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How climate change affected on water level in Ha Long coastal area in the period 1974–2020: results from the mann-kendall test and sen’s slope estimate

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ABSTRACT

The impact of climate change on sea level has attracted much attention from scientists worldwide. The analysis of sea-level change at global and regional scales is based on altimetry and/or tide gauge data. The main objective’s study relied on statistical tests to highlight the significant long-term changes in sea level in Ha Long coastal area through the 47 years (1974–2020) historical tide gauge record of the Bai Chay station. The average water level in this area was 207.9 cm, which tended to be higher in recent years, especially from 2006 to the present (above 210 cm). Moreover, sea level trends were carried out separately for the whole period (1974–2020) and the last 19 years (2002–2020) by the Mann-Kendall test and Sen’s slope estimator. The results showed a significant sea-level rise (SLR) trend with a 95–100% confidence level. The average annual rates of sea-level were 3.14 mm/year and 5.83 mm/year in 1974–2020 and 2002–2020, respectively, indicating an SLR of about 14.76 cm over 47 years and significant acceleration in SLR recently (11.01 cm over the last 19 years).

Keywords: Sea-level rise, climate change, Mann-Kendall, Sen’s slope, Bai Chay, Ha Long.

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INTRODUCTION

Sea level change draws much attention as it represents a significant consequence of global climate warming. Global Mean Sea-level (GMSL) has been the object of apparent increase since the late nineteenth century [1]. More recently, GMSL increased at a rate close to 2 mm/year in the twentieth century [2–4]. In addition, the IPCC [5] reported that the average rate of SLR has increased faster than expected in a few recent decades: 1.3 mm/year (1901–1971), 1.9 mm/year (1971–2006), and 3.7 mm/year (2006–2018).

The regional variability in the GMSL trend is due to large-scale changes in ocean density in response to forcing factors (e.g., wind force, heat, and freshwater exchange to the air-sea interface) and their consequences on ocean circulation. Thus, the most significant regional variabilities of the sea-level are mainly due to changes in ocean temperature (i.e., nonuniform thermal expansion). Still, in some regions, ocean salinity variations are also significant [1]. As a result, local mean sea level changes usually differ from global oceans. The sea level in the East Vietnam Sea has continued to rise, at 1.0 cm/year from 1993 to 1999 [6].

SLR significantly affects socioeconomic communities in many coastal areas worldwide [7]. Increased coastal erosion due to accelerated SLR poses a severe threat to economies worldwide. As the population increases, coastal regions will likely experience additional stresses from land use and hydrological changes [8]. These changes can have devastating effects on coastal habitats further inland, leading to flooding of wetlands, salt contamination of aquifers and agricultural soils, and loss of habitat for fish, birds, plants, and many species [9]. In Viet Nam, the sea level's role in environmental conditions has been reported in many studies. For example, Vinh and Ouillon (2021) [10] showed the effect of tidal stages to develop double ETMs on the Cam Nam Trieu estuary. Hai et al., (2019) [11, 12] indicated the impact of SLR due to climate change on hydrodynamic and morphological change in the Van Uc estuary area. Moreover, the sea level also significantly impacts water quality in Hai Phong coastal and the North-Central coastal region in Viet Nam [13, 14].

