11	13	98		12
VLM (mm/yr.)	-0.68 ± 0.63		-0.58 ± 0.19		-0.82 ± 0.08

Table 2: Estimated components of the periodic sea-level variations

Period (y)	Sine (mm)	Cosine (mm)
18.6	-16.48 ± 2.85	N/S
11.1	NS	6.17 ± 2.70
Annual	84.73 ± 2.50	-19.77 ± 2.50
Semi-annual	20.91 ± 2.08	4.70 ± 2.10

N/S: Not Significant

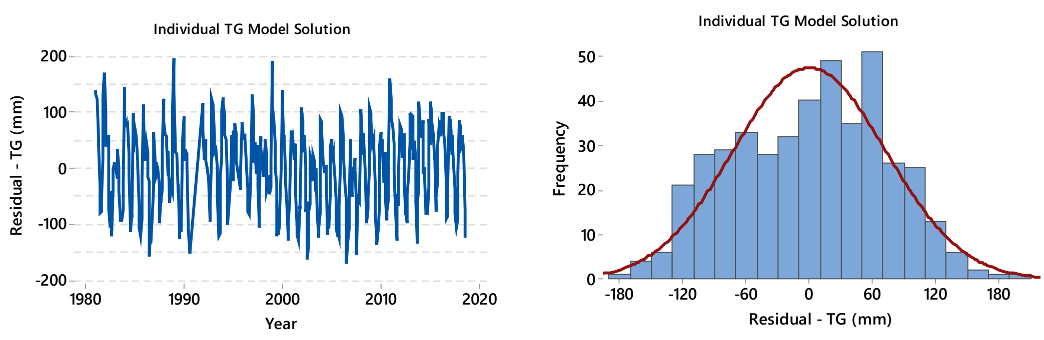

Figure 5a: Residuals and their histograms for the TG-only model solution

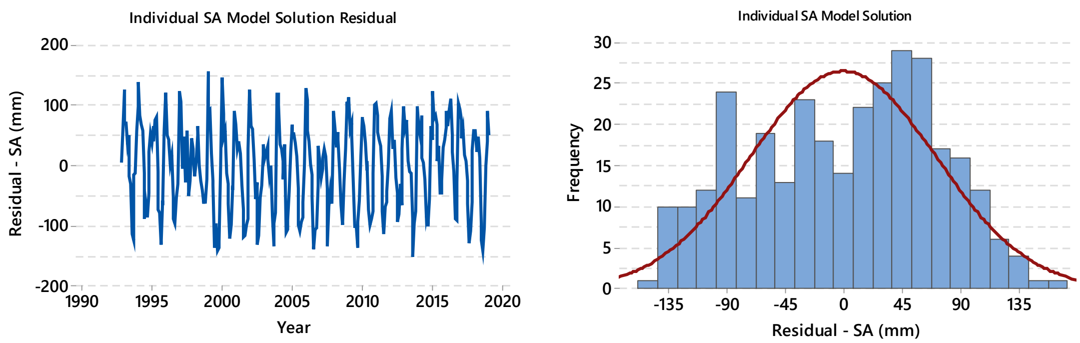

Figure 5b: Residuals and their histograms for the SA-only model solution

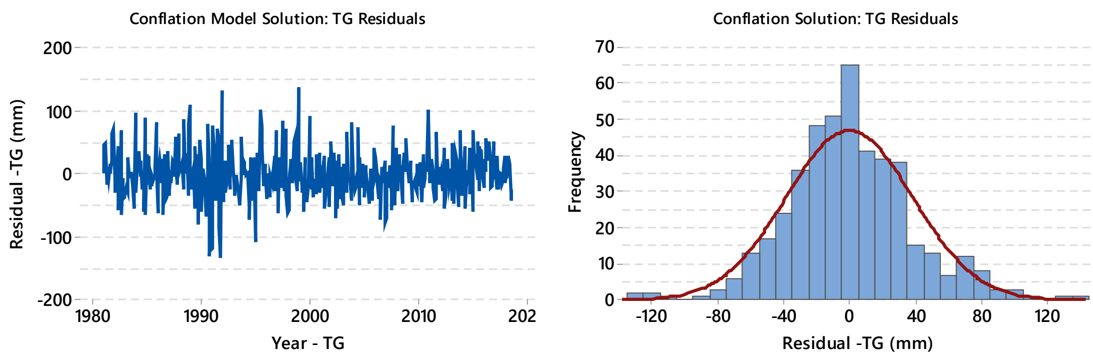

Figure 5c: Residuals and their histograms for SA from the conflation model solution

