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Forecasting sea level rise and its fluctuations in Khanh Hoa coastal area in Vietnam

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Abstract

Sea level are increasing under the influence of climate change, especially in recent decades. Assessing the trend (increase/decrease) and forecasting changes in sea level makes an important contribution to socio-economic development planning and national defense and security in coastal areas. Water level fluctuations in Khanh Hoa water basin over the past decades (1975-2021) were analyzed using linear regression method, from hourly actual water level data measured at the Oceanographic and Environmental Monitoring station Cau Da beach school that is managed by the Institute of Oceanography. Average sea level tends to decrease from 1975 to around 1998, then increases rapidly from 1998 to 2021, the period of local sea level decrease is recorded from 2016 to 2021. In general, in the period from 1975 to 2021, the average sea level tends to increase with an estimated increase of 2.58 ± 0.38 mm/year. It is forecasted that in the near term (the next 10 years), the average sea level will increase by about 2,521 cm.

Keywords: Mean sea level fluctuations; Trend; Mann-Kendall; Linear regression; Cau Da station.

1. Introduction

Global sea level rise is a negative important signal for life on Earth that has been warned about for nearly a century. The increase is becoming more and more serious with global warming climate change that is caused ice melting on the poles rapidly. Furthermore, in

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general, rising sea levels at low and medium rates that endanger the survival of most species caused fewer effects on the semi-tropical areas (Serajoddin and Noori, 2019).

In recent decades, Vietnam has experienced a significant rise in sea levels. This phenomenon is primarily attributed to global warming and the subsequent melting of glaciers and ice caps, as well as the expansion of seawater due to increased temperatures. In fact, sea level rise poses a particularly severe threat due to its long coastline and low-lying delta regions. The Mekong Delta, for example, is highly in danger to inundation as it is situated at or below sea level. Globally, the Intergovernmental Panel on Climate Change (IPCC) has reported that sea level has risen by an average of about 3.6 millimeters per year between 2006 and 2015. This rate is significantly higher than the average observed during the 20th century. If greenhouse gas emissions continue unabated, projections suggest that global sea level could rise up to one meter by the end of this century (Thuc *et al*., 2016).

From data measurement at the stations around the world, the rising trend of sea level is determined. Douglas (1991) through data analysis of 21 points with an average length of 76 years, stated that the water level trend increased by an average of 1.8 - 1.9 mm/year ± 0.1 for the cycle 1880-1980. At that time, many scientists believed that the average global water level increase was only about 1 mm/year or less than that within 100 years from 1880 to 1980. In 1997, Douglas reviewed many studies and updated them and analyzes and concluded that the increase in global sea level is nearly 2 mm/year. According to NOAA's updated analysis results in 2019, almost all stations' water levels tend to increase significantly compared to the results of Douglas (1997) (Table 1).

Church and White (2006) stated that since the 20th century, global sea level fluctuations have increased by an average annual rate of 1.7 ± 0.3 mm/year; and Holgate and Woodworth (2004) reported that sea level during 55 years (1948- 2002) increased by about 1.7 ± 0.2 mm/year, of which it is noteworthy that the period higher than in previous decades. Spada and Galassi (2012) showed that global sea level rise is 1.5 ± 0.1 mm/year during the period 1888- 2010.

Many issues raised up by the researchers related to the trend of increasing global sea levels, moreover due to thermal expansion, and also melting ice, vertical movement of the Earth's crust and other water sources such as floods, tsunamis, surges, etc. The vertical movement of the Earth's crust was later gradually resolved by measuring absolute gravity of the Earth's crust movement, or satellite applications to measure sea surface elevation. Assessing the amount of freshwater added to global sea level rise, Chao (1991) and Gornitz *et al*. (1997) calculated that over 40 years, an additional amount of water equivalent to 0.7-0.9 mm /year global sea level rise has been stored in large and small reservoirs and other basins, so the current Global Sea Level Rise (GSLR) rate is higher than the increasing trend of water level recorded at tide stations.