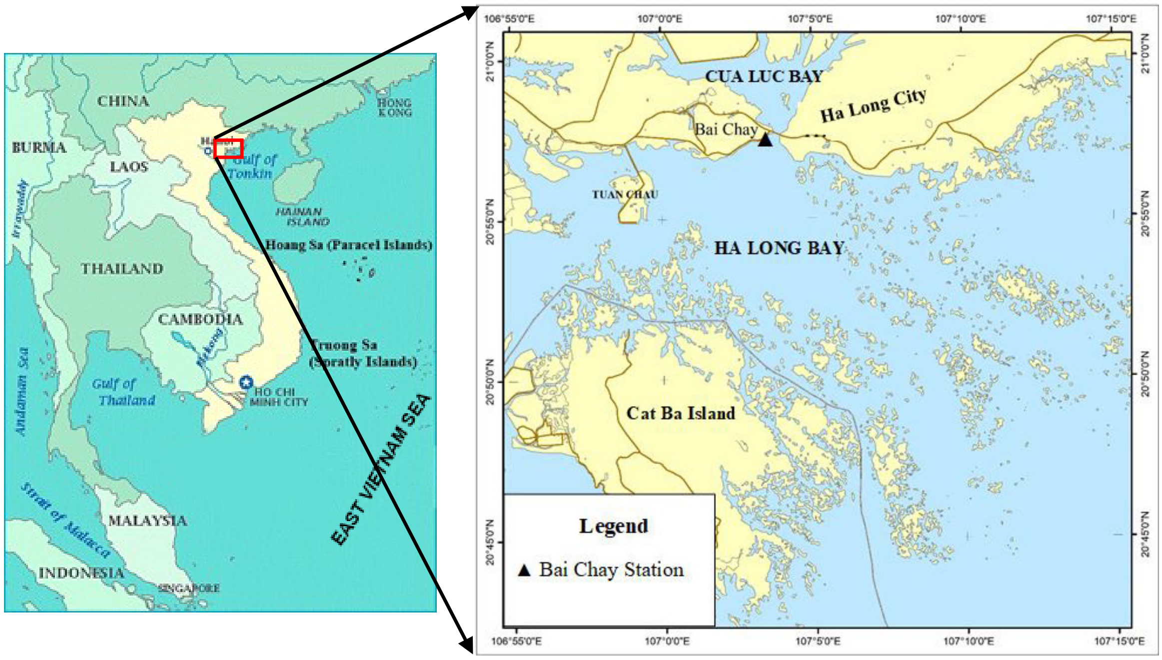

Figure 1. The Ha Long coastal area and the Ha Long station

Climatologic and hydrological trend analysis have several approaches, such as Mann-Kendall (MK) trend test, the Sen slope estimator by Pranar Kumar Sen [15], and the innovative trend analysis (ITA) [16]. One of the commonly used non-parametric trend tests is the MK test. This method was widely used in many types of research: hydrometeorological time series such as groundwater [17], water quality [18–20], streamflow [21, 22], lake level [23], temperature, and precipitation [24, 25], and SLR [26–29]. One advantage of the Mann-Kendall test is that data do not need any particular distribution. The second advantage of the test is its low sensitivity to abrupt breaks (change-points) in the time series [30]. Sen's method uses a linear model to estimate the slope of the trend (change per unit time), and the variance of the residuals should be constant in time [31]. However, the trend results from the MK method sometimes do not reflect the reality when there are many extreme values in serial data. The MK is affected by serial correlations within the time series, which may lead to a disproportionate rejection of the null hypothesis of no trend, whereas it is true [32].

Vietnam is considered one of the most affected countries by climate change [4, 33, 34]. Thus, many studies have estimated the manifestations of climate change here, especially SLR. According to [35], SLR varied between 1.75 mm/year and 2.56 mm/year during 1961–2000 in four coastal stations of Vietnam: Hon Dau (North), Da Nang, Quy Nhon (Center), and Vung Tau (South). MONRE [36] reported that the sea level in Bai Chay station increased by 1.54 mm/year in 1962–2014, which was 0.91 mm/year lower than the mean sea-level of all tide gauges in Vietnam. Recently, Ca [28] illustrated that the Bai Chay tide gauge sea level increased by 2.07 mm/year from 1961 to 2012. Some recent studies use Mann-Kendall, Sen's slop, and the Empirical mode decomposition methods (EMD) to calculate water level and temperature trends due to climate change at annual, seasonal, and monthly scales at the Hon Dau station as well as show the relationship between ENSO and these factors [37, 38]. However, all research in Ha Long coastal area only calculated annual SLR and did not analyze the trend of SLR on monthly and seasonal scales. Therefore, this study will examine the sea-level trend as annual, seasonal, and monthly at the Bai Chay tide gauge from 1974 to 2020, explicitly analyzing the recent trend from 2002 to 2020.