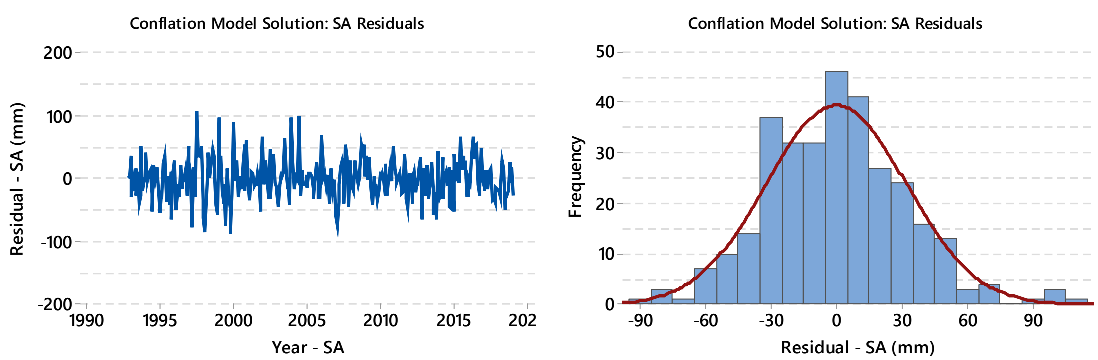

Figure 5d: Residuals and their histograms for TG from the conflation model solution

CONCLUSION

This study analysed the sea-level variability at Colombo, Sri Lanka using tide gauge and satellite altimetry measurements combined under a single model. This is the first-ever study of sea level in this locality. Relative and absolute sea-level trends and acceleration with a linear rate of change in VLM at this locality were estimated simultaneously using SA and TG records. Modelling conflated satellite altimetry and tide gauge measurements revealed that since 1981 the tide gauge station experienced a geocentric local sea-level rise of 3.56±0.32 mm/y, with no evidence of uniform acceleration. The measurements also disclosed statistically significant periodic changes in sea level of luni-solar origin and strong contributions by the annual and semi-annual variations. This investigation also quantified the statistically significant VLM at the TG station 0.58 ± 0.19 mm/y, which is verified using the GNSS measurements carried out independently at a nearby monitoring station. The conflation model explains 98% of the sea-level variability at the station in Colombo, Sri Lanka, and it is suitable for accurate sea level predictions at this locality.

Conflicts of interest

The authors declare that they have no conflict of interest.

Availability of data and material

Four types of datasets were used for this study:
Tide Gauge data (TG): A floating-type TG data was obtained from the Colombo Port Authority of Sri Lanka. The data set in different time periods is available at Permanent Service for Mean Sea Level (PSMSL) website:
http://www.ioc-sealevelmonitoring.org/station.php?code=colo
http://www.psmsl.org/data/obtaining/

Satellite Altimetry data (SA): SA data obtained from the data set produced by the NASA's MEaSURe's program, which were downloaded in July 2021 for the region 6^0N, 79^0E–7^0N, 80^0E for the period October 1992 to June 2019. The data available at:
https://podaac.jpl.nasa.gov/dataset/SEA_SURFACE_HEIGHT_ALT_GRIDS_L4_2SATS_5DAY_6THDEG_V_JPL1812

GNSS data: VLM data were downloaded from the continuous GNSS station, SGOC, from SONEL. Data is available at: https://www.sonel.org/?page=gps&idStation=3582

Mean Sea Level Pressure (MSLP) data: MSLP data from 1981 to 2019 were used for IB computation. The data set was extracted from the Mean Sea-level Pressure (MSLP) data set of the Met Office Hadley Centre at: https://www.metoffice.gov.uk/hadobs/hadslp2/

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