In the 5th report of the IPCC (IPCC, 2013) and also observations before 1971 confirmed that the increase in global average sea level contributed up to 75% from global thermal expansion in ocean and ice melting mainly in Antarctica. By the early 1990s, this issue continued to increase. This report also represented that the increase in global average sea level during 1993-2010 was up to 90% due to the contribution of water from ocean thermal expansion and mass loss of glaciers. IPCC (2013) forecast with different climate change and ice melt scenarios showed a global average sea level rise of 0.26-0.55 m with the RCP2.6scenario from 0.45- 0.82 m with the RCP8.5scenario in the period 2081- 2100 compared to the period 1986- 2005. Oppenheimer and colleagues (2019) suggested a new statistical method and said that the global average sea level (GMSL) increased by an average of 1.38 mm/year during the period 1901-1990.

Table 1. Results of sea level trend analysis by Douglas (1997) and NOAA (2019)

Station / Country	Douglas (1997)		NOAA (2019)	
	Trend (mm/year)	String length	Trend (mm/year)	String length
Newlyn / England	1.7	1915-1991	1.84	1915-2018
Brest / France	1.4	1880-1991	1.01	1807-2018
Cassias / Portugal	1.3	1882-1988	1.32	1882-1993
Lagos / Portugal	1.5	1902-1990	1.62	1908-1999
Tenerife / Spain	1.5	1927-1991	1.67	1927-2017
Marseille / France	1.2	1885-1991	1.3	1885-2018
GENOVA/ Italy	1.2	1884-1989	1.18	1884-1997
Trieste / Italy	1.2	1905-1991	1.31	1875-2018
Auckland / New Zealand	1.3	1904-1989	1.29	1903-2000
Dunedin / New Zealand	1.4	1900-1989	-	-
Littleton / New Zealand	2.3	1904-1989	2.76	1924-2018
Wellington / New Zealand	1.7	1901-1988	2.72	1944-2018
Honolulu / US	1.5	1905-1991	1.51	1905-2019
San Francisco / US	1.5	1880-1991	1.99	1897-2019
Santa Monica / US	1.4	1933-1991	1.55	1933-2019
La Jolla / US	2.1	1925-1991	2.13	1924-2015
San Diego / US	2.1	1906-1991	2.2	1906-2019
Balboa / Panama	1.6	1908-1970	1.43	1908-2018
Cristobal / Panama	1	1909-1970	-	-
Quequen /Argentina	0.8	1918-1983	-	-
Buenos Aires / Argentina	1.5	1905-1988	-	-
Pensacola / US	2.2	1923-1991	2.46	1923-2019
Key West / US	2.2	1913-1991	2.47	1913-2019
Fernandina / US	1.8	1897-1991	2.15	1897-2019
Average	**1.56**		**1.796**	

According to Dangendorf *et al*. (2019), subsequent updates are based on new statistical method proposals. Frederikse *et al*. (2020) stated that the GMSL increased by an average of 1.35mm/year in the period 1901-1990; moreover, Palmer *et al*.'s (2021) results were 1.3-1.4mm/year from 1901-1990. The IPCC report (IPCC, 2021) updated that the GSLR rate has increased faster than expected in the last few decades: 1.3 mm/year (period 1901-1971), 1.9mm/year (period 1971-2006) and 3.7mm/year (period 2006-2018), on average during the period 1901-2018, sea level increased by 0.15- 0.25 m (Kale, 2020).

Water level fluctuation trends in the East Sea and surrounding areas are assessed through NOAA analysis (https://tidesandcurrents.noaa.gov/sltrends/mslGlobal-TrendsTable.html). Above analysis was according to the information from different tidal testing stations, China (10), Malaysia (6), the Philippines (5), Thailand (4), Vietnam (4), Singapore (3), Indonesia (1), and Taiwan (1). The trend of sea level rise has certain differences, most of them have an increasing trend, only Qinhuangdao station (China) has a decreasing trend (- 0.04 mm/year); Fort Phrachula Chomklao station (Thailand) and Manila station (Philippines) have the largest increasing trends, 16.87 and 14.54 mm/year respectively. The northern part of the East Sea has a smaller average increase trend than the southern part. On average, the stations in China and Taiwan increase by 1.82 mm/year, while stations in Malaysia, Thailand, and Indonesia have an average increase up to 4.02 mm/year. On the coast of Vietnam, Vung Tau station has the largest increase in sea level with 3.7 ± 0.96 mm/year, Da Nang station reaches 3.17 ± 0.73 mm/year, Hon Dau station reaches 2.05 mm/year. ± 0.46 mm/year, Quy Nhon station increased 0.2 ± 1.17 mm/year.