MATERIAL AND METHODS

Ha Long coastal area

The Ha Long coastal area has a total area of 1,553 km, including 1,969 large and small islands, with high biodiversity, affluent marine resources, and high economic activities. Based on observations from 1990 to 2017 at the Bai Chay station, the average air temperature was 23.2–24.1 ^{o}C. While the average temperature was below 20 ^{o}C in the winter (November–December, January–March), it was above 26.8 ^{o}C in summer (from May to September). Analysis of measurements from 1997–2016 at the Cua Ong station showed that the average annual rainfall oscillated from 1,626.6 mm (2002) to 321.5 mm (2015). Like as Hai Phong coastal area, the rainy season extended from May to October and occupied 84–92% of totally annual rainfall [39]

The Ha Long coastal area has the Northeast-Southwest shoreline; the wave directions in the Northeast monsoon are Northeast and Northeast, and South and Southeast in the Southwest monsoon. Wave heights in these seasons are 2.5–3 m and 3–3.5 m, respectively. The average storm wave is 5–7 m high, and the maximum is 10 m. This area is influenced by diurnal tide, with an amplitude of 2.6–4.0 m in spring tide and about 0.5–1.0 m in the neap tide, higher than Hai Phong coastal area [40]. Besides, the encroachment activities in the coastal area of Ha Long took place firmly due to urbanization and socio-economic development. Vinh et al., [41] reported that encroachment activities significantly influenced the mean field current in Cua Luc inlet, in the middle of Ha Long bay and south-southwest of Tuan Chau island. These activities also made the accretion rate increase in the middle of Cua Luc embayment (5–15 mm/year), in Cua Luc inlet (20–30 mm/year), in the middle of Ha Long bay (5–10 mm/year) and south of Tuan Chau island (30–50 mm/year).

Data and methods

Hourly sea-level measurements at the Bai Chay station (20°57’4.29”N,107°03’38.2”E) were collected by the Vietnam Hydro-Meteorological Data and Information Center and analyzed from 1974 to 2020 (47 years) to calculate the sea-level trend. To clarify the recent trend, this study separately analyzed data from 2002 to 2020 (19 years). The tidal data at Bai Chay station was measured by staff/tide poles before 2014 and the Stevens Type A-04 (made by the USA) after 2014.

The trend is defined as the general movement of a series over a long period or the change in the dependent variable over a long time [42]. The non-parametric Mann-Kendall test was derived from Mann [43] by Kendall [44]. The Sen slope calculation is based on a 1950 proposal by Theil, developed by Sen in 1968 [14, 45]. This method is commonly used to quantify linear trends in time series [46]. In addition, the mean, standard deviation (SD), and coefficient of variation (CV) of sea level were calculated.

The Mann-Kendall test

The Mann-Kendall test is a widely used statistical test for analyzing climatological and hydrological time series trends. It avoids the local maximum values of the data series. The null hypothesis, H_0, is that the data compare the relative magnitude of elements in the data series, a population with independent realizations that does not follow any trend. The alternative hypothesis, H_1, is that the data follow a clear trend.

The Mann-Kendall S statistic is calculated by analyzing all possible pairs of measurements in the data set. If the earlier measurement is less magnitude than a later one, S is incremented by one. On the other hand, if an earlier value is greater in magnitude than a later sample, S is decremented by one.

The Mann-Kendall statistic parameter, S is computed as follows:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sign\left(X_j - X_i\right) \quad (1)$$

where: X_i and X_j are random variables (divided the given time series X into two variables, as $X_1, X_2, \ldots, X_i$; and $X_{i+1}, X_{i+2}, \ldots, X_j$).

$$Sign\left(X_j - X_i\right) = \begin{cases} 1 \text{ if } X_j - X_i > 0 \\ 0 \text{ if } X_j - X_i = 0 \\ -1 \text{ if } X_j - X_i < 0 \end{cases} \quad (2)$$

The variance of S, $VAR(S)$ is given by:

$$VAR(S) = \frac{n(n-1)(2n+5) - \sum_{p=1}^{m} t_p\left(t_p - 1\right)\left(2t_p + 5\right)}{18} \quad (3)$$

