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Sea-level trends and variability along the coast of Vietnam over 2002-2018: Insights from the X-TRACK/ALES altimetry dataset and coastal tide gauges

Pham Dat T. [1, *], Llovel William [2], Nguyen Truong M. [1], Le Huy Q. [3], Le Minh N. [4], Ha Huong T. [1]

[1] VNU University of Science, Vietnam National University, Ha Noi, Viet Nam
[2] Univ Brest, CNRS, Ifremer, IRD, Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, F29280, Plouzané, France
[3] University of Twente, the Netherlands
[4] Vietnam Institute of Meteorology, Hydrology and Climate Change, Ha Noi, Viet Nam

* Corresponding author : Dat T. Pham, email address : phamtiendat@vnu.edu.vn

William.Llovel@ifremer.fr ; truongnm@vnu.edu.vn ; huylq2@gmail.com ; nhatminhle1510@gmail.com ; huonghat76@gmail.com

Abstract :

The changes in coastal sea levels are now considered a significant concern for densely-populated coastal regions such as Vietnam, which hosts a long coastline and two large deltaic areas. In this study, we used high-resolution (20-Hz) altimetry data from the X-TRACK/ALES product to investigate the trends and variability of sea-level anomalies (SLA) along the Vietnam coast from 2002 to 2018. We conducted comparisons of SLAs from X-TRACK/ALES with SLAs from four coastal tide gauges, and the results present a good root mean square error (0.03 m on average) and good statistically significant correlation (for $p < 0.05$) with an average value of 0.66. There is an exception for the Quy Nhon site ($r \sim 0.5$) as its closest altimetry points lie in the open ocean. Regarding trend calculations, the tide gauge sites exhibit two-to-three times larger trends than altimetry points, indicating a significant deviation from the coast to the open ocean. We then examined the contribution of various forcing factors by stepwise regression analysis for the 2002 – 2018 and 2008-2018 periods. The stepwise model can explain the observed data in the latter period (about 63% on average). As local factors, SST and meridional wind stress appear important, whereas PDO and ENSO are significant as remote factors, particularly at the southern sites. However, we could not find the best common forcing factors for all sites suggesting the inconsistent mechanisms causing sea-level variability along Vietnam's coast. Our study demonstrates complicated regional sea-level variability and emphasizes the benefit of high-resolution altimetry data in studying dynamic coastal regions.

Highlights:

► Sea-level trends show a large spatial deviation from the coast to open ocean. ► Sea-level variabilities are locally complicated and reveal inconsistent mechanisms. ► PDO and ENSO, as remote forcings, show significant influence at the southern sites.

Keywords : sea level anomalies, tide gauge, Vietnam coasts, X-TRACK satellite altimetry, coastal altimetry

1. Introduction

Global mean sea-level rise is one of the most direct and vital consequences of ongoing global warming. With high confidence, the latest Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) concluded that the increasing global mean sea level in the 20th century was the fastest in the last 3000 years (Fox-Kemper et al., 2021). The trend of mean sea level, however, does not rise uniformly and exhibits a sizeable spatiotemporal variability (e.g., Hamlington et al., 2020). Regional and local sea-level changes have been noted as primary challenges for improving regional and global sea-level projections in future (Milne et al., 2009) based on coupled climate model outputs. The long-term variabilities of regional sea-level changes result from a combination of different processes in different time scales (Woodworth et al., 2019). Thus, identifying driven forcing factors in specific areas that experience complicated atmospheric-oceanic interactions is not a straightforward task. In addition, according to IPCC AR6 (Fox-Kemper et al., 2021), regional sea level has also been attributed to changes in extreme sea levels in both magnitude (high confidence) and frequency (medium confidence) over the next century and that, in turn, would make coastal locations suffered more from coastal hazards.

The variability of regional sea level is also presented in the changes in the time-varying rate. For instance, the Indo-Pacific region experienced a linear rise three times faster than the global mean trend over the altimetric period (1993-2015; Llovel et al., 2018).

There is a significant contrast between the two sides of the Pacific Ocean where the rate of sea level rise is highest in the Western side and lowest on the opposite side over the 1993-2018 (Fox-Kemper et al., 2021). This suggests that coastal countries in the Western Pacific would be a "hotspot" of sea level change over the 21st century. Among them, Vietnam has been reported as one of the most vulnerable countries under the influence of sea level change (The World Bank Group, 2022).

Vietnam, which is nearby the most immense marginal sea of the western Pacific –East Vietnam Sea (EVS), is more threatened by sea-level variations as its coastline is 3260km long. The long coastline stretching from north to south exposes the country more to coastal hazards such as tropical storms, which would introduce more risks from changes in extreme sea levels (Pham et al., 2019). Furthermore, Vietnam hosts two highly populated deltaic regions: the Red River delta in the north and the Mekong delta in the south (~23.4% and 18% of national population, respectively; Central Population and Housing Census Steering Committee, 2020). Thus, long-term changes in sea level may have socio-economic impacts on Vietnam. For example, sea-level rise and water resources exploitation could enhance the risk of salinity intrusion in the future. By the end of the 21st century, the 1‰-salinity penetration inland may increase to more than 20 km in the Mekong delta and about 10 km in the Red River delta (IMHEN and UNDP, 2015). Given that importance, it is needed to investigate how sea level varies along the Vietnam's coastline. Among these changes, sea-level trends have been attracting the most attention from sea-level communities as the trends reflect a combination of complex phenomena that operate on a wide range of spatial and temporal scales.

The trend of coastal sea level, however, might significantly differ from the open-ocean areas (Woodworth et al., 2019). Yet, whether the drivers of the sea-level trend in shallow water could be the same as the nearby deep ocean is still an ongoing debate. Woodworth et al. (2019) discussed that several processes would change from the coastline to open ocean regions including tides, extreme sea levels, atmospheric surface pressure, winds and ocean circulation. However, the spatial variations of sea-level trends from the coast to open ocean have been less well-studied, mainly due to the lack of sea-level data in the shallow water regions. Recent developments in altimetry data have provided valuable information to address such issues, even within 3-5km from the coastline (e.g., X-TRACK product, Birol et al., 2021). The use of tide gauges (TGs) data in combination with altimetry data now can bring an opportunity to reveal the spatial deviation between coastal and open-ocean sea-level trends. Recently, there have been several studies in different regions that used satellite-based sea-level data to explore the spatial progression of the trends with the distance from the coast, such as along the Baltic Sea (Passaro et al., 2021); the Mediterranean Sea (Dieng et al., 2021, Gouzenes et al., 2020); the western coast of Africa (Marti et al., 2021) and Hong Kong (Xu et al., 2018). Most of these studies used along-track satellite data and the nearby or the closest TGs to validate and explore the trends between the two sites. The different trends found in the abovementioned works are assigned to various processes, such as local ocean circulation (Gouzenes et al., 2020); surface wind stress (Passaro et al., 2021); or temperature-salinity variations of seawater from coastline to open sea (Dieng et al., 2021). These results imply that the mechanism that drives sea-level trends varies locally and that there is a need for an in-depth understanding of atmospheric-oceanic characteristics of the interested study area.

This study aims to examine the variability of sea-level trends along the Vietnam's coastline by using a combination of satellite-tide gauge data sets. We target to address two scientific questions:

1. How did sea-level trends in Vietnam's coastal region vary from 2002 to 2018?

2. What process(es) drive those trends and sea-level variabilities?

To the best of our knowledge, this study is the first to consider the changes in sea-level trends and variability in spatial scale in Vietnam's coast. We focus on the coastal region from 102°E-112 °E to 7 °N-25 °N (Fig. 1). We organize the paper as follows: Section 2 describes the data and signal processing; Section 3 gives details of statistical methods used in this study; Section 4 follows with results and discussions from the validation of satellite data, trend calculations and governing processes; and finally, we make some conclusions in Section 5.

2. Data and Signal processing

2.1. Altimetry data

This study uses the latest and high-resolution satellite-based sea-level data processed by X-TRACK/ALES system (Birol et al., 2021). The 20Hz X-TRACK/ALES is a product developed in the ESA Climate Change Initiative project context. This sea-level data is an upgraded version of X-TRACK 2017 (Birol et al., 2017) product using the Adaptive Leading-Edge Subwaveform (ALES) retracker (Passaro et al., 2014) to improve the quality of sea level anomaly up to 3-5km on average to the coast. The X-TRACK/ALES consists of along-track sea level anomaly (SLA) data at 20 Hz sampling altimeter measurements (i.e. ~ 350m spatial resolution between two successive points in a track) compared to 1 Hz sampling (i.e. ~ 6-7km in space) of the older version. The 20-Hz SLA data are produced from all Jason satellite cycles and regularly extended for six regions, including South East Asia. A detailed description of the X-TRACK/ALES data can be largely found in Birol et al. (2021), and Benveniste et al. (2020), and the data for South East Asia come from: https://data.ceda.ac.uk/neodc/esacci/sea_level/data/XTRACK_ALES_SLA/SLA/v1.1_202006/SE_ASIA

Due to high resolution and high quality, the X-TRACK/ALES has recently been used in several studies to analyze the trends globally (e.g., Prandi et al., 2021, Benveniste et al., 2020) or between coastal regions and open ocean (e.g., Gouzenes et al., 2020, Marti et al., 2021, Dieng et al., 2021). The data, however, has never been used for either the EVS or South East Asia; thus, we are the first to use this detailed SLA data in the region.