Thus, the southern part of the East Sea has a higher sea level rise than the northern part of the East Sea. Although there have been quantitative results for sea level rise, there are some unusually high results such as in Manila (Philippines) and at Fort Phrachula Chomklao (Thailand), as well as quite large differences. There is still no reasonable explanation between stations. Hourly water level at the Cau Da Oceanographic and Environmental Monitoring station is conducted by the Institute of Oceanography (VAST) and has stored quite complete data from 1975 to present. Fluctuations of average sea level using data from 1975- 2008 at this station have been described by Nguyen (2010), sea level decreased in the period of 1975- 1992, increased during 1992- 2008. Results with the trend of average sea level increase in the period 1992-2008 is quite consistent with many studies by other scientists around the world (Holgate and Woodworth, 2004; Church and White, 2006; Spada and Galassi, 2012; IOC-UNESCO, 2022), showed that the water level increased rapidly in the years from 1993 to 2002. Nguyen (2010) also said that there was a fluctuation with an average cycle of nearly 6 years in Cau Da water level. Chung *et al*. (2018, 2019) analyzed fluctuations in typical monthly, seasonal, and annual average water levels from 1975-2016 and found that historical high water level fluctuations often occurred during the La Nina period, and is related to processes with seasonal, inter-seasonal, annual, and multi-year cycles, and increased sharply from 2006-2016.

Updating measured data until the end of December 2021, using a combination of methods such as regression analysis, Mann-Kendall trend analysis, and Pettitt change point determination (Conte *et al*.,2019), the article shows the changing in average sea level trend in different periods and moreover it forecasts the average sea level fluctuations in the future time (from 2022-2031).

2. Materials and methods

2.1. Data

Cau Da station on the coast of Nha Trang Bay, Khanh Hoa province, Vietnam is managed by the Institute of Oceanography (VAST). The station's coordinates are: 109° 12.46' E and

12° 12.96' N. Hourly water level data from February 1975 to December 2021 at Cau Da Oceanography and Marine Environment Monitoring Station (Institute of Oceanography). In particular, there are some periods without data such as:

- 1989: Due to repairing and upgrading the station, the water level was not measured;
- June 1975; November 1975; December 17, 1984-December 31, 1984; November 1987; August 1988; from October 1988 to December 1989; February 1990; March 1990; May 1990; March 1, 2002 - March 11, 2002; from September 8, 2006 - November 10, 2006;

2.2. Method

Analyzing sea level series trends from 1975-2021 using the linear regression model RegressIt (2020), announced in 2014 and developed up to now. This is a model built to run on MS Excel, easy to use and free. The model provides statistical parameters before linear regression analysis.

Before using the regression model, the monthly average characteristics; the annual average, needs to be calculated. When determining these characteristics, months and years with missing data or errors exceeding 20% will be considered as having no data. RegressIt can run even for data strings with certain spaces.

The Mann-Kendall up/down trend method is a widely performed test for observing trends in a series over time. This non-parametric test has the advantage that the data need not follow any specified distribution (Mann, 1945; Kendall, 1955; Kendall, 1976), also known as a non-parametric test. The non-parametric Kendall correlation coefficient is calculated according to Equation (1) as follows:

$$\tau = \frac{S}{n(n-1)/2} \qquad (1)$$

$$S = \sum_{i=1}^{n-1} \sum_{k=i+1}^{n} sgn(x_k - x_i) \qquad (2)$$

which, x_i (i = 1, 2, …, n-1) and x_k (k = i + 1, …, n) are time series. Where S is the test statistic; S is positive if the variable increases over time, or the number of concordant pairs is x_i and x_k. On the contrary, S is a negative number if the number of discordant pairs is xi and x_k. When the number of samples is greater than 10, S is replaced by Z_c - a statistic approximated by a normal distribution according to Equation (3). This formula is used by most statistical software.