The standard test statistic Z_S is calculated as follows:

$$Z_S = \begin{cases} \dfrac{S-1}{\sqrt{VAR(S)}} & \text{for } S > 0 \\ 0 & \text{for } S > 0 \\ \dfrac{S+1}{\sqrt{VAR(S)}} & \text{for } S > 0 \end{cases} \quad (4)$$

where: n is the number of data points; m is the number of unique values (without duplicates); and t_p is the frequency of the p^{th} value. If $|Z_S|$ is greater than $Z_{\alpha/2}$, where α represents the chosen significance level (α =10% at the 90% confidence level with $Z_{0.05}$ = 1.65; α =5% at the 95% confidence level with $Z_{0.025}$ = 1.96; α =1% at the 99% confidence level with $Z_{0.005}$ = 2.58), then the null hypothesis is invalid implying that the trend is significant.

A positive value of Z indicates an increasing trend, and *a* negative value indicates a decreasing trend. Using P-value calculated for Z, H_0 is rejected if $P < \alpha$.

The Sen slope estimator

Sen [14] proposed the non-parametric Sen's slope statistics. The slope for each pair of data may be calculated as follows:

$$Q_k = \frac{X_j - X_i}{t_j - t_i} \tag{5}$$

where: $k = [1, n(n-1)/2]$, $I = [1, n-1]$, $j = [2, n]$. X_j and X_i are the data values at time t_j and t_i, respectively.

Sen's slope estimator can be calculated as follows:

$$Q_m = \begin{cases} Q\left[\dfrac{n+1}{2}\right] & \text{if } n \text{ is odd} \\ \dfrac{Q_{n/2} + Q_{(n+2)/2}}{2} & \text{if } n \text{ is even} \end{cases} \tag{6}$$

The Q_m sign reflects data trend, while its value indicates the steepness of the trend.

RESULTS

Temporal variation of the sea-level

The measured data at the Bai Chay station were analyzed between 1974 and 2020 and illustrated in Figure 2. The result showed that the average water level was 207.9 cm; from 2006 to the present, the average water level was above 210 cm. The highest annual average sea-level was reached 218.56 cm in 2017, while the lowest value was 187.08 cm in 1986. The maximum sea-level varied from 203.19 cm (1986) to 244.59 cm (2020), withvalues were higher than 220 cm. The minimum values were less than 210 cm, especially about 173.7 cm in 1986. From 2006 to 2020, they were higher than 200.85 cm, except in 2011 (199.51 cm).

During 1974–2020, the maximum monthly water levels were above 213 cm, significantly more than 220.23 cm in January, July, August, September, October, November, and December, and less than 218.94 cm from February to June. The minimum monthly water level varied between 173.75 and 203.19 cm. The lower values occurred from January to Jun, below 179.56 cm. Average monthly water levels tend to be higher between September and December (215.11–218.87 cm), especially in October (204.05 cm), while the lowest value was about 199 cm in March (Figure 3, Table 1).

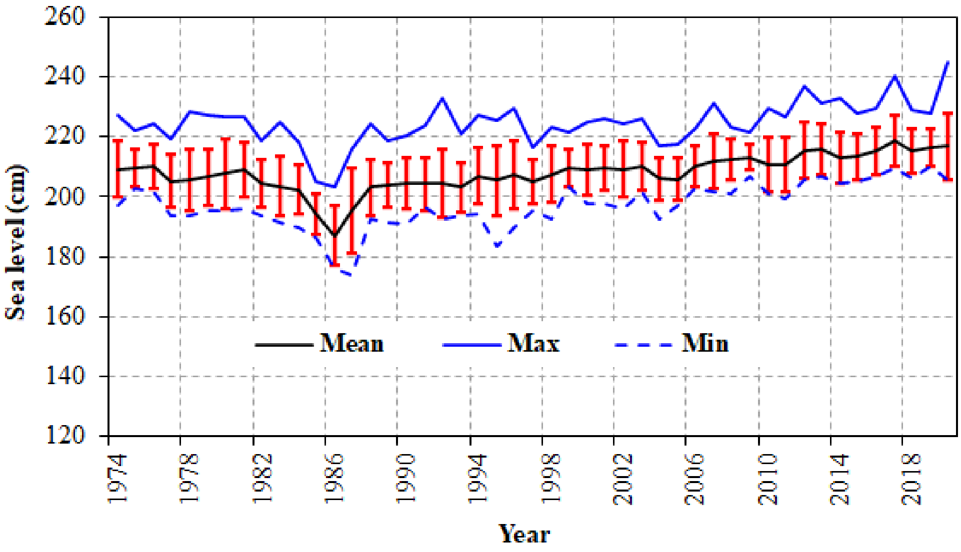

Figure 2. Average annual sea-level at the Bai Chay station (1974–2020)