From X-TRACK/ALES data for South East Asia, we selected six tracks for the present objective, including #001, #038, #077, #140, #153 and #216 for the period from Jan 2002 to

May 2018, when the tide-gauge data is also available for the sites of interest. These tracks are the closest to the coastal TGs along the Vietnam's coast, which are described in section 2.2 below.

We then selected from each satellite track the closest point to the nearby tide gauge for further analysis (e.g., data validation, trend calculations and variability analysis). If a tide gauge is close to more than one track, we read and found the closest points from each track and consider them equally in the analysis. For example, there are two Jason tracks (#001 and #038) passing through the Gulf of Tonkin and that are close to the Hon Dau tide gauge (Fig. 1). Thus, we extracted the closest points from both #001 and #038 tracks, namely HD001 and HD038. However, if there are too many NaN values at the closest point (due to land contamination), we abandoned that point and found another point nearby that contains less NaN values but is not too far away from the tide gauge. We then took a 10-point segment (~ 3.5 km along the altimetry track) from the chosen point to the offshore direction. We next calculated the mean of 10 data point to produce a single altimetry time series for further analyses. Table 1 shows the coordinates and distance from TGs of selected satellite points in this study. We finally calculated the monthly average (as we care about the long-term trend and interannual variability) for each SLA time series that we call SLA_{sat}.

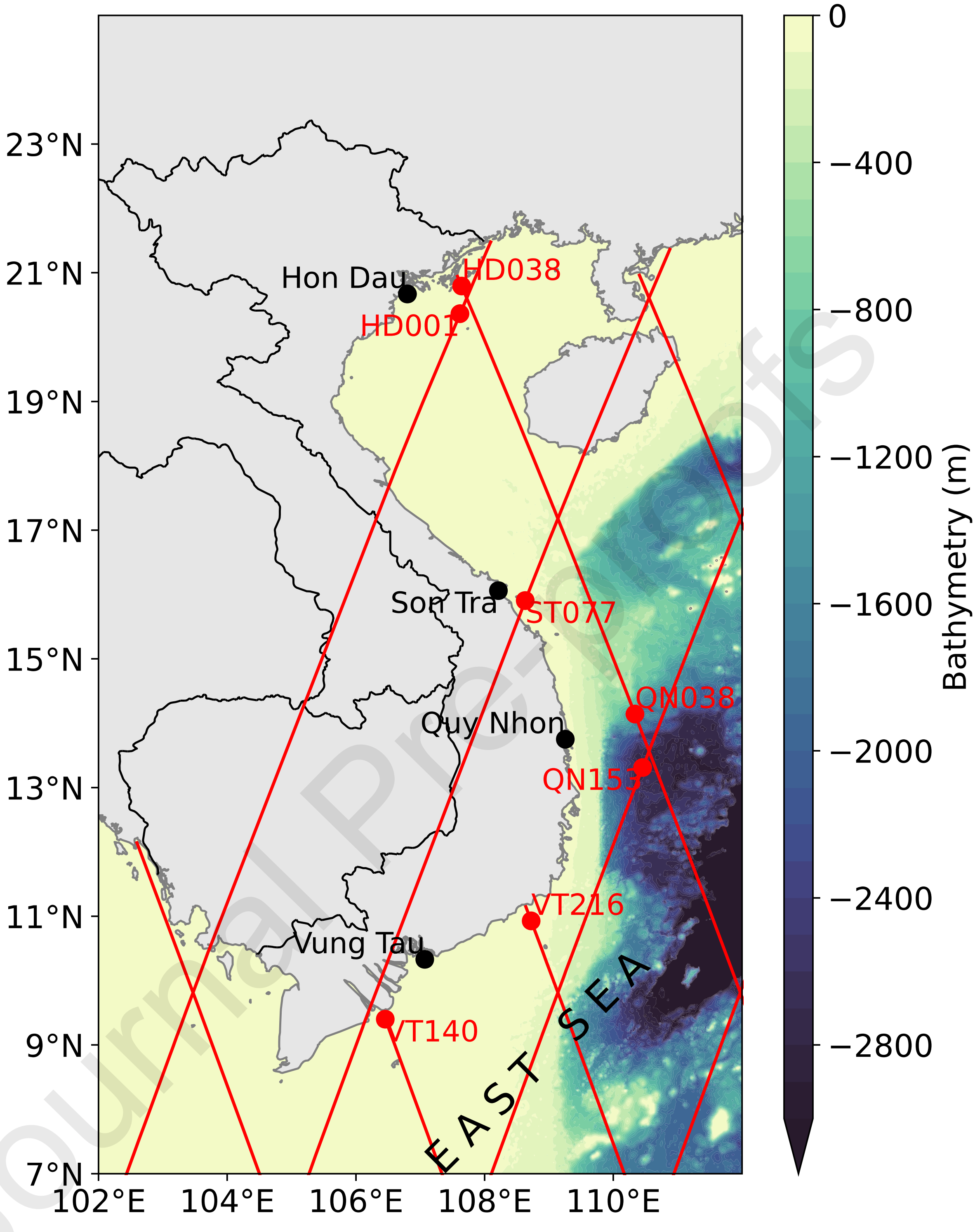


Fig. 1: (a) Location of tide gauges (black dots) and the first selected altimetry points from each Jason track (red dots) along Vietnam's coastline. The letters on altimetry points show the closest tide gauge and the number indicating the number of Jason track from XTRACK/ALES data.

2.2. Tide gauge data

In this study, we obtained hourly sea-level records of four TGs along the Vietnamese coastline for analyses: Hon Dau in the north (the Red River delta); Son Tra in the central; Quy

Nhon in the south-central; and Vung Tau in the south of Vietnam (the Mekong delta; Fig. 1). The hourly sea level data are provided by Center of Marine and Hydrological Research (Vietnam) for the same period as the X-TRACK/ALES data in order to make two data sets consistent to each other. As done in Pham et al. (2019), we performed a careful quality check for each sea-level record. We used the Utide program (Codiga, 2011) to obtain tidal signals from observed sea-level records and then plotted both time series on month-by-month for each calendar year. We then visually check and remove any suspect spikes, sudden jumps and datum shifts.

In order to bring the tide gauge data to a comparable format with altimetry data, we followed the wisely-used procedure that had been done in several studies (e.g., Dieng et al., 2021, Marti et al., 2021). Firstly, we eliminated the tidal signals by using the UTide program. This tidal package has been widely used for removing tide from hourly sea-level records in numerous studies as it can deal with gappy data and does not require a year-to-year basis period for tidal analysis (e.g., Pham et al., 2019, Marcos et al., 2015). Secondly, we corrected the non-tidal signal sea-level time series for Dynamic Atmospheric Correction (DAC). This correction is important for our work as the study area is strongly influenced by seasonal signals from the monsoon and atmospheric pressure (Pham et al., 2019). The DAC data was obtained from AVISO (at http://ftp-access.aviso.altimetry.fr/) with a spatial resolution of 0.25^o x 0.25^o and temporal sampling at 0:00, 6:00, 12:00, 18:00 GMT for each day from 1992-present. We thus interpolated DAC data to each site and to hourly data points. Finally, we took a monthly mean of sea-level data after removing tide and correcting for DAC. We then called this sea-level data as SLAtg.

Regarding vertical land motion (VLM), several GNSS stations and GPS data nearby coastal tide gauges exist (available from the Nevada Geodetic Laboratory GPS Networks Map data center: http://geodesy.unr.edu/NGLStationPages/gpsnetmap/GPSNetMap.html). However, most GPS data exhibit either large differences between rates and uncertainties or data length does not match the period in this study. Thus, we could not correct coastal tide gauges for VLM. We also did not correct the GIA-related VLM as the values are small for the Vietnamese coastline varying in the range of 0.23 – 0.36 mm/year (data is from the Permanent Service for Mean Sea Level – PSMSL website: https://psmsl.org/train_and_info/geo_signals/gia/peltier/). For all abovementioned reasons, the tide gauge data in this study was not corrected to any VLM.

2.3. Data of forcing processes

To address the research question (2), we considered six forcing factors/processes: u and v wind stress components, El Niño and Southern Oscillation via Multivariate ENSO Index (MEI), Pacific Decadal Oscillation (PDO), Indian Ocean Dipole index and sea surface temperature (SST) field in the study area.

We extracted 10-m u and v windspeed components and SST data from the ERA5 global reanalysis (Hersbach et al., 2020). These data are monthly mean at 0.25^o x 0.25^o and must be, therefore, interpolated to each site and satellite point. We then calculated the u and v wind stress components by using Matlab program from Climate Data Toolbox (Greene et al., 2019).