$$Z_c = \begin{cases} \frac{S-1}{\sqrt{var(S)}} & S > 0 \\ 0 & S = 0 \\ \frac{S+1}{\sqrt{var(S)}} & S < 0 \end{cases} \qquad (3)$$

If α is called the statistical significance level, the value corresponding to the confidence level of the statistic, $Z_{\alpha/2}$ will receive the corresponding value: α = 10% at the confidence level of 90% with $Z_{0.05} = 1.65$; $\alpha = 5$ % at the 95 % confidence level with $Z_{0.025} = 1.96$; $\alpha = 1$ % with 99% confidence level with $Z_{0.005} = 2.58$). If $|Z_c| > Z_{\alpha/2}$, the trend meaning that there is a clear trend. Furthermore, negative values of τ identify a decreasing trend, while positive values of τ identify an increasing trend, and there is no obvious trend when τ = 0; Mann-Kendall trend analysis can be performed on the website built by Wessa (2017).

The non-parametric change point determination method was first proposed by Pettitt (1979) with the aim of distinguishing important changes in the mean value of a time series. Change score analyzes were performed using R statistical software (R Core Team, 2022). The hypothesis of this analysis is that the variables follow distributions with similar location parameters and there is no change point, as opposed to the alternative hypothesis that a change point exists, that is called the null hypothesis. The formulas used to analyze change points are:

$$K_T = \max|U_{t,T}|, \mathrm{t} = 2 \ldots \mathrm{T} \quad (4)$$

$$U_{t,T} = \sum_{i=1}^{t} \sum_{j=t+1}^{T} sgn(x_i - x_j) \quad (5)$$

In Equations (4) and (5), K_T is the null hypothesis, $U_{t,T}$ checks whether the two variables x_i ($x_1, \ldots, x_t$) and x_j ($x_{t+1}, \ldots, x_T$) are in the same set or not. The probability of association (p) is used to calculate the significance level. The change point occurs when Equation (4) is satisfied.

3. Results and Discussion

3.1. Seasonal sea level fluctuations in Cau Da

Seasonal sea level at Cau Da Station has a SIN shape, the months with high water levels are above the average value of many years from October to January of the following year (highest in November), the months with lower water levels are the lower average for many years from March to August, and the months of February and September have water levels approximately equal to the average water level for many years (Figure 1). Thus, the months with higher average water levels every year coincide with periods of rain and storms in the area (Vlasova *et al*., 2020). Therefore, if high water levels and storm surges occur at the same time, it can easily cause negative impacts on marine economic activities such as maritime, fisheries, tourism and agriculture. In comparison with the results of the study by Mahsafar et al. (2017) Urmia lake's level simulation during 2000- 2100 based on the climatic variables showed a declining trend in the water level in the future. The highest reduction values in the lake's level, simulated by HadCM3 model was obtained on September that may be due to the sharp rise of temperature in the months of August to February and a remarkable decline in inflows to the lake in the months of November to April.

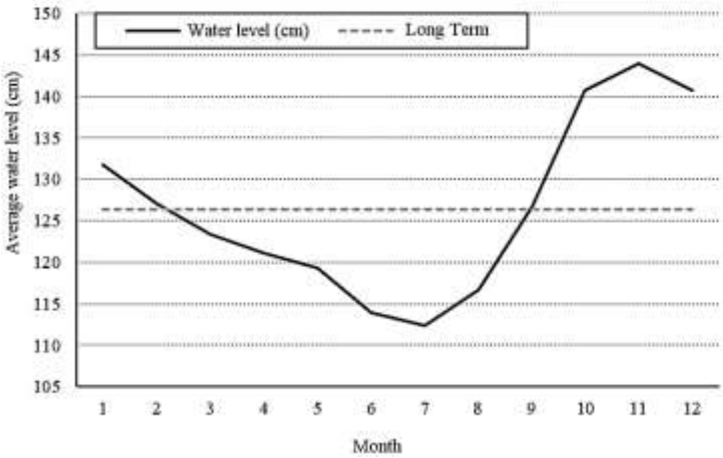

Figure 1. Seasonal fluctuations of average water level from 1975 to 2021, Cau Da Station-Nha Trang, Vietnam