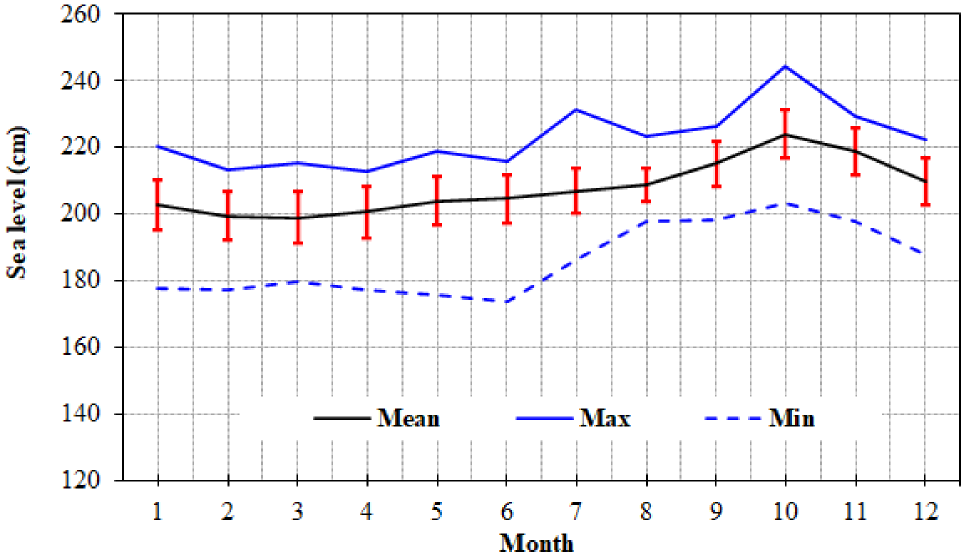

Figure 3. Average monthly sea-level at the Bai Chay station (1974–2020)

Table 1. Statistical information of sea-level (cm) at the Bai Chay station (1974–2020)

Month	Maximum	Minimum	Mean	SD (cm)	CV (%)
January	220.23	177.84	202.99	7.47	3.68
February	213.30	177.35	199.55	7.29	3.66
March	215.42	179.56	199.02	7.78	3.91
April	213.06	177.09	200.69	7.64	3.81
May	218.94	175.79	204.08	7.24	3.55
Jun	215.91	173.75	204.68	7.24	3.54
July	231.25	186.46	207.06	6.65	3.21
August	223.33	197.60	208.79	4.91	2.35
September	226.44	198.30	215.11	6.88	3.20
October	244.59	203.19	224.05	7.33	3.27
November	229.49	197.88	218.87	6.84	3.12
December	222.43	187.73	209.88	6.89	3.29
Average	218.56	187.08	207.90	5.94	2.86

The calculated standard deviation (SD) showed that sea-level values were close to the mean from July to December (except October), with an Std Dev less than 6.9 cm and a coefficient of variation (CV) of about 3.3% (Table 1). However, the higher Std Dev in March and April (transition season), with 7.78 and 7.64 cm, respectively, showed that the mean sea-level varied over a broader range.

The time series of annual sea levels at the Bai Chay station showed an apparent increase for all months, with a positive slope value ($a > 0$) (Figure 4). The coefficient of determination R^2 varied from 0.178 to 0.4432. That means this linear regression model explains 17.8–44.32% of the variability in the annual sea level.