For climate indices, we downloaded the monthly time series for Pacific Decadal Oscillation (PDO; Mantua et al., 1997); the Multivariate ENSO Index (MEI; Wolter and Timlin, 1998) and the Indian Ocean Dipole (DMI; Saji et al., 1999). Prior to further analysis, we subtracted all monthly mean time series from their mean and then removed seasonal signals (annual and semi-annual cycles) by harmonic analysis, as we only care about the trend and interannual variability. Ultimately, we further applied a 12-month moving average for all non-seasonal time series.

3. Methodology

3.1. Trend calculation

Sea-level records reflect the influence of various processes that vary in different timescales (Pugh and Woodworth, 2014). Thus, sea-level data should be treated as a nonlinear and nonstationary time series. Wu et al. (2007) discussed that the trend of such time series should be "an intrinsic property of the data", and the methods used to extract the trend has to be adaptive and be based on the time scale of the data itself. Thus, to extract the trend from each sea-level time series (from both TGs and altimetry data), we adopted the Ensemble Empirical Mode Decomposition (EEMD) method (Huang et al., 1998, Wu and Huang, 2009). The EEMD can adaptively decompose the original time series into different modes (or intrinsic functions), and the trend is the last mode from the result. This indicates that the trend extracted from the EEMD might not be contaminated by various processes on different time scales. The EEMD is helpful for processing nonlinear and nonstationary data such as sea-level records, and hence, it has been applied to study the sea-level trend in some coastal regions (e.g, Saramul and Ezer, 2014, Ezer, 2013). In this study, we used one of the latest improved variation of EEMD, CEEMDAN - Complete Ensemble Empirical Mode Decomposition with Adaptive Noise (Colominas et al., 2014), which can provide better spectral separation of the modes.

After extracting the trend from the CEEMDAN, we estimated the trends by fitting the ordinary linear least squares. We took 1-sigma standard error as uncertainties of the estimation. The error estimated from EEMD was reported smaller than linear regression as the method eliminated other processes (e.g., Saramul and Ezer, 2014).

3.2. Statistical analysis for forcing factors

One of the major goals of this study is to find the relation between some potential forcing factors and sea-level trends and interannual variability. We aim at finding out which processes and/or factors have the most impact on the sea level at each site. The impact or contribution of each potential forcing factor can be estimated by a multiple regression model expressed in general form as below:

$$SLA_{(x,y,t)} = \beta_0 + \beta_1 U_{ws} + \beta_2 V_{ws} + \beta_3 MEI + \beta_4 PDO + \beta_5 DMI + \beta_6 SST + \varepsilon \quad (1)$$

Where the left-hand side of (1) represents the SLA time series at each TG station/satellite point, the right-hand side of (1) displays regressors used in this analysis: (i) local factors: zonal wind stress (U_{ws}), meridional wind stress (V_{ws}) and SST; (ii) remote or external factors: Multivariate ENSO Index representing ENSO phases (MEI), Pacific Decadal Oscillation (PDO), and Indian Ocean Dipole (DMI). ; the coefficient β_0 is constant whereas $\beta_1 - \beta_6$ are the regression coefficients of each regressor in (1) and ε is random error.

We, however, would rather like to spot a few factors that can explain most variability of sea level from a combination of selected forcing factors. Thus, we used a stepwise linear regression model with a forward selection approach. The stepwise model will add each regressor into the model step by step and then check whether that regressor significantly contributes to sea-level variations based on their statistical significance. If not, that regressor will be removed from the models. By doing this, we could know the explained variance of sea level by individual factors. This stepwise approach has been employed in several sea-level studies at both global (e.g., Calafat and Chambers, 2013) and regional scales (e.g., Dangendorf et al., 2013, Sterlini et al., 2016).

The multiple linear regression approach, however, may face multi-collinearity in which independent variables (or forcing factors) are highly correlated, and thus, they would share or measure the same variance of a dependent variable (i.e. sea level in our study). This makes the statistical model difficult to correctly estimate the contribution of each independent variable to the dependent variable. To overcome that, we applied the Variance Inflation Factor (VIF) to detect the multi-collinearity before doing any analysis (e.g., Sterlini et al., 2016). The VIF measures the correlation between regressors and how strong the correlation is. In particular, the VIF value are calculated for each regressor from the multivariate data at each site/tide gauge. For a given multiple regression model in (1), the VIF of the *i^th^* regressor will be:

$$VIF_i = 1/(1 - R_i^2) \quad (2)$$

Where R_i^2 is the R^2 value calculated by regressing the i^{th} regressor on the rest of the regressors. Normally, if the VIF values are more than 10, indicating very strong multicollinearity and needed to be corrected. In our study, we checked VIF for each regressor and removed the regressor with the highest VIF value and is over 10. As a result, statistical results could be more reliable and significant, although some important forcing factors would probably be lost from the orginal data. Prior to stepwise analysis, all timeseries are detrended (by fitting a simple least square) as we focus more on the variability of sea level.

4. Results and Discussion

4.1. Comparisons between tide gauge and satellite altimetry

This section will show comparisons between the tide gauge and satellite altimetry (sat_tg_comparison) timeseries (i.e., SLAsat and SLAtg data described in section 2) at each point/site in this study. Most sites have two comparison results as we used the two closest tracks to the TG, except the Son Tra tide gauge. We used the Pearson correlation coefficient and the Root Mean Square Error (RMSE) to check the goodness of the comparison statistically. We also applied the *t-test* to examined the statistical significance of correlation coefficients.

We present the results of sat_tg_comparison in Fig. 2 and Table 1. We note that the mean distance from TGs to their closest altimetry points is ~ 115 km, which is fairly far compared to other studies. For example, Dieng et al. (2021) validated X-TRACK/ALES data with TGs within 30 km of the altimetry point. We, however, observed fairly good and statistically significant (for $p < 0.05$) correlations between SLA_{sat} and SLA_{tg}, with an average value of 0.66 (Table 1). At Hon Dau, Son Tra and Vung Tau , the coefficient correlations of sat_tg_comparison vary in the range from $r = 0.63 – 0.81$ whereas, the SLA_{sat} is less correlated to SLA_{tg} at Quynhon with $r = 0.49$ (at track #153, QN153) and $r = 0.5$ (at track #038, QN038). The less-correlated results at Quynhon might come from the fact that the two closest points on track #038 and #153 are located in the deep-water area ~ 2000 m (Fig. 1). This could suggest that the variability of SLA at the coastal regions might differ from the open-ocean area or that there are other oceanic signals only observed in deep waters (as discussed in Dieng et al., 2021). For example, both SLA_{sat} time series at track #038 and #153 represent a peak of SLA around the year of 2011, which is not captured by the nearby tide gauge (Fig. 2). The 2011 peak in SLA_{sat} at Quy Nhon might correlate to a regional climatic/oceanic as discussed in previous studies (e.g., Woodworth et al., 2019, Boening et al., 2012, Feng et al., 2013). Firstly, as the Equatorial Pacific warm pool shifts towards the west, the ocean heat content builds up in the Maritime continent region and thus, regional sea level increases. Secondly, the extreme 2010/11 La Niña event, the strongest ENSO cold phase since the altimetry era, is considered to have mainly caused the large change in global sea level from early 2010 to mid-2011 (Boening et al., 2012) and raised sea level anomalies in the tropical western Pacific as a result of increasing easterly wind stress (Feng et al., 2013). This is what we observed for QN038 and QN153 in 2011 but not for the TGs suggesting contrasting impacts of atmospheric forcings between the open ocean and coastal TGs. We, however, will investigate this interesting result in future work.

The good agreement between altimetry and tide gauge data indicates the robustness of the data processing method used in the sat_tg_comparison of this study. We also observed an acceptable RMSE between the two data sets with a mean of 0.03 m (Table 1). The highest RMSE is 0.04 m at QN153, where the correlation between SLA_{sat} and SLA_{tg} is also the lowest, as described above. The RMSE in our study is comparable to that of Dieng et al. (2021) around Corsica but is significantly lower than that of Passaro et al. (2021) in the Baltic Sea. It is worth noting that the mean distance between TGs and altimetry points in Dieng et al. (2021) is much closer than that of our study.