As it is seen in Figure 2, the minimum average water level at Cau Da station fluctuates in the form of two annual SIN shapes (with two peaks and two legs); with the high peak occurring in October (reaching 67.18 cm relative to station “0”) and the low peak occurring in March (reaching 52.78 cm relative to station “0”); low leg in July (reaching 20.11 cm compared to station “0”) and high leg in January (reaching 44.84 cm compared to station “0”). The minimum water level value (absolute minimum) also occurs in July (2 cm in July 1979).

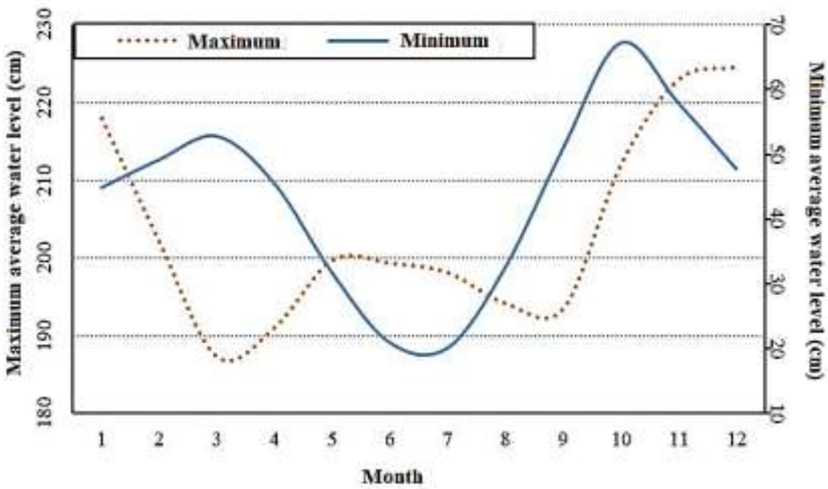

Figure 2. Seasonal fluctuations of maximum and minimum water levels from 1975 to 2021, Cau Da Station - Nha Trang

3.2. Sea level trend at Cau Da station

The annual average water level evolution at the Cau Da Oceanographic Monitoring Station and marine environment is quite complicated, with increases/decreases interspersed between years. However, in general, it shows that sea level tends to increase gradually from 1975 to 2021 (Figure 3). Using the Mann-Kendall trend analysis method and finding change points in the trend using the Pettitt method (1979) shows that the period 1975-2021 has an increasing trend with the coefficient τ reaching 0.45 and the year of change is 1998 (Table

2). As stated, τ takes values from -1 to +1, showing that the water level in the period 1975-2021 has a clear increasing trend.

At the period 1975-1998 and from 1998-2021 increasing/decreasing trend is clearly seen. The results show that, in the period 1975-1998, sea level had a small decreasing trend with the coefficient τ reaching -0.16. During the period 1998-2021, sea level tends to increase with the coefficient τ reaching 0.30 (Figure 4). Looking in more detail for each period, it can be seen that from 1975-1991, the sea level decreased, from 1991-1998 the water level was almost unchanged, from 1998-2015 the water level increased quite sharply with the coefficient τ reaching 0.56, In the recent period from 2016 to 2021, the water level decreased quite sharply with the coefficient τ reaching 0.50. Thus, before 1998, the water level had less fluctuation than from 1998 to 2021. Especially from 2016 to 2021, the water level tended to decrease quite sharp.

This is distinct from the global mean sea level trend, which scientists say is increasing rapidly (IPCC, 2021; Oppenheimer *et al.*, 2019; Dangendorf *et al.*, 2019; Palmer *et al.*, 2021) and the increasing trend of sea level in the period 2001-2020 in Hon Dau waters - Vietnam (Nguyen, 2022). Sea level changes in the period 1975-1998 analyzed here are consistent with the results given by Nguyen (2010).