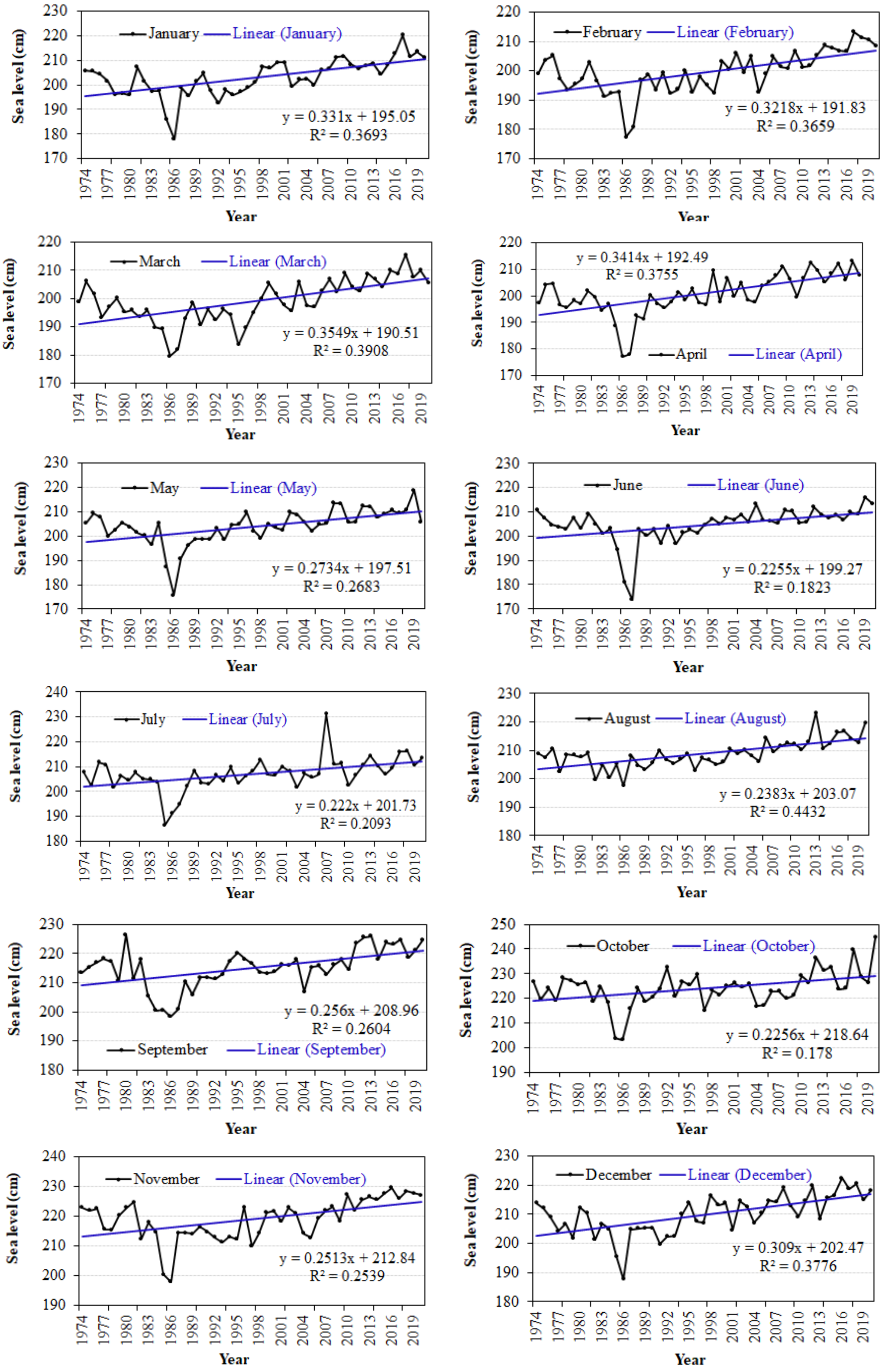

Figure 4. Monthly average sea level at the Bai Chay station (1974–2020)

The trend of sea level in the Ha Long coastal area

The sea-level trend at the Bai Chay station was analyzed based on the Mann-Kendall test and Sen's slope estimator for the periods 1974–2020 and 2002–2020. The results of the Mann-Kendall test on the monthly data are presented in Tables 2 and 3. For the annual trend, the Mann-Kendall test *Z*-parameters (5.61 in 1974–2020 and 4.34 in 2002–2020) were higher than 1.65, confirming a significant increasing trend. The *P*-values were 0 and 0.000014 in 1974–2020 and 2002–2020, respectively, and were below the considerable level $\alpha = 0.05$, indicating a 95–100% confidence level trend. Based on Sen's slope, the rising sea-level trend was 5.83 cm/year from 2002–2020, which was 2.69 higher than in 1974–2020 (Table 2 and Table 3).