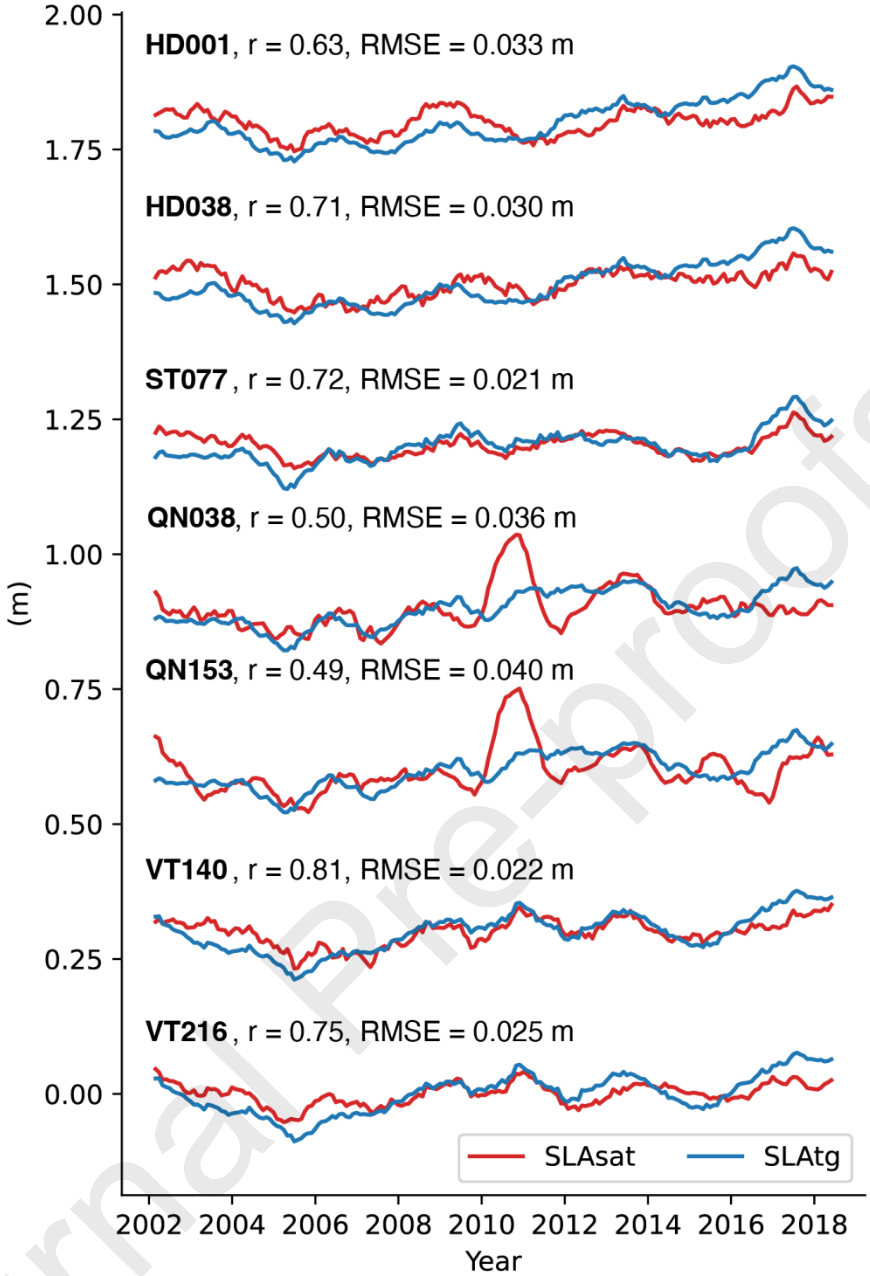


Fig. 2: Comparison of SLAtg and SLAsat time series in the present study, with an arbitrary offsets on the vertical axis

Altimetry points	Coordinates	Distance to coast (km)	Distance to tide gauge (km)	Tide gauge trend (mm/yr)	Altimeter trend (mm/yr)	RMSE(m)/ Correlation
HD001	(20.363884°N - 107.617004°E)	28.0	91.5	7.3 +/- 0.23	1.75 +/- 0.08	0.033/0.63
HD038	(20.793793°N - 107.64264°E)	15.2	88.7		2.86 +/- 0.07	0.03/0.71
ST077	(15.906066°N - 108.63068°E)	9.0	47.7	3.53 +/- 0.03	0.42 +/- 0.08	0.021/0.72
QN038	(14.141697°N - 110.33585°E)	109.0	124.6	4.96 +/- 0.04	3.38 +/- 0.04	0.036/0.50
QN153	(13.310798°N - 110.45549°E)	115.6	138.5		1.86 +/- 0.02	0.040/0.49
VT140	(9.400061°N –	15.5	123.2	4.66 +/- 0.06	2.41 +/- 0.11	0.022/0.81

	106.45643^{o}E)					
VT216	(10.927686^{o}N - 108.723236^{o}E)	26.2	192.5		1.11 +/- 0.03	0.025/0.75

Table 1: Sea-level trends of SLAsat and SLAtg time series for 2002-2018. The last column presents RMSE and correlation coefficients in comparison between SLAsat and SLAtg. Note that the Coordinates are at the first selected altimetry point.

4.2. Sea-level Trends

We used a linear regression model to calculate the trend extracted from the CEEMDAN method. We note that all sea-level trends are statistically significant for $p < 0.05$ and the R-squared values from the linear regression model for most cases are > 70%, except for the Son Tra tide gauge ~ 13% (not shown). The results of trend estimations are shown in Fig. 3 and Table 1, which clearly indicate an increase in sea level over 2002-2018 at all TGs and altimetry points along and offshore Vietnam's coast. It is also found that the rate of sea-level rise at coastal TGs is two-to-three times larger than the open sea altimetry points. The largest discrepancy is observed at the northern sites: Hon Dau and Son Tra TGs. At Hon Dau, the sea-level trend tide gauge is highest at 7.3 +/- 0.23 mm/year compared to the rate of 1.75 +/- 0.08 mm/year at HD001 and 2.86 +/- 0.07 mm/year at HD038. This tendency is even higher at Son Tra where the trend at tide gauge (3.53 +/- 0.03 mm/year) is much higher than that of altimetry points (0.42 +/- 0.08 mm/year). An interesting result is that the 1st satellite-altimetry-based trends are larger for the deltaic region than for the central Vietnam coast and the 2nd satellite-altimetry-based trends highlight quite similar values but for Son Tra.

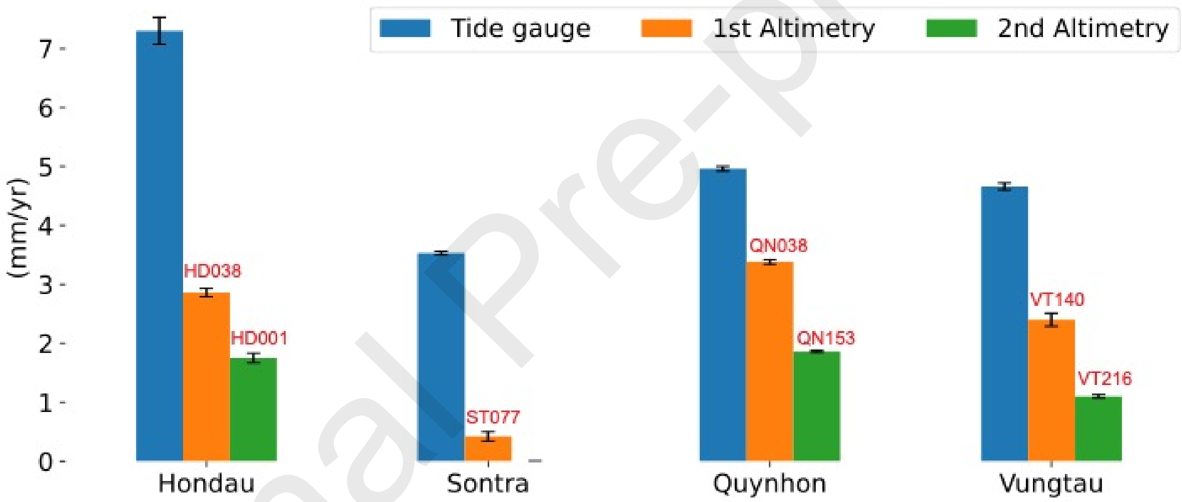


Fig. 3: Sea-level trends of each tide gauge and altimetry time series in this study.

The results of sea-level trends in this study indicate a significant spatial deviation: higher rates close to the coastline and lower rates to the open-ocean area. We also spotted a variation in the rates between altimetry points at each site (Fig. 3), the effect of distance-to-coast might explain. For example, the point VT216, which is further from the coastline than VT140 (Fig. 1, Table 1), shows a two-time lower rate of sea-level rise (1.11 +/- 0.03 mm/year) compared to that of VT140 (2.41 +/- 0.11 mm/year). Another piece of evidence comes from point HD001 which is located in an open area and expresses a lower rate (1.75 +/- 0.08 mm/year) than HD038 (2.86 +/- 0.07 mm/year). This might suggest different processes that spatially affect the trends of sea level in the study. There are various local atmospheric/oceanic forcing factors that might be attributed to such deviation of sea-level trend, as discussed in a number of studies (e.g., Dieng et al., 2021, Passaro et al., 2021, Marti et al., 2021, Gouzenes et al., 2020). In a recent study, Gouzenes et al. (2020) also found a slow increase in sea-level trend from the coast to open area at the Senetosa (Corsica) using the XTRACK/ALES data. The authors concluded that the results are not attributed to the data itself (including errors in geophysical corrections and the ALES retracking) but might be due to small-scale physical processes (waves and currents). Their hypothesis was yet to be conclusive but was a promising approach explaining the statistical analyses. Compared to Gouzenes et al. (2020), our results show the same behaviour. However, we used more TGs that are located in different locations, and altimetry points are pretty far away from the TGs (the closest distance from a tide gauge to the altimetry point is ~ 48km at Son Tra – Fig.1). Given that far distance, we can also draw a similar conclusion that the dissimilar sea-level trends between coastal TGs and near-shore altimetry points are not assigned to the erroneous corrections of the XTRACK/ALES data. Our results, however, contradict a global study by Benveniste et al. (2020) who used the XTRACK/ALES data to investigate whether the sea-level trends differ from 429 TGs worldwide. The authors find that there is no significant difference in trends between altimetry points from the open ocean (~ 14-16 km on average from the coast) to the coastal zone in most places, including Vietnam coastal zone (Fig.11 in their study). To explain, we hypothesize that most of our altimetry points compared to TGs are further from the coast than that of Benveniste et al. (2020) or this discrepancy might come from differences in data processing (e.g., we used CEEMDAN to extract the trend before fitting by least square regression). However, it is worth noting that Benveniste et al. (2020) only showed the comparison in trends between altimetry data and TGs with a GPS station within 50 km, and that was not the case for Vietnam's TGs.