Table 2. Results of Mann-Kendall trend analysis and Pettitt change points by stage

Period 1975- 2021	Period 1975- 1998	Period 1998- 2021
τ value: 0.45	τ value: -0.16	τ value: 0.30
Year of change: 1998	-	-

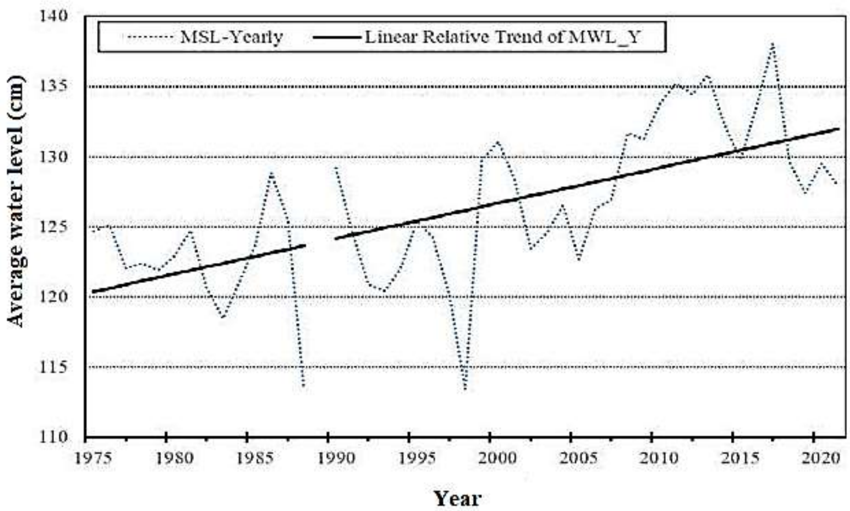

Figure 3. Change trend of average annual water level from 1975 to 2021, Cau Da Station - Nha Trang

Analyzing sea level trends from 1975 to 2021 using the RegressIt model shows that the average sea level trend at Cau Da station increases about 2.58 ± 0.38 mm/year with 95% confidence level (Figure 5). According to the analyzed trend, it is forecast that in the period up to 2031, the average sea level will increase by 2,521 cm compared to 2021, reaching a height of 125,322 - 143,685 cm (compared to station "0") with the conditions Not to mention the increase in the greenhouse effect and the increase in ice melting at the poles.

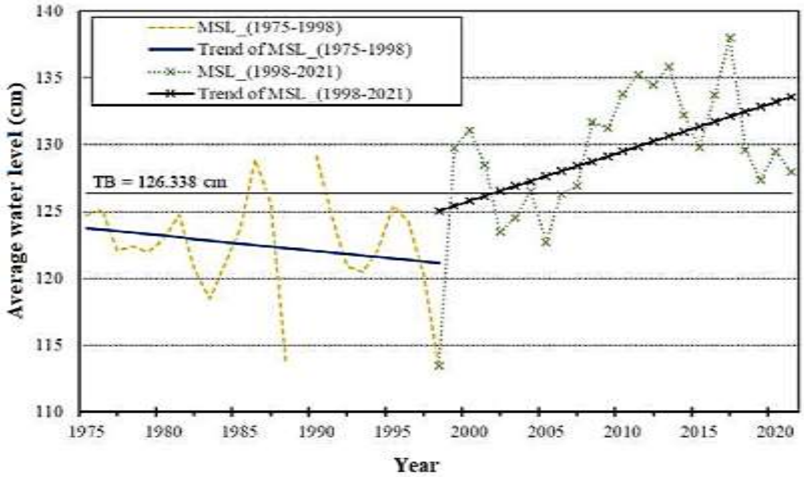

Figure 4. Trend of average sea level change through each period, Cau Da Station - Nha Trang

Sea level trends for each period at Cau Da Station are shown in Figures 6 and 7. During the period 1975-1998, the water level here decreased on average -0.47 mm/year. During the period 1998-2021, the water level here will increase by an average of 4.00 mm/year (a sharp increase). The average sea level rise trend at Cau Da Station from 1975 to 2021 which is higher than the global sea level rise trend given by Douglas (1997) with average value of 1.56 mm/year, and higher than the trend given by NOAA analysis in 2019 with average of 1,796 mm/year (Table 1), but quite consistent with IPCC report in 2021, 1.9 mm/year in the period 1971-2006 and 3.7 mm/year in the period 2006 -2018. NOAA's (2019) analysis results for water level stations in the East Sea, of which Vietnam has four stations, give an average result of 3.06 mm/year, higher than the analysis results at Cau Da station.

The relationship between sea level fluctuations and influencing ocean-atmosphere factors have not yet been evaluated and the processes such as sea surface wind stress, sea surface temperature, sea water density, especially the Pacific Decadal Oscillation (PDO) are responsible for most of the increased sea level rise (SLR) that has been observed in the western tropical Pacific since the 1990s (Oppenheimer *et al*., 2019). The PDO is associated with continual increases and decreases in sea level over a decade or more, making changes in coastal areas. In the coming time, updating more water level data and data on related processes will give a better understanding of sea level fluctuations in the Nha Trang - Khanh Hoa region and their relationship with atmosphere-ocean processes.

This result does not show whether during the period 1975-2021 there was geological shifts that change the elevation of the gauge. Hopefully, after comparison with satellite altitude data, better results can be obtained. The trend of sea level decrease in recent years (2016-2021) and a fluctuation of sea level with a cycle of about 6 years was reported by Nguyen (2010) through analysis of sea water level fluctuations from 1975-2008 at Cau Da station.

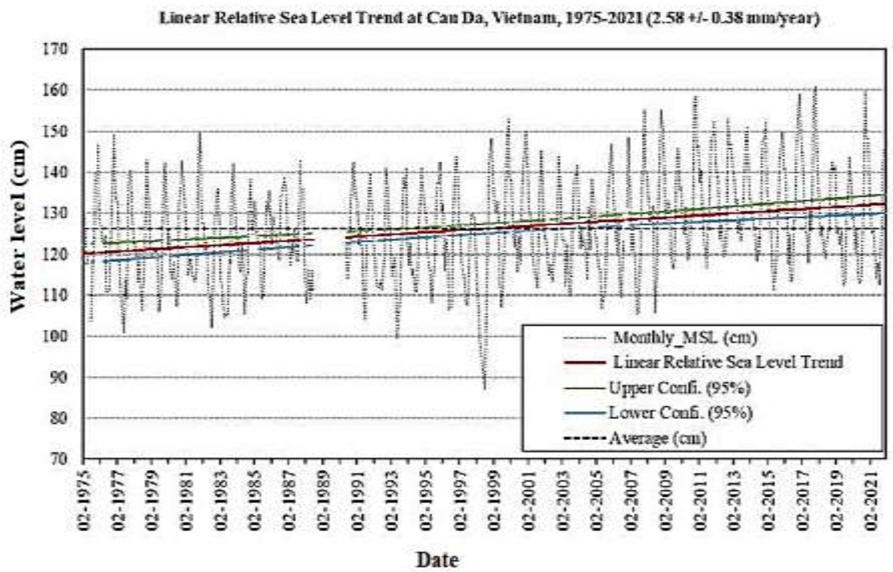

Figure 5. Trend of monthly average sea level fluctuations from 1975 to 2021 with 95% confidence, Cau Da Station - Nha Trang.

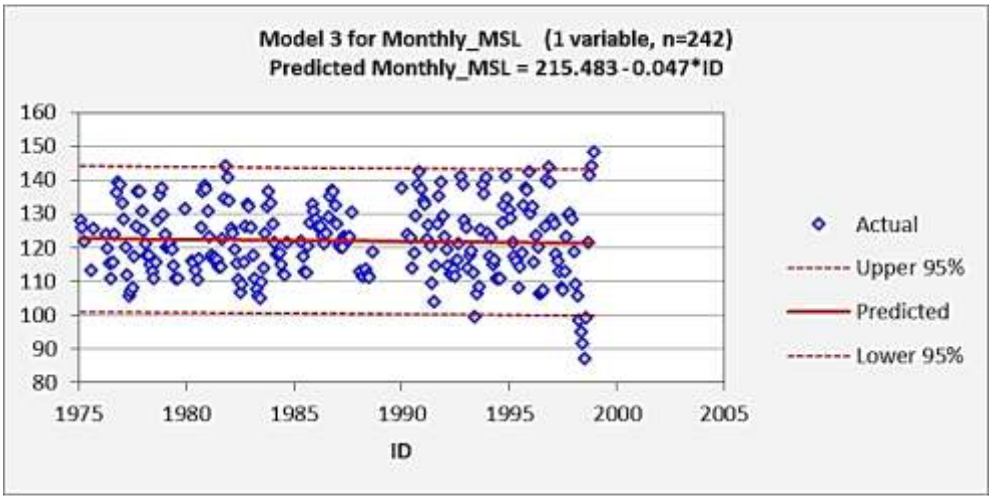

Figure 6. Trend of average sea level fluctuations from 1975-1998, Cau Da Station - Nha Trang

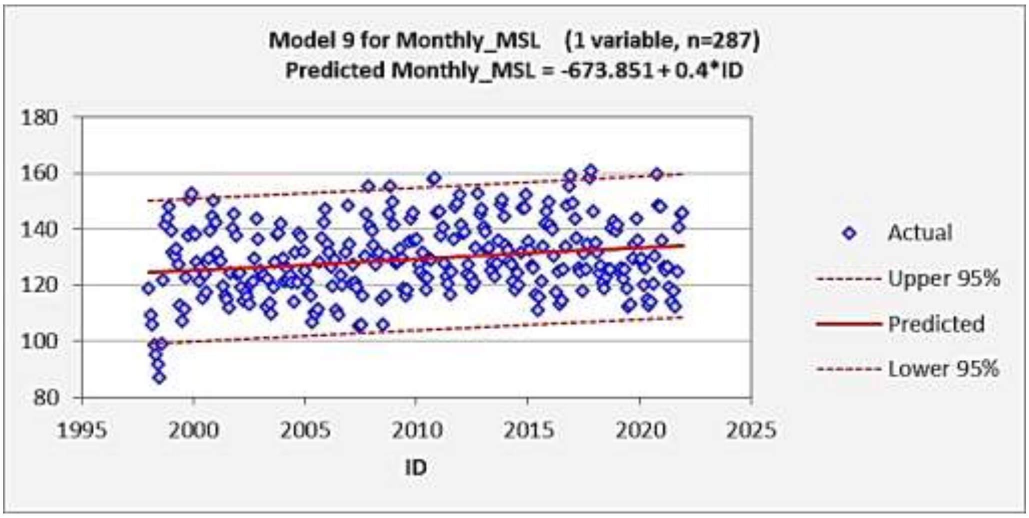

Figure 7. Trend of average sea level fluctuations from 1998 to 2021, Cau Da Station - Nha Trang

Conclusions

Analyzing sea level fluctuations at tidal stations in general and at Cau Da station in particular contributes to clarifying the picture of global sea level rise, especially the sharp increase in recent decades. Sea level at Cau Da station has increased by an average of 2.58 mm/year during the period 1975-2021, this increase includes a slight decrease from 1975-1998 (average -0.47 mm/year) and a period of strong increase from 1998 to 2021 (average 4 mm/year), thus, 1998 was the year when the trend changed.

As a result, coastal erosion, saltwater intrusion into freshwater sources, and increased flooding have become more frequent and severe in many parts of the country. The consequences of rising sea levels are far-reaching. They include increased coastal erosion, loss of land and habitats, displacement of communities, damage to infrastructure and agriculture, salinization of freshwater sources, and heightened vulnerability to storm surges and extreme weather events. To mitigate these impacts, Vietnam and also the international community have been taking measures such as implementing coastal protection strategies, constructing dikes and embankments, promoting sustainable land use practices, enhancing early warning systems for floods and storms, and advocating for global efforts to reduce greenhouse gas emissions.

However, addressing sea level rise requires concerted efforts at both local and global levels. It necessitates not only adaptation measures but also substantial reductions in greenhouse gas emissions to limit further warming of the planet. International cooperation is crucial in order to effectively tackle this complex issue and protect vulnerable coastal regions around the world.

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Conflict of interest

The authors state that here is no conflict of interest with this paper.

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