We applied the Mann-Kendall test to test the trend and calculated Sen's slope to distinguish between SLR in the dry and rainy seasons. An increasing seasonal trend was detected for both periods ($Z > 0$), with *Z*-stat greater than $Z_{0.005} = 2.58$, indicating a significant trend at the 99% confidence level. From 1974–2020, the SLR in the dry season was 3.54 mm/year, which was 1.12 mm/year higher than in the rainy season. Over 2002–2020, they were 5.88 mm/year and 4.1 mm/year in the dry and the rainy seasons, respectively. In both periods, the SLR in the dry season was higher than in the rainy season (Table 2 and Table 3).

The monthly sea-level time series at the Bai Chay station was analyzed to show varying trends between 1974 and 2020. The Z-stat values varied from 2.31 to 4.99, indicating a significant positive trend ($Z > 0$) for all months from 1960–2020. The monthly average rate in this period varied from 1.54–3.64 mm/year, lower than 2002–2020. SLR was higher than 3 mm/year in December and from January to April. They were lower from May to November, with 1.54–2.71 mm/year values. *P*-values (0.000002–0.020835) below the significant level $\alpha = 0.05$ confirm a trend at a 95% confidence level.

Table 2. The trend of sea-level rise (mm/year) in the Bai Chay station (1974–2020)

Month	*P*-value	*Z*-stat	Rate of sea-level	Trend
January	0.000001	4.84	3.35	Significant
February	0.000003	4.7	3.38	Significant
March	0.000004	4.62	3.64	Significant
April	0.000001	4.99	3.22	Significant
May	0.000037	4.13	2.54	Significant
June	0.000152	3.79	1.88	Significant
July	0.000302	3.61	1.79	Significant
August	0.000001	4.89	2.34	Significant
September	0.000087	3.93	2.64	Significant
October	0.020835	2.31	1.54	Significant
November	0.000429	3.52	2.71	Significant
December	0.000002	4.77	3.09	Significant
Dry season	0	5.32	3.54	Significant
Rainy season	0	5.08	2.42	Significant
Average	0	5.61	3.14	Significant

The MK test and Sen slope were also applied to the monthly data for 2002–2020. The results showed that the monthly average sea level increased from 2.06–8.15 mm/year. There was a statistically significant trend in most of the months of the year: January, February, March, April, July, August, October, November, and December, as the *P*-values were less than 0.05, indicating a confidence level of 95%. Two months (May and June) had no significant statistics due to *P*-values being more than 0.1. While the monthly sea level was the highest in October, at 8.15 mm/year, the lowest value was 3.83 mm/year in December.

Table 3. The trend of sea-level rise (mm/year) in the Bai Chay station (2002–2020)

Month	*P*-value	*Z*-stat	Rate of sea-level	Trend
January	0.0003	3.64	6.47	Significant
February	0.0002	3.78	6.59	Significant
March	0.003	3.01	6.45	Significant
April	0.004	2.87	5.36	Significant
May	0.142	1.41	2.48	No significant
June	0.132	1.5	2.06	No significant
July	0.05	1.96	4.49	Significant
August	0.001	3.22	4.26	Significant
September	0.003	2.98	6.12	Significant
October	0.004	2.87	8.15	Significant
November	0.0004	3.57	5.60	Significant
December	0.017	2.38	3.83	Significant
Dry season	0.000119	3.85	5.88	Significant
Rainy season	0.001007	3.29	4.1	Significant
Average	0.000014	4.34	5.83	Significant

Discussion

This study analyzes in-situ tidal gauge measurements at the Bai Chay station over different periods. All months showed a statistically significant increasing trend (95–99%), except May and June in 2002–2020 (85.8–86.8%). The annual average rate of SLR in 2002–2020 was 5.83 mm/year, higher than 2.69 mm/year during the period 1974–2020, indicating an SLR of about 14.76 cm over 47 years (11.01 cm over the last 19 years) and significant acceleration in SLR recently. The SLR trends are consistent with this area's previous results [28, 36]. However, the rates of SLR in1974–2020 and 2002–2020 were higher than the result obtained by Ca [28] for the period 1962–2012 (2.07 mm/year) and more significant high than the calculation by MONRE [36] from in situ data of the Bai Chay station between 1962 and 2014 (1.54 mm/year). While, in 1974–2020, SLR in Bai Chay station (3.14 mm/year) was lower than the average water level rise at all coastal stations of Vietnam in the period 1993–2014 (3.5 mm/year) [36], the opposite trend was found for the period 2002–2020 (5.83 mm/year). These results provide further evidence of the rise of sea-level in the Ha Long coastal area has been more in recent years, which was caused by some reasons such as climate change, tectonic, ENSO, encroachment,… The signs and effects of the subsidence are a very complex issue. Therefore, in this study, the sea level rise did not consider the effects of tectonic uplift and subsidence. Moreover, the impact of ENSO on SLR has also been interpreted in recent studies. Hai et al., [38] showed the contribution of ENSO to SLR at Hon Dau station varied from -3.7 to 7.2 cm from 1972–2020 [47]. SLR at the Hon Dau station in 1960–2020 was 3.56 mm/year [38], slightly higher than Bai Chay station in 1974–2020 (3.14 mm/year). But from 2002–2020, there was a marked difference in SLR between the Hon Dau and Bai Chay stations, with 7.78 mm/year and 5.83 mm/year, respectively. Besides, the impacts of encroachment activities on sediment transport and deposition in the Ha Long-Bai Tu Long coastal area were expressed in the study of Vinh et al., [41]; therefore, these activities also might influence SLR in this area. In addition, global SLR also shows considerable variability in its rate. While mean sea-level has risen very little over the past, recent analyses indicated a much more significant global SLR, with 1.5–2.0 mm/year for the 20th century [2] and ten times higher than in previous centuries [48]. It was a noticeable increase in the global mean sea-level rate: about 1.6 mm/year in 1880–2009; 3.2 ± 0.4 mm/year and 2.8 ± 0.8 mm/year in 1993–2009 from satellite and in-situ data, respectively [49]. The latest IPCC report [5] indicated that the average rate of sea-level had increased faster than expected in recent decades: 1.3 mm/year (1901–1971), 1.9 mm/year (1971–2006), and 3.7 mm/year (2006–2018). The reasons for this rise result from two major processes: the thermal expansion of the ocean caused by variations in the thermal content of the sea and the inflow of freshwater into the sea caused by the melting of the polar ice caps and mountain glaciers, as well as potential exchanges with continental water reservoirs [50–52]. Besides, the volcanic eruptions of Mt Agung in 1963, El Chichon in 1982, and Mt Pinatubo in 1991 are likely to have contributed to the small sea-level drops in the next few years [53, 54].

CONCLUSION

This study estimated the mean sea-level change in the Ha Long coastal area from the in-situ data of the Bai Chay station for 1974–2020 and 2002–2020. The Mann-Kendall test and Sen’s approach are performed to identify statistically significant trends and magnitudes of the changes in these series. The results showed an increasing sea-level with a 95–100% confidence. The rates of mean sea-level were 3.14 mm/year and 5.83 mm/year in 1974–2020 and 2002–2020, respectively, indicating a sea-level rise of about 14.76 cm over 47 years and 11.01 cm over the last 19 years. These trends were also observed for months, with a more marked increase in the dry season than in the wet season. Over the period 1974–2020, the monthly average rates of SLR varied from 1.54 mm/year to 3.64 mm/year (a difference of 2.1 mm/year), while in 2002–2020, almost all values were higher than 4 mm/year.

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