The disagreement of the sea-level trends between coastal TGs and altimetry points can also be explained by unrelated-to meteo-hydrological processes, in which, VLM is the key factor for regional sea-level studies (Wöppelmann and Marcos, 2016). As mentioned in section 2.2, we did not correct TGs for VLM due to a lack of reliable GPS data in the study area, but here, we conducted a simple VLM-rate calculation by using differenced Altimetry-Tide gauge time series at each coastal site. For sites closed to more than one altimetry tracks (i.e., Hon Dau, Qui Nhon and Vung Tau), we averaged two SLAsat time series and generated a single differenced Altimetry-Tide gauge time series at each site. We then repeated trend calculation procedure as described in section 3.1. The preliminary results of VLM rates at coastal TGs are shown in Table 2.

Table 2. VLM rates estimated from differenced Altimetry-TG time series at each site

Site	**VLM rate (mm/year)**
Hon Dau	-4.66 +/- 0.12
Son Tra	-2.32 +/- 0.02
Quy Nhon	-2.46 +/- 0.14
Vung Tau	-3.29 +/- 0.07

VLM rates estimated from this study show subsidence at all sites. If one considers those rates, the discrepancy of sea-level trends between TGs and altimetry points would reduce significantly as the trend values are now closer to each other. We, however, are aware of the simplicity of our VLM rate calculations. Compared to other VLM rates, our results present much larger subsidence rates. For example, VLM rates estimated from Permanent Service for Mean Sea Level data sets show the rates of -0.34 +/- 0.32 mm/year (at Hon Dau, quality is medium), -0.5 +/- 0.37 mm/year (at Quy Nhon, quality is poor) and -1.33 +/- 0.4 mm/year (at Vung Tau, quality is poor) (data is available from http://geodesy.unr.edu/vlm.php). Hence, the lack of needed data leads to unconsistency VLM rates and a large spread of quality. This issue also raises doubt about using VLM rates to correct coastal TGs in our study area, or at least, a much more complicated data processing is needed to obtain reasonable VLM rates (e.g., Kleinherenbrink et al., 2018). Such work is yet beyond the scope of the present study.

Despite the challenge that remains in the estimation of VLM, our results still provide a meaningful and detailed comparison of sea-level trends between altimetry points and TGs in the region. Hence, questions of what forcing factors/processes drive those spatial deviations and whether they are the same at locations in distant are needed to investigate. We will partly address these research questions in the next section.

The second major feature of sea-level trends along the Vietnam coast is that the coastal sea levels have risen significantly since the beginning of the 21st century. All rates of sea-level rise at TGs and close-to-coast altimetry points (i.e., HD038 and VT140, Table 1) are equal to or considerably higher than the rate of global mean sea-level rise. This finding agrees well with the trends estimated for South East Asia by Benveniste et al. (2020) (Fig.6 in their paper). The intensification of sea-level rise in the study area was also mentioned in the IPCC AR6 conclusion stating that the Western Pacific has observed the highest rate of sea-level rise in the Instrumental Era (1993-2018) (Fox-Kemper et al., 2021). This finding also suggests that the effect of forcings/physical processes on sea level might have been intensified in our study area. As concluded with medium confidence in the IPCC AR6, the high rate of sea-level rise will be strongly related to the increase in the frequency of extreme still water levels - which consist of relative sea level, tide, and surges - over the next century. This would cause more risks for the coastal regions, including those of Vietnam, in the decades to come. Most Vietnam sea-level studies have been only estimated the trend for the whole length of observed data. For example, the Vietnam Climate Change Scenarios (Viet Nam Ministry of Natural Resources and Environmen, 2016) also showed an increase in sea-level changes at Hon Dau (for the period of 1966-2018), Son Tra (1978-2018), and Vung Tau (1978-2018) tide gauges with pretty similar magnitude of: 2.3 mm/year, 2.6 mm/year and 2.9 mm/year, respectively. These results are significantly lower than our study but are understandable as different in the data length. This might be indicative of a possible sea-level acceleration on the Vietnam coast, which is also in line with the finding of regional sea-level acceleration in the majority of tide gauges spotted by Wang et al. (2021). The outcomes from our study, however, suggest a need to consider sea-level trends in different periods of time, not in the entire data length. This comes from the fact that, as we mentioned earlier, the trend should not be considered a stationary process. Thus, given the context of climate change, our results provide a better understanding of sea-level changes along the Vietnam's coastline since the new century.

4.3. Regression analysis

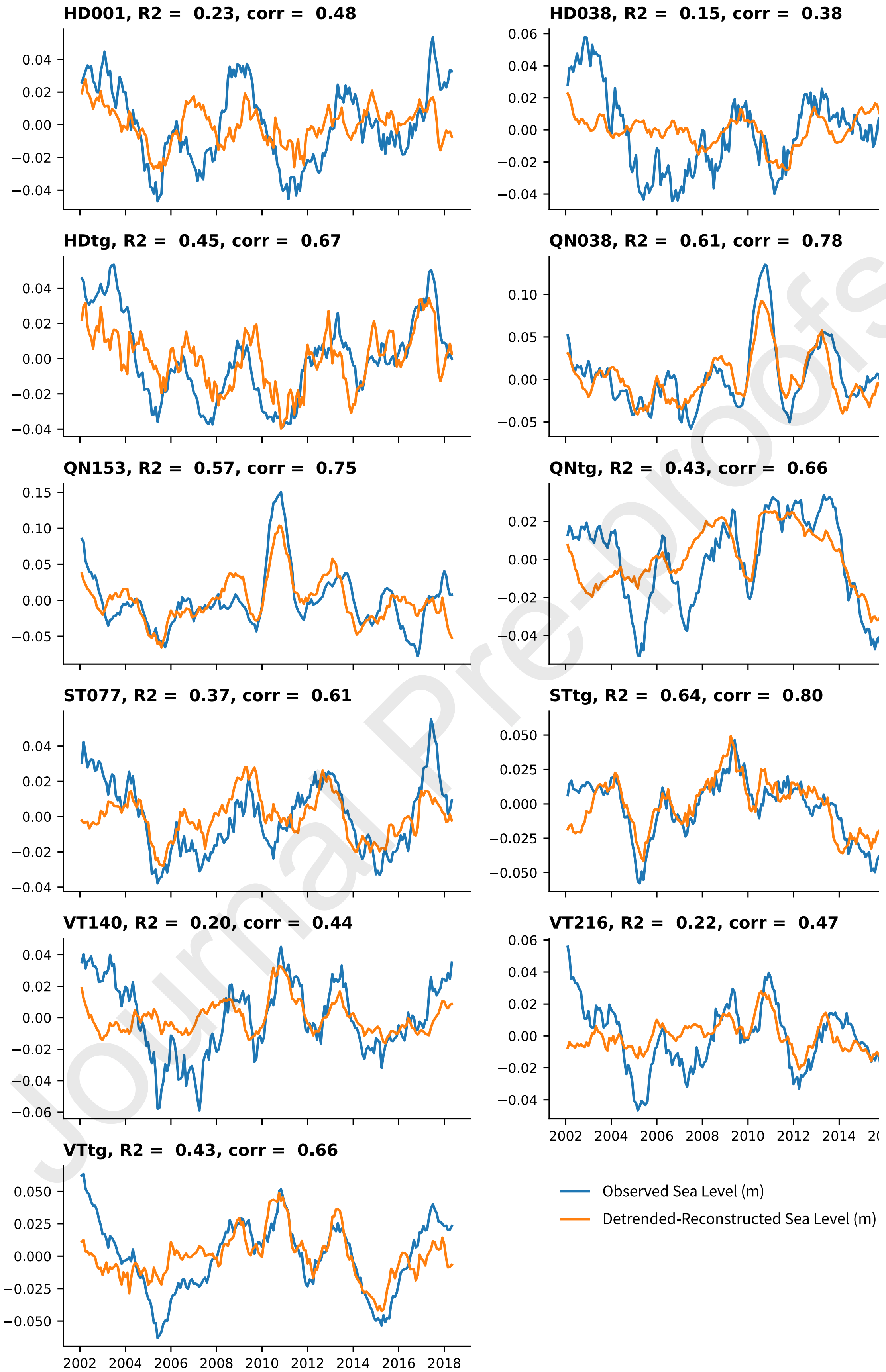
4.3.1. Stepwise regression

We conducted stepwise regression for each tide gauge and altimetry point for two periods: 2002-2018 and 2008-2018. The reason for the latter period was based on the results of some studies discussing a decent shift of sea level in the Pacific recently (e.g., Hamlington et al., 2016) and that, there are some strong ENSO phases such as La Niña 2010/11 and El Niño 2015/16 that could significantly affect sea level in the study area. Hence, we examined to see whether a recent change in drivers of sea-level variability in the 2008-2018 period and, if yes, how much their contributions are.

The SLA variability from multi-linear regression for the period of 2002-2018 is presented in Fig. 4. The blue lines represent the observed SLA from either tide gauges or satellite altimetry point (detrended and deseasoned time series). In contrast, the orange lines present the reconstructed SLA after applying the stepwise model. The R-squared values, which express the explained variance of the model, vary in an extensive range from about 15% to 64% and 39% on average (Fig. 4). We observed the lowest R-squared value at HD038 point (15%) and the highest value at the Son Tra tide gauge (64%) (Fig.4 and Table 2). Regarding correlation coefficients between the observed and reconstructed SLA time series, the results show a large spread of values ranging from 0.38 (at HD038) to 0.8 (at the Son Tra tide gauge) and 0.61 on average. All the values of R-squared and correlation coefficients are presented in Table 3. Overall, our stepwise model appears to be reliable in reconstructing the non-seasonal detrended sea level variability over 2002-2018.

It can be seen from Fig. 4 that all SLA timeseries show very strong interannual variabilities over 2002-2018. The statistical model reproduced such variability well at some sites/points such as the Son Tra tide gauge and QN038-QN153 altimetry points (Fig.4 and Table 3). These sites exhibit the highest explained variances (64%, 61% and 57%, respectively) and correlation (0.80, 0.78 and 0.75, respectively). Here, the model can well capture the high and low peaks compared to the observed variability. For example, the low peak around the 2004/05 winter at the Son Tra tide gauge and the high peak around the 2010/11 winter at QN038 and QN153 are well reproduced (Fig. 4). We hypothesize that those two events are likely related to ENSO episodes: weak El Niño 2004/05 phase for Son Tra and strong La Niña 2010/2011 phase for QN153. The impacts of ENSO on sea-level variabilities at interannual timescale have been reported in numerous studies (see Woodworth et al., 2019 for a detailed review) and our results should be the case (see more discussion in 4.1).

Fig. 4:


HD001, R2 = 0.23, corr = 0.48
HD038, R2 = 0.15, corr = 0.38
HDtg, R2 = 0.45, corr = 0.67
QN038, R2 = 0.61, corr = 0.78
QN153, R2 = 0.57, corr = 0.75
QNtg, R2 = 0.43, corr = 0.66
ST077, R2 = 0.37, corr = 0.61
STtg, R2 = 0.64, corr = 0.80
VT140, R2 = 0.20, corr = 0.44
VT216, R2 = 0.22, corr = 0.47
VTtg, R2 = 0.43, corr = 0.66
2002 2004 2006 2008 2010 2012 2014 2016 2018
Observed Sea Level (m)
Detrended-Reconstructed Sea Level (m)

Detrended and deseasoned SLA time series and reconstructed SLA time series from regression analysis at each site/point for 2002-2018. (HDtg: Hon Dau tide gauge, STtg: Son Tra tide gauge, QNtg: Quy Nhon tide gauge and VTtg: Vung Tau tide gauge)

However, the performance of the multi-linear regression model is weaker in other sites, particularly at the HD038 altimetry point. At this point, the model can only explain about 15% variance (Table 3) and show the least correlation. We observed similar performances at the VT140 and VT216 altimetry points but the model performs better after 2008 and can reproduce some remarkable peaks (Fig. 4).

Regression analysis results over the 2008-2018 are shown in Fig. 5 and Table 3. We generally find a significantly better performance (in both R-squared values and coefficient correlations) of the model in the central and southern sites/points. There are five sites/altimetry points that the model can explain more than 75% of the observed variability: Son Tra, Quy Nhon, Vung Tau tide gauges and ST077, VT140 altimetry points. In addition, all these sites/points also show the highest correlations ($r = \sim 0.9$). One of the best results is at the Vung Tau tide gauge, with 80% explained variance and 0.9 coefficient correlation. Moreover, the reconstructed time series can reproduce very well all notable large sea level variability throughout the data length (Fig. 5). The model, however, does not perform well at HD001 (altimetry point in the northern site) with the R-squared values and correlation coefficients are lower than that of the 2002-2018 period.

The regression analysis results indicate that the statistical model can explain principal sea-level variability in most cases in this study area, especially after 2008. The decent performance of the model after 2008 suggests that the impacts of selected regressors on sea-level variability in the model might have been more dominant. Yet, the lower explained variances at some altimetry points (HD001, HD038 and QN038, see Fig. 5 and Table 3), particularly after the year 2008, also indicate that the regressors used in this study might not be suitable for those sites. On the other hand, other forcing factors/processes might play a more important role in sea-level variability there.

Over 2002-2018, our result reveals no consistent mechanism for sea-level changes at altimetry points (in the open ocean) and coastal TGs in our study. We take all pairs of TGs – Altimetry points as the case to discuss. At each site, the coastal tide gauge consistently shows a clear difference in explained variance and correlation (between observed and reconstructed time series) in contrast to near-shore altimetry points (Fig.4, Table 3). We observe higher values at Hon Dau, Son Tra, and Vung Tau tide gauges, whereas the Quy Nhon tide gauge presents lower explained variance and correlation than altimetry points. This finding indicates that coastal tide gauge would be strongly impacted by both coastal processes and/or river processes (e.g., river discharge as found in Piecuch et al., 2018). Futhermore and interestingly, the case of Quy Nhon tide gauge also suggests that the coastal sea levels behaves differently and locally, and that, in turn, reflects inconsistent influences of forcings/processes on coastal sea levels.

While the stepwise model performs better for the 2008-2018 period, we notice more consistency in statistical results at two pairs of TGs-Altimetry points: Son Tra – ST077 and Vung Tau – VT140 (Fig. 5 Table 3). The very high explained variance and correlations at Vung Tau – VT140 show a strong co-varying during this period and suggests the subset of regressors might dominate sea-level variability in this coastal region. It is also important to note that the distance to the coast of ST077 and VT140 altimetry points are relatively close (< 15 km, Table 1), likely explaining remarkably similar variability. Considering the VT216 altimetry point, we obtained lower statistical results than VT140 and Vung Tau, which might be attributed to further distance from the coastline (26.2 km) than VT140 (15.5 km). The distance-to-coast effect can also be seen at HD001 (28 km to coast), where statistical results are the lowest (11% explained variance and 0.33 correlation coefficient) and much lower than HD038 (15.2 km to coast). Together with the difference between the Quy Nhon tide gauge and its altimetry points, they support the working hypothesis that coastal sea levels vary differently with near-shore regions.

Table 3: R-squared values (explained variance) from regression analysis and correlation coefficients between observed and reconstructed SLA time series. The values are presented in two periods 2002-2018 and 2008-2018.

Tide gauge/altimetry point	R-squared (2002-2018)/(2008-2018)	Correlation coefficients (2002-2018)/(2008-2018)
Hon Dau	45%/52%	0.67/0.72
HD001	23%/11%	0.48/0.33
HD038	15%/47%	0.38/0.69
Son Tra	64%/77%	0.80/0.88
ST077	37%/77%	0.61/0.88
Quy Nhon	43%/81%	0.66/0.90
QN038	61%/51%	0.78/0.71
QN153	57%/64%	0.75/0.80
Vung Tau	43%/80%	0.66/0.90

VT140	20%/84%	0.44/0.91
VT216	22%/67%	0.47/0.82

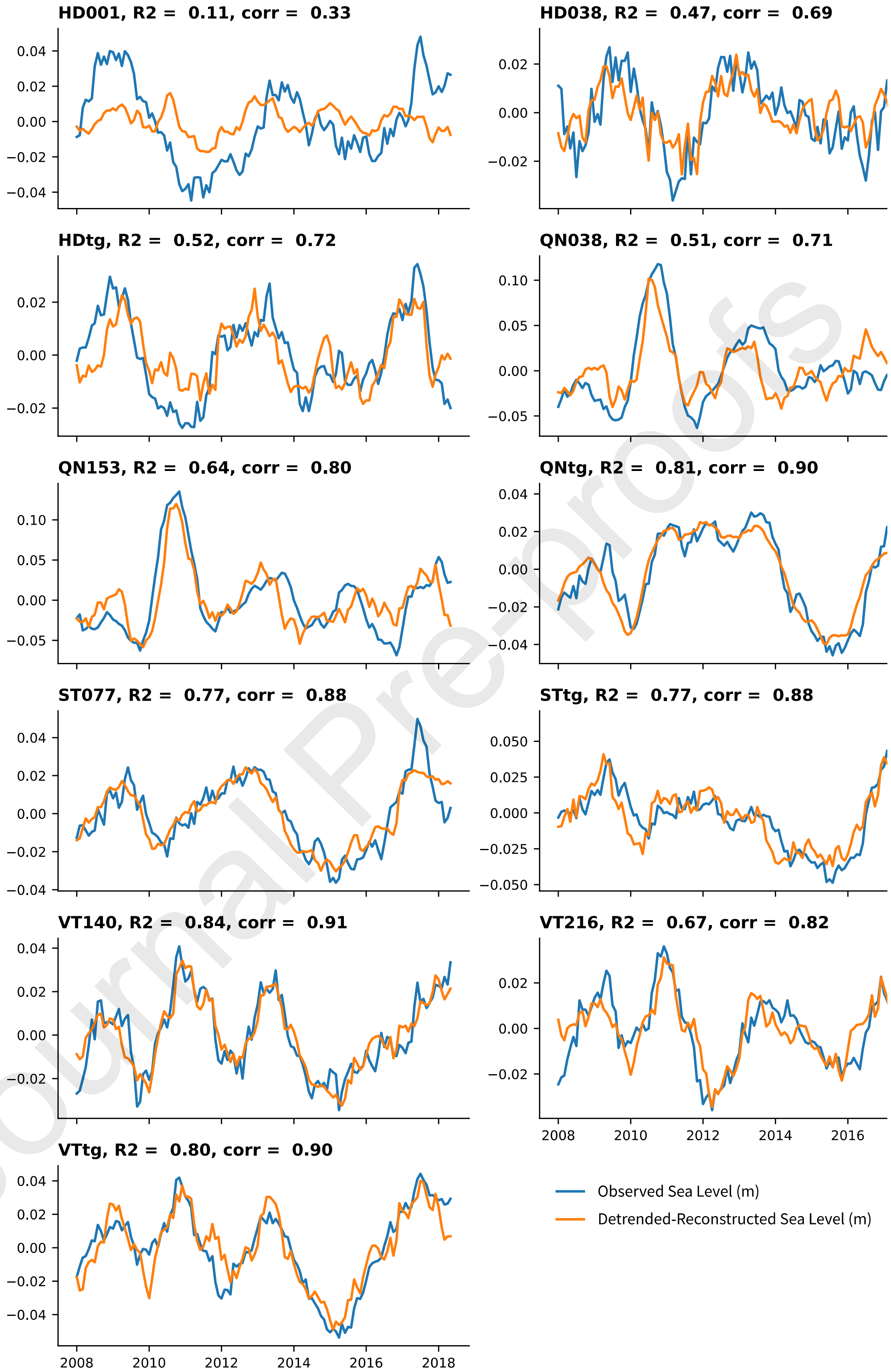


Fig. 5: Same as Fig. 4 but for 2008-2018.

As stated above, we used stepwise analysis to explore subsets of regressors that can explain most of the variability of data. Fig. 6 shows the total explained variance and the contribution of significant regressors at each site/altimetry point for the period of 2002-2018 (Fig. 6a) and 2008-2018 (Fig. 6b). It can be seen from Fig. 6 that the contribution of each forcing factor varies significantly in space. However, SST and the meridional wind stress (*tauy*) considerably impact sea-level variability at most of the sites/points for both two periods of running analysis. The impact of SST, however, is more dominant than the meridional wind stress during the 2002-2018 period when this regressor can explain more than 20% of the variance at half a number of sites (Hon Dau and Son Tra tide gauges, QN153, QN038 and ST077 point). For the period of 2008-2018, the role of meridional wind stress is more significant. This wind stress components dominate and account for more than 30% of observed variability at half a number of sites/points. We note strong contribution of meridional wind stress at Vung Tau tide gauge, VT140 and VT216 with 49.3%, 41.9% and 55.7% of explained variance, respectively. To some extent, the zonal wind stress contributes more to sea-level variability during 2002-2018.

The other important feature from the stepwise analysis is that: there are more regressors added to the model and that helps to improve the performance of the model (i.e., explain more variance) at each site/point over 2008-2018 (Fig. 6). Among remote forcings, PDO and ENSO contribute remarkably more than DMI. We observed a very strong impact of PDO at the Quy Nhon tide gauge (~ 74% of the explained variance during 2008-2018 and ~ 40% during 2002-2018), ST077 (~50%), VT140 (~40%) and Vung Tau tide gauge (~20%). ENSO signals are slightly weaker than PDO in both two periods, and the outcome only shows strong impact of ENSO at QN038 altimetry point (~20%). Moreover, there is an unexpected result with no or very less effect of ENSO at the Vung Tau tide gauge and two altimetry points (about 3% at the VT140 point). These sites and points are located in the southern EVS and are close to the area where the signals of ENSO in sea-level variability in the study area has been reported elsewhere (e.g., Soumya et al., 2015, Rong et al., 2007).

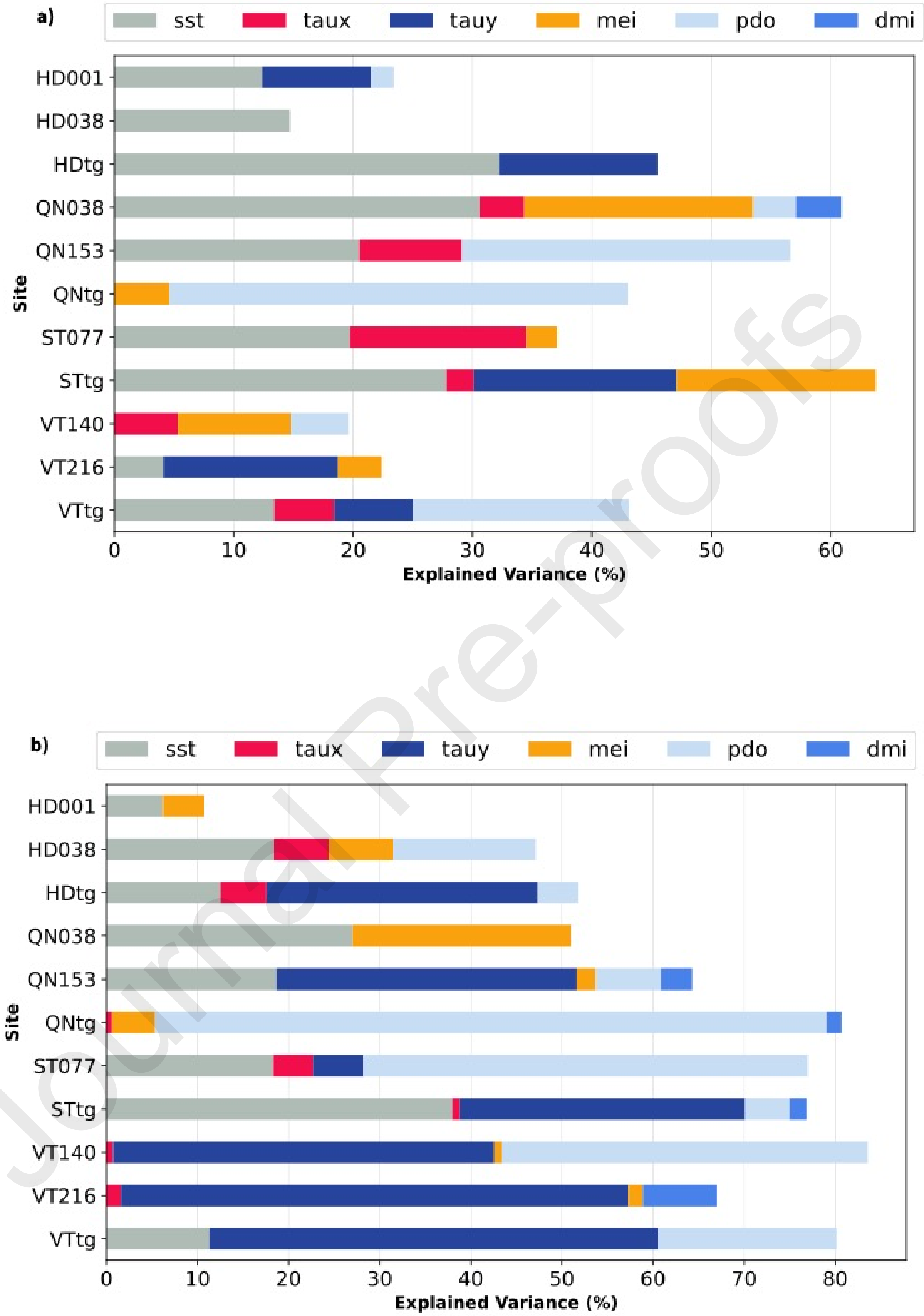


Fig. 6: Results of stepwise regression for each site/point showing the contribution of each regressor. **Fig. 6a** for the 2002-2018 period. **Fig. 6b** for the 2008-2018.

The results from stepwise regression indicate that local forcings (SST, the meridional and zonal wind stresses) contribute more to sea-level variability than remote forcings (ENSO, PDO and DMI) to some extent. Changes in sea level due to the SST factor have been very well-known as SST is related to the ocean heat content, and that, in turn, drives the thermal expansion of the water column in shallow mixed layer depth. In our results, SST appears to be a significant regressor in most sites, except for the Quy Nhon tide gauge, and since the sea-level trends in the coastal regions increase considerably (see section 4.2) so we expect that there has been an increase of SST along the Vietnam's coastline recently. Changes in sea-level variability with the varying winds have also been discussed in several studies. For example, Merrifield et al. (2012) discussed the changes in sea level in the western tropical Pacific, which are likely related to the fluctuations of trade wind forcing. In a recent study, Passaro et al. (2021) discovered the role of the meridional wind component in producing a North-South gradient in SLA at the Baltic Sea. In our study, after the 2008, the meridional wind stress is considerable dominant forcings to the for sea-level variability (Fig. 6b), and these results might provide an insight into the recent intensification of wind forcing.

Our results also indicate that there is no common subset of regressors (i.e., forcings) that can fully explain the sea-level variability at all sites/points. On the other hand, the effect of forcings on sea level along the Vietnam's coastline is not uniform and is complicated. We find no consistent mechanism for sea-level changes at each site, and thus, we conclude that the SLA in our study varies locally and differently even within a distance of 100-200 km. As a result, we recommend that other forcings should be more suitable for the statistical model for the study area, but there would be difficult to identify a universal proxy for sea-level variability.

4.3.2. Corrected sea-level trends estimated from regression coefficients

In this section, we used regression coefficients estimated from the multi-linear regression model applied to the non-detrended SLA time series to get the regression response, including the trends induced by the forcings (hereafter called forcing-induced sea level time series). The purpose of this approach is to explore the impact of selected regressors on the SLA trends (e.g., Dangendorf et al., 2013, Dangendorf et al., 2014). The results are shown in Fig. 7 (2002-2018 period) for the rates of raw SLA time series estimated in section 4.2 and those of corrected SLA time series. The corrected sea level is defined by subtracting the raw SLA time series from the forcing-induced sea level time series, which separates the slow climate component from the measured SLA time series (Dangendorf et al., 2014).

For the period from 2002-2018, we observed lower trends at 9/11 sites/points after corrections. The exceptions are the Quy Nhon tide gauge and VT140 altimetry point, where the corrected sea level shows slightly higher trend. Removing forcing-induced sea level results in significantly lower trends at most sites/points, except for a slight decrease at Vung Tau tide gauge, indicating that the forcing factors selected from stepwise regression are able to explain sea-level variability well. At the HD001, ST077, QN038 and QN153 altimetry points, the corrected trends are small and even negative (less than -0.5 mm/year) suggesting a slight decrease in sea level there. The lower sea-level trends can be explained by the lower interannual variability in the corrected sea level, which can lead to a lower fraction of background noise (Dangendorf et al., 2014). However, the results are changed for the period of 2008-2018 (not shown here) as we only observed 5/11 sites/points showing lower trend of corrected sea level and at some sites/points, the corrected trends are even considerably higher than the raw sea level. This unexpected result might be attributed to complicated sea-level variations and inconsistent mechanisms (or forcings) at each site as regression analysis mentioned above. Another reason is that the period 2008-2018 might be quite short for accurate trend analyses even though the R-squared values of least square regressions are still pretty high at most of sites/points. As a consequence, we decide not to use the results of trend estimations in the period of 2008-2018 in further discussion.

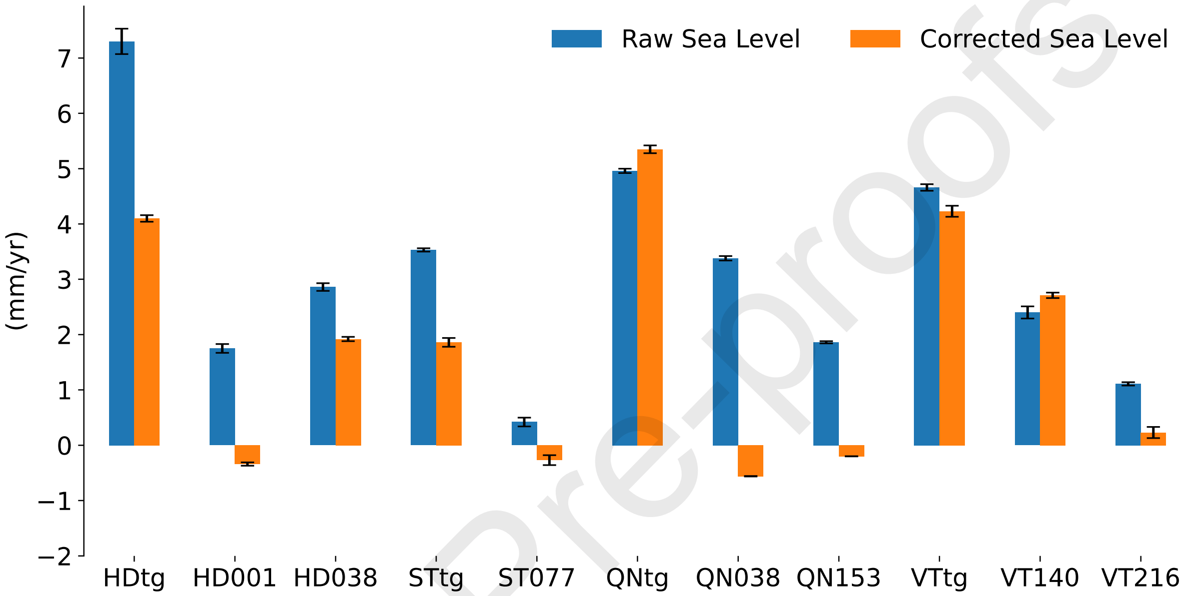


Fig. 7: Observed and corrected sea-level trends at each site/point for the 2002-2018 period

5. Summary and conclusions

This paper presents the first detailed investigation of sea-level trends and variability along the Vietnam's coastline using a combination of coastal tide gauge and altimetry data (X-TRACK/ALES product) from 2002-2018. Such investigation of regional sea-level changes in the past is highly relevant as the country has two low elevated delta regions and a long coast of 3260 km. Furthermore, the population density reaches more than 1000 persons per square km at an altitude ~ 10m above sea level all along the coastline (https://reliefweb.int/map/viet-nam/vietnam-population-density-within-and-outside-10m-low-elevation-coastal-zone).

This paper highlights good agreements in both correlations and RMSE, although the distances between the altimetry points and tide gauge sites are not close compared to other studies. The low correlations at the Quy Nhon site and points can be explained by the locations of altimetry points in the open ocean area producing different sea-level behaviors compared to coastal regions. In general, we obtained a good validation of X-TRACK/ALES along the coast of Vietnam, and the data can be used for further purposes.

One of the research questions that we would like to address in this study is that do the coastal sea-level trends vary differently from those of the open ocean areas? The answer to that question could bring more understanding and insights into regional sea-level variability, which has recently become increasingly important. We estimated the trends of the SLA time series and found that there is a spatial deviation of the trends between the coastal and open sea. The rate of sea-level rise at the coastal TGs and altimetry points is two to three times greater than at the open-ocean points. This finding contradicts a global study by Benveniste et al. (2020), where the authors find no difference in sea-level trends in our study site. The dissimilar sea-level trends should likely be attributed to local coastal processes and further distance between TGs and satellite data.

We applied a stepwise regression model to find a subset of regressors that can explain the most variance at each site/point for two periods, that is, the 2002-2018 and 2008-2018. The results show that the explained variance in the model varies significantly from place to place. It is challenging to generate a group of standard forcings for all TGs and altimetry points. This conclusion suggests that the mechanisms for sea-level variability in this study alter locally and complicatedly. We, however, note that the model performs better in the second period and local forcings (i.e., SST and wind stress components) are dominant regressors compared to remote forcings (climate patterns). The corrected sea-level trends are lower at most sites indicating that the selected regressors are able to explain the observed variability. Hence, this suggests again more detailed studies to investigate sea-level variations in one place to unveil what forcings or processes control such complicated sea-level variability in the study area. As discussed in other studies, small-scale coastal processes (e.g., wave, current or temperature-salinity gradient) might contribute to such variations (Gouzenes et al., 2020, Dieng et al., 2021). To do that, fine-resolution numerical models are definitely needed to examine changes in sea level. Finally, our study clearly emphasizes the remarkable deviation between regional and global sea level.

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DAC data can be downloaded from http://ftp-access.aviso.altimetry.fr/ ; SST and 10-m winds are available from https://cds.climate.copernicus.eu/api/v2/resources/reanalysis-era5-single-levels-monthly-means ; climate time series can be extracted from https://psl.noaa.gov/enso/mei/ for MEI index (MEI.v2), https://psl.noaa.gov/gcos_wgsp/Timeseries/Data/dmi.had.long.data for DMI index and https://www.ncei.noaa.gov/pub/data/cmb/ersst/v5/index/ersst.v5.pdo.dat for PDO index. People who would like to use the raw tide gauge data need to ask the Center of Marine and Hydrological Research (Vietnam Institute of Meteorology, Hydrology and Climate Change) for permission.

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Highlights:

- Sea-level trends show a large spatial deviation from the coast to open ocean.
- Sea-level variabilities are locally complicated and reveal inconsistent mechanisms.
- PDO and ENSO, as remote forcings, show significant influence at the southern sites.

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: