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Long-Term Relative Sea-Level Variability and Its Relationship with Large-Scale Climate Modes along the South Central Coast of Vietnam

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ABSTRACT

This study investigates long-term relative sea-level variability along the South Central Coast of Vietnam using tide-gauge observations spanning 40 years at Quy Nhon and 51 years at Cau Da, and examines its relationships with major large-scale climate modes. Sen's slope estimation indicates that relative sea level increased at both stations at rates of 1.91–2.36 mm yr⁻¹, with trend significance at the 90% confidence level. Empirical Mode Decomposition separated the sea-level series into six components. Among them, Intrinsic Mode Functions (IMF) 3 and IMF4, with dominant periods of 2.13–2.37 and 5.33 years, respectively, represent interannual variability associated with El Niño–Southern Oscillation (ENSO), whereas IMF5, with a common period of 10.67 years at both stations, reflects decadal variability likely related to Pacific Decadal Oscillation (PDO). Composite analysis revealed that sea-level anomalies decreased by 2.9–3.2 cm during El Niño events and increased by 2.4–3.2 cm during La Niña events. Correlation analyses showed significant negative relationships between sea-level anomalies and the Oceanic Niño Index (ONI) and PDO, with response lags of 1–4 months and 1–2 months, respectively, whereas the Indian Ocean Dipole (IOD) exhibited only weak or statistically insignificant correlations. Partial correlation and multiple regression analyses further identified ENSO and PDO as the important large-scale climate drivers influencing interannual sea-level variability. ENSO exerted a stronger influence at Cau Da, while PDO contributed more substantially at Quy Nhon. Together, these climate modes explained approximately 22–25% of the observed interannual sea-level

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variance. These findings provide new insights into regional sea-level dynamics and support future assessments of sea-level change and coastal adaptation along the South Central Coast of Vietnam.

Keywords: Sea Level Variability; Long-Term Trends; Large-Scale Climate Modes; Interannual Sea-Level Variance; South Central Coast of Vietnam; ENSO; PDO; Empirical Mode Decomposition

1. Introduction

Sea-level rise is widely recognised as a key manifestation of ongoing climate change. Beyond reflecting climate variability, it increasingly threatens coastal environments through flooding, shoreline erosion, saltwater intrusion, and ecosystem degradation. Quantifying long-term sea-level trends and understanding the processes responsible for their variability are therefore essential for oceanographic research, coastal management, and climate-change adaptation.

The global mean sea level (GMSL) rise has been indicated in numerous reports and publications, confirming a rise rate of approximately 1.7 mm yr^{-1} during 1901–2010 and 3.2 mm yr^{-1} during 1993–2010^[1]. This long-term increase is generally attributed to ocean thermal expansion together with the ongoing loss of glacier and ice-sheet mass. However, regional sea-level changes may differ substantially from the global mean trend due to the influences of ocean circulation, temperature and salinity variations, large-scale climate change, Glacial Isostatic Adjustment (GIA), and Vertical Land Motion (VLM)^[2, 3]. Long-term tide-gauge observations indicate an increase of approximately $1.4\text{--}1.9 \text{ mm yr}^{-1}$ during the twentieth century^[4–8], particularly acceleration in recent decades under the combined effects of oceanic thermal expansion, increased ice-mass loss, and large-scale atmospheric circulation^[9–11].

Through the analysis of satellite altimetry data over the last three decades, global sea level rise reveals rapid global sea-level rise together with pronounced regional differences, with the tropical Western Pacific region being one of the regions experiencing significantly higher sea level rise rates than the global average^[11–13]. Many studies indicate that, in addition to long-term rising trends, sea level change is also strongly influenced by natural climate variations on interannual and decadal timescales^[14–16]. The El Niño–Southern Os-

cillation (ENSO) and Pacific Decadal Oscillation (PDO) changes can explain much of the sea level variability in the Western Pacific region through changes in trade winds, ocean circulation, and temperature distribution in the basin^[11, 12]. Furthermore, PDO oscillations are closely related to ENSO through ocean-atmosphere interactions in the North Pacific, and the combination of these two oscillations creates an East-West Pacific “see-saw” pattern that strongly affects temperature, precipitation, and sea level throughout the Pacific basin^[17, 18]. Rising sea levels in coastal areas also increase saltwater intrusion and degradation of water under land in many coastal areas^[19, 20].

The IPCC AR6 report emphasizes that regional sea-level assessments should simultaneously consider natural climate oscillations and the intrinsic variability of the climate system to distinguish externally forced signals from internal climate variability^[21, 22]. Wang^[23] also argues that the simultaneous assessment of the effects of climate oscillations such as ENSO, PDO, and the Indian Ocean Dipole (IOD) is necessary to identify the mechanisms governing regional sea-level variability.

The South China Sea (East Sea) is a marginal sea on the western Pacific where many countries with the most dynamic socio-economic activities are strongly influenced by the Asian monsoon, water exchange with the Pacific Ocean, and basin-scale climate oscillations. Publications have indicated that the effects of atmospheric pressure, monsoon stress, and oceanic dynamic processes can alter sea level in the South China Sea. These influencing factors can explain about 66% of its seasonal variation^[24]. In addition, variability of mean sea level, tides, and extreme climatic conditions also contribute to extreme sea level rise^[25, 26]. Analysis of tide-gauge observations and satellite altimetry data in recent decades shows a faster increase in sea level in the South China Sea, similar to its increase globally. However, the rise has been estimated at a higher rate, approximately 3.9–

4.4 mm/year, and has annual, interannual, decadal, and long-term variability trend components^[27–31]. In particular, many recent studies have highlighted the role of large-scale climate oscillations in regional sea level variability. The combined influence of ENSO with PDO or IOD significantly increases extreme sea level rise^[26], while ENSO also influences coastal hazard processes and coastal flood risk^[32, 33]. In the seas around Hainan Island in the South China Sea, La Niña events can raise sea level by about 15 cm with a lag of about six months^[34]. In the southern South China Sea, such as the Java Sea, sea level decreases during El Niño events and increases during La Niña events. In this sea area, the influence of IOD on sea level change is more dominant than that of ENSO^[35–38]. Overall, it can be seen that sea level variation in the South China Sea is simultaneously influenced by multiple climate-oceanographic processes and regional and time scale changes.

In Vietnam, studies on sea level change are mainly based on long-term tide-gauge records to assess trends and impacts of climate change. Nguyen et al.^[39, 40] applied the Mann–Kendall test, Sen’s slope estimator, and Innovative Trend Analysis (ITA) to assess sea-level trends at the Hon Dau tide gauge during 1961–2020. Their results indicated mean sea-level rise rates of approximately 3.08–3.38 mm yr^{−1}, with more rapid increases occurring in recent decades. Analysis using Empirical Mode Decomposition (EMD) further revealed the presence of interannual oscillations associated with ENSO, with characteristic periods of approximately 2–6 years^[40]. In the coastal waters of Vietnam, the result of a regression analysis shows that ENSO and PDO have played an important role in explaining sea level variation as the large-scale climatic factors^[41]. In addition, rising sea levels were thought to increase wave height, reduce current speed, and total sediment volume, causing more dangerous impacts on coastal erosion on the western side of Nha Trang Bay, South Central Vietnam^[42].

Although numerous studies have examined sea-level rise and the influence of climate oscillations in the South China Sea and along the Vietnamese coast, the understanding of sea-level variability along the South Central Coast of Vietnam remains limited. Most previous studies have focused either on long-term sea-

level trends or on the relationship between sea level and ENSO alone, while the relative contributions of ENSO, PDO, and IOD across different timescales have not been comprehensively evaluated. In particular, although the influence of ENSO has been referred to in several works^[40, 41], the simultaneous impact of ENSO, PDO, and IOD on sea level variation along the Vietnamese coast has not yet been systematically evaluated. Meanwhile, previous studies have demonstrated that these oscillations can interact to change ocean circulation, winds, and sea level in space and time^[11, 19, 20, 23, 26].

In addition, previous studies in Vietnam have mainly focused on the Hon Dau station in the South China Sea, or satellite altimetry records available since 1993. By contrast, long-term tide-gauge observations (from 40 to 51 years) in the South Central Coast of Vietnam remain largely underutilised. This region is characterised by complex oceanographic processes, including the combined influence of the Northeast and Southwest monsoons, coastal upwelling, the circulation, and basin-scale climate variability. Consequently, sea level variability in this area may exhibit responses that differ substantially from those observed elsewhere in the South China Sea.

Furthermore, most existing studies have examined the relationship between sea level and individual climate indices separately, whereas the combined effects of ENSO, PDO, and IOD across multiple temporal scales, as well as their spatially varying influence and lagged responses along the Vietnamese coastline, remain poorly understood. Distinguishing the long-term sea level rise signal from natural variability associated with these large-scale climate modes therefore remains an important research challenge, with direct implications for improving sea level projections and supporting the development of effective climate change adaptation strategies.

Therefore, this study uses long-term tide-gauge observations from the South Central Coast of Vietnam to: (i) assess long-term relative sea-level trends using the Hamed–Rao modified Mann–Kendall test, Sen’s slope estimator, and Innovative Trend Analysis (ITA); (ii) decompose sea-level variability into different temporal-scale components using Empirical Mode Decomposition

(EMD); and (iii) clarify the roles of ENSO, PDO, and IOD in driving sea-level variability through correlation analysis, partial correlation analysis, and multiple regression. The results contribute to a better understanding of the mechanisms controlling sea-level variability along the South Central Coast of Vietnam and provide a scientific basis for future sea-level projections and climate-change adaptation strategies in coastal regions.

2. Materials and Methods

2.1. Coastal Waters of South Central Vietnam

The South Central coast of Vietnam extends approximately from 11° N to 16° N along the western margin of the South China Sea. The region is characterised by a narrow continental shelf and a steep offshore bathymetry, making it highly responsive to regional and basin-scale oceanographic processes, including monsoonal forcing, South China Sea circulation, storm surges, and large-scale climate variability (**Figure 1**).

The study area is located within the tropical monsoon zone and is alternately influenced by the North-

east Monsoon (October–March) and the Southwest Monsoon (May–September). Seasonal variations in monsoon winds strongly affect sea-level fluctuations, ocean circulation, and coastal–offshore water exchange.

The coastal area surrounding Quy Nhon station is located on a relatively wider continental shelf and is strongly influenced by freshwater discharge from the Kon-Ha Thanh River system, making it more susceptible to coastal processes. In contrast, Cau Da station is situated on a narrower continental shelf with a steeper bathymetric gradient and is more directly connected to the open South China Sea, facilitating greater water exchange between the coastal zone and the offshore ocean. Furthermore, Cau Da Station is located adjacent to the South Central Vietnam upwelling region, where the Southwest Monsoon, coastal circulation, and basin-scale ocean dynamics more strongly influence sea-level variability. These differences in continental shelf morphology, coastline orientation, monsoon forcing, coastal–offshore water exchange, and freshwater influence from rivers may contribute to the contrasting sea-level responses to large-scale climate modes such as ENSO, PDO, and IOD.

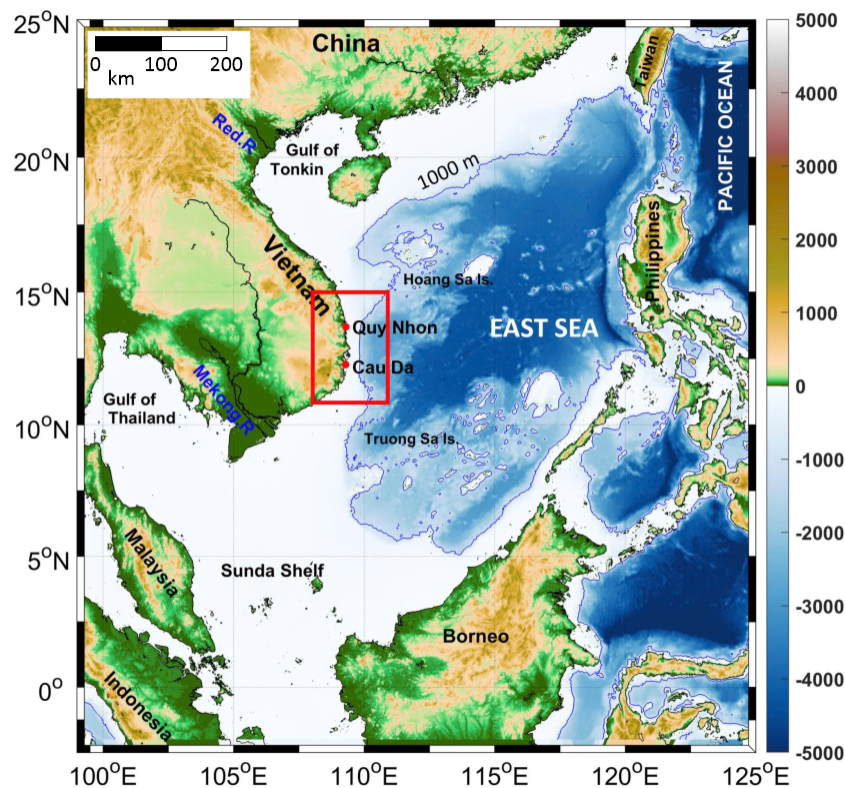


Figure 1. Study area and tide gauge stations for data collection.

The regional tidal regime is classified as irregular diurnal, with a mean tidal range of approximately 1.5–2.0 m. Consequently, observed sea-level variability reflects the combined influence of astronomical tides, monsoon-driven processes, large-scale climate oscillations, and long-term sea-level rise.

Two long-term tide-gauge stations were selected to represent the study area: Quy Nhon station in the northern sector and Cau Da station in the southern sector (**Figure 1**). The Quy Nhon record is relatively continuous from 1986 onward, whereas Cau Da provides one of the longest sea-level records in Vietnam, with observations available since 1975. These long-term datasets provide a robust basis for assessing sea-level trends, temporal variability, and the influence of large-scale climate modes along the South Central coast of Vietnam. **Figure 1** shows the geographical location of the study area and the distribution of the two tide-gauge stations used in this study.

2.2. Data Collection

Hourly sea-level data from January 1975 to December 2025 (51 years) at the Cau Da tide gauge (coordinates: 12°12' N, 109°13' E), located in the coastal waters of Khanh Hoa Province, Vietnam, and managed by the Institute of Oceanography, VAST, were used in this study. The Cau Da tide gauge station was constructed and operated by the French since the 1950s. However, data from the early period until 1975 were stored incompletely, and the vertical datum was unclear; therefore, they were not used in this study.

Hourly sea-level data from the Quy Nhon station (coordinates: 13°46' N, 109°14' E) from April 1986 to December 2025 (40 years), located in the coastal waters of Gia Lai Province (formerly Binh Dinh Province), Vietnam, and managed by the Vietnam Meteorological and Hydrological Data and Information Center, were also utilised.

Monthly average Oceanic Niño Index (ONI) data from 1975 to 2025 were collected from the NOAA website (NOAA Center for Weather and Climate Prediction database): <https://www.cpc.ncep.noaa.gov>. These data are based on a 3-month running mean of SST anomalies in the Niño 3.4 region (5° N–5° S, 120° W–170° W),

used to identify El Niño (warm phase) and La Niña (cold phase) conditions in the tropical Pacific.

Monthly average of the Pacific Decadal Oscillation (PDO) data from 1975 to 2025 was collected from the NOAA website (<https://psl.noaa.gov>; accessed on 10 March 2026). The PDO index is defined as the leading empirical orthogonal function (EOF) mode of monthly SST anomalies in the North Pacific Ocean (20° N–70° N), after removal of the monthly climatological mean SST (based on the 1920–2014 climate mean). Positive and negative PDO phases correspond to distinct basin-scale SST and sea-level pressure anomaly patterns in the North Pacific Ocean and represent an important mode of decadal climate variability^[17, 43].

The Indian Ocean Dipole (IOD) was represented by the Dipole Mode Index (DMI), which was also collected from the NOAA website (<https://psl.noaa.gov>). The DMI is calculated from the SST anomaly difference between the western equatorial Indian Ocean (50° E–70° E, 10° S–10° N) and the southeastern equatorial Indian Ocean (90° E–110° E, 10° S–0° N). Positive DMI values indicate a positive IOD phase, whereas negative values correspond to a negative IOD phase^[44].

2.3. Methodology

2.3.1. Data Preprocessing

Tide-gauge records may contain data gaps caused by instrument maintenance, equipment malfunction, or extreme weather conditions. Therefore, a quality-control procedure was applied before analysis. The hourly tide-gauge data were annually quality-controlled by the Vietnam Meteorological and Hydrological Data and Information Center. Sea levels were primarily measured using float-operated tide gauges, with pressure-based gauges deployed in parallel at some stations since the 2000s. Each station is referenced to a permanent benchmark, and any instrument replacement or gauge adjustment is reset relative to this benchmark. Obviously erroneous data were removed during quality control, whereas short-term extreme events (e.g., storm surges) were kept because they represent really variable processes in the ocean.

The Cau Da tide-gauge record exhibits an overall

monthly data completeness of 95.53%. Most missing data occurred during 1988–1990, when the tide well and recording system underwent major repairs. The Quy Nhon record is more complete, with a monthly data availability of 98.75%, although several months were affected by station maintenance and instrument servicing.

To ensure the reliability of monthly mean sea-level estimates, only months with at least 80% of the expected hourly observations were retained for analysis. Months with lower data availability were treated as missing values and excluded from subsequent analyses. No interpolation was applied to reconstruct missing monthly data. This threshold is consistent with quality-control practices commonly adopted in long-term sea-level analysis and by the Permanent Service for Mean Sea Level (PSMSL) database^[45].

For EMD analysis, months with missing data were excluded before decomposition, and EMD was applied to the remaining valid records. Because the monthly data are highly complete (95.53% at Cau Da and 98.75% at Quy Nhon), the number of excluded months is small and is unlikely to substantially affect the extracted variability modes. Correlation and regression analyses were performed using only concurrent valid observations without filling missing values.

Monthly mean sea level (MSL), monthly highest sea level, and monthly lowest sea level were subsequently calculated from the quality-controlled hourly observations and used for trend, variability, and climate-impact analyses.

2.3.2. Hamed–Rao Modified Mann–Kendall Test

Long-term changes in monthly mean sea level were assessed using the non-parametric Mann–Kendall (MK) test^[46, 47], while the test variance was adjusted following the approach of Hamed and Rao^[48] to account for serial correlation. Because the MK test is distribution-free and relatively insensitive to extreme observations, it has become a standard tool for detecting monotonic trends in time series, such as hydroclimatic and sea-level.

For a time series $x_1, x_2, \dots, x_n$, the MK statistic S , is determined from the signs of all pairwise differences:

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i)$$

The standardised test statistic, Z , is then derived from S and its variance. A positive Z indicates an increasing trend, whereas a negative Z indicates a decreasing trend. The statistical significance of the trend is assessed using the standard normal distribution.

To evaluate the significance of the identified monotonic trend, the MK statistic S is transformed into the standardised test statistic Z using its estimated variance. Positive and negative Z values indicate increasing and decreasing trends, respectively, while statistical significance is inferred from the corresponding standard normal distribution.

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & S > 0 \\ 0, & S = 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & S < 0 \end{cases}$$

Temporal autocorrelation in sea-level records can violate the independence assumption of the original MK test, resulting in an inflated probability of detecting statistically significant trends. To address this issue, the variance of the MK statistic was corrected following the method of Hamed and Rao, which incorporates an effective sample size estimated from statistically significant autocorrelation coefficients. The corrected variance is expressed as:

$$n^* = \frac{n}{1 + \frac{2}{n(n-1)(n-2)} \sum_{k=1}^{n-1} (n-k)(n-k-1)(n-k-2)\rho_k}$$

where n is the original sample size and n^* is the effective sample size after accounting for serial correlation, ρ_k is the autocorrelation coefficient at lag k .

The statistical significance of a trend is determined when $|Z| > Z_{1-\alpha/2}$, with significance levels of 0.05 and 0.10 corresponding to confidence levels of 95% and 90%, respectively. To quantify the direction and strength of the monotonic trend in the MK test statistic, we consider Kendall's rank correlation coefficient (τ).

2.3.3. The Sen Slope Estimator

To quantify the rate of long-term sea-level variation, the non-parametric Sen's slope estimator^[49] was employed. This method, originally introduced by Theil^[50], estimates the overall trend from the median of all pairwise slope values and is well suited to meteorological applications because it is largely unaffected

by extreme observations and does not require normally distributed data.

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

In which: Q_k is the slope between any two observations; X_j and X_i are the data values at times t_j and t_i , respectively.

The Sen's slope estimate (Q_m) is obtained as the median of all pairwise slopes Q_k . A positive value of Q_m indicates an increasing trend, whereas a negative value indicates a decreasing trend. The magnitude of Q_m represents the rate of change of sea level over time.

The trend magnitude (Q_m) is obtained as the median of all pairwise slope estimates (Q_k). Positive Q_m values indicate rising sea levels, whereas negative values correspond to falling sea levels, with the absolute magnitude of Q_m representing the average rate of change throughout the data series period.

In this study, the Sen estimator complemented the Hamed–Rao modified Mann–Kendall test, providing an estimate of trend magnitude for sea level changes that were identified as statistically significant.

2.3.4. Innovation Trend Analysis

As a complementary trend-detection technique, Innovative Trend Analysis (ITA)^[51] was applied to examine long-term sea-level behaviour. The procedure separates the original time series into two equal parts, orders each part from the smallest to the largest value, and compares the resulting distributions with a 1:1 reference line. Trend direction was represented by the ITA index (D), where positive and negative values denote increasing and decreasing tendencies, respectively, while values close to zero indicate little or no systematic change.

$$D = \frac{1}{n} \sum_{i=1}^{\frac{n}{2}} (X_{2,i}^s - X_{1,i}^s)$$

Where X_1^s and X_2^s denote the sorted values of the first and second halves of the time series, respectively.

The strength of the detected trend was further described by the regression slope (S) derived from the relationship between the two ordered subsets. ITA was used in conjunction with the Hamed–Rao modified Mann–Kendall test and Sen's slope estimator to provide an independent evaluation of long-term sea-level change.

2.3.5. Correlation and Partial Correlation Analysis

Monthly sea-level anomalies (SLA) were calculated by subtracting the long-term climatological mean for each calendar month from the corresponding observed monthly sea-level values.

Linear relationships between SLA and the major climate modes, represented by the Oceanic Niño Index (ONI), Pacific Decadal Oscillation (PDO), and Dipole Mode Index (DMI), were quantified using Pearson correlation analysis^[52, 53]. Correlation coefficients were used to describe both the strength and direction of the associations between regional sea-level variability and large-scale climate forcing.

To investigate possible delayed responses of regional sea level to large-scale climate variability, lagged Pearson correlation analyses were conducted between monthly SLA and each climate index over lag intervals from −24 to +24 months. Positive lag values indicate that variations in the climate index precede changes in SLA, whereas negative values indicate that SLA changes occur before the corresponding climate-index variability. At each lag, correlations were computed only from overlapping observations after shifting the corresponding time series.

Partial correlation analysis was further employed to isolate the relationship between SLA and ONI after removing the influence of PDO, DMI, and their combined effects. This approach provides a clearer estimate of the direct ENSO contribution to regional sea-level variability.

Because ENSO, PDO, and IOD are not entirely independent modes of climate variability, partial correlation analysis was used to distinguish the component of regional sea-level variability directly associated with ENSO from variability that is simultaneously explained by PDO and DMI.

Since both SLA and climate-index time series exhibit temporal autocorrelation, conventional significance tests may overestimate the effective degrees of freedom. To account for this effect, the statistical significance of zero-lag correlations, lagged correlations, and partial correlations was evaluated using the Effective Sample Size (ESS) method. Following Pyper and

Peterman^[54], the effective sample size (N_{eff}) was estimated from the lag-1 autocorrelation coefficients of the paired time series, and ESS-adjusted significance levels (Pe_{ff}) were subsequently determined. Correlations were considered statistically significant when $Pe_{ff} < 0.05$. Because multiple lag intervals were evaluated, isolated significant correlations were interpreted with caution, whereas greater confidence was placed on persistent patterns extending across neighbouring lag values and on agreement between the two tide-gauge stations.

2.3.6. Empirical Mode Decomposition

Empirical Mode Decomposition (EMD) is used to investigate the multi-scale variation of SLA, in which a nonlinear and non-stationary time series is decomposed into a finite set of intrinsic mode functions (IMFs) and a residual trend component^[55, 56]. The IMFs represent oscillations operating over different characteristic temporal scales, while the residual reflects the slowly varying background evolution of sea level.

$$x(t) = \sum_{k=1}^n IMF_k(t) + r_n(t)$$

In which: $IMF_k(t)$ represents the intrinsic mode functions, $r_n(t)$ is the residual or long-term trend, and n is the number of IMFs obtained.

Since the proportion of missing observations was small (4.47% at Cau Da and 1.25% at Quy Nhon), no gap-filling procedure was applied. Instead, decomposition was carried out exclusively on valid observations after removing months with missing data, thereby avoiding potential artefacts introduced by interpolation.

Individual IMFs were identified according to their dominant periodicities and subsequently grouped into seasonal, interannual, and decadal variability components. The residual component was interpreted as the long-term trend. Recognising that EMD can be influenced by endpoint effects and mode mixing, only IMFs with physically meaningful temporal characteristics were considered in subsequent analyses. Their interpretation was further constrained by comparison with independent correlation analyses involving the ONI, PDO, and DMI climate indices, providing additional confidence in the identification of climate-driven sea-level variability.

2.3.7. Multiple Regression Analysis

Multiple linear regression^[53, 57] was employed to evaluate the combined effects of ENSO, PDO, and DMI on regional sea-level variability. In this analysis, SLA is a dependent variable, and the three climate indices are predictor variables.

$$SLA = \beta_0 + \beta_1 ONI + \beta_2 PDO + \beta_3 DMI + \varepsilon$$

In which: SLA is the sea-level anomaly; ONI, PDO, and DMI are the respective climate indices; β_0 is the intercept; $\beta_1, \beta_2, \beta_3$ are the regression coefficients; and ε is the random error.

Standardised regression coefficients β are utilised to evaluate the relative importance of each climate index toward sea-level variability.

To ensure that regression coefficients were not adversely affected by correlations among predictors, multicollinearity diagnostics were performed using the variance inflation factor (VIF) and its reciprocal, the tolerance statistic. Predictor variables were considered sufficiently independent when VIF values remained below 5 and tolerance values exceeded 0.2, indicating that collinearity was unlikely to bias coefficient estimates.

Statistical inference for individual predictors was based on Student's t -tests, whereas the significance of the complete regression model was evaluated using the F -statistic. Model performance was assessed using the adjusted coefficient of determination (Adjusted R^2), which represents the proportion of SLA variability explained by the climate predictors after accounting for model complexity.

The regression framework further enabled comparison of the relative contributions of ENSO, PDO, and DMI between the Quy Nhon and Cau Da tide-gauge stations. By examining standardised regression coefficients, the analysis provides an objective measure of the dominant large-scale climate processes controlling sea-level variability along the South Central coast of Vietnam.

2.3.8. Change-Point Detection Method

Potential change points in the monthly mean sea-level series were identified using the non-parametric Pettitt test^[58], which detects a single abrupt shift in the median of a time series. A significance level of 0.05 was

chosen. The detected change points were used only to divide the records into sub-periods for assessing the initial changes in the series before and after the changes.

The estimated change points were used exclusively to subdivide the observations into periods before and after the detected change. These sub-periods served as a framework for comparing changes in sea-level behaviour rather than as evidence of a physical regime shift.

3. Results

3.1. Characteristics of Sea-Level Variability at Tidal Gauges in the Coastal Waters of South Central Vietnam

The coastal waters of South Central Vietnam are characterised by an irregular diurnal tidal regime, with typical tidal ranges of approximately 100–200 cm during diurnal tides and generally less than 100 cm during semidiurnal conditions.

Based on the detected change points in the monthly mean sea-level records (August 2007 at Cau Da and September 2008 at Quy Nhon, $p < 0.05$), the time series were divided into two periods: before 2008 and 2008–2025. At both stations, the monthly mean sea level during the earlier period was lower than that observed after 2008.

A similar pattern was observed for monthly maximum sea levels. At Cau Da, the average monthly maximum sea level increased from 200.84 cm before 2008 to 211.12 cm after 2008, while at Quy Nhon it increased from 232.10 cm to 238.03 cm. Monthly minimum sea levels also increased at Cau Da, from 41.06 cm to 45.90 cm.

In contrast, the average monthly minimum sea level at Quy Nhon decreased slightly from 79.92 cm before 2008 to 75.28 cm during 2008–2025.

The overall characteristics of the monthly sea-level records are summarised in **Table 1**. Over the entire observation period (1975–2025), monthly sea level at Cau Da ranged from 87.1 to 161.1 cm, with a mean value of 126.79 cm. At Quy Nhon (1986–2025), monthly sea level varied between 127.8 and 196.3 cm, with an average of 156.24 cm. The corresponding standard deviations were 37.84 cm and 37.30 cm, respectively. The coefficient of variation reached 29.84% at Cau Da and 23.87% at Quy Nhon, indicating substantial temporal variability in sea level at both stations. Data completeness was high, with missing data rates of only 4.47% at Cau Da and 1.25% at Quy Nhon, supporting the reliability of subsequent trend and climate-variability analyses.

3.2. Long-Term Sea-Level Trend Analysis Using MK–Hamed Rao, Sen’s Slope Estimator, and ITA

The MK–Hamed Rao test combined with Sen’s slope estimation revealed positive long-term sea-level trends at both tidal-gauge stations in the coastal waters of South Central Vietnam (**Table 2**; **Figures 2 and 3**).

At Quy Nhon station, the Mann–Kendall rank correlation coefficient was $\tau = 0.214$, indicating an increasing monotonic trend over the period 1986–2025. The corresponding p -value (0.072) suggests that the trend is statistically significant at the 90% confidence level. Sen’s slope estimator showed a sea-level rise rate of 1.91 mm yr^{−1}, with a 95% confidence interval ranging from 1.39 to 2.40 mm yr^{−1}.

Table 1. Summary statistics of monthly mean sea-level records at tide-gauge stations along the South Central Coast of Vietnam.

No.	Station	Obs. Period	Min (cm)	Max (cm)	Mean (cm)	SD (cm)	CV (%)	Miss (%)
1	Cau Da	2/1975–12/2025	87.12	161.11	126.79	37.84	29.84	4.47
2	Quy Nhon	4/1986–12/2025	127.77	196.32	156.24	37.30	23.87	1.25

Note: SD = standard deviation; CV = coefficient of variation; Miss = missing data.

Table 2. Monotonic trend assessment and sea-level rise rates derived from the MK–Hamed Rao test and Sen’s slope estimator in the coastal waters of South Central Vietnam.

Station	Data Period	τ	p -Value	Slope (mm/y)	CI95
Quy Nhon	1986–2025	0.214	0.072	1.91*	[1.39–2.40]
Cau Da	1975–2025	0.349	0.057	2.36*	[2.02–2.70]

Note: τ is the rank correlation coefficient; p -value is the probability of statistical significance to the Mann–Kendall test with Hamed–Rao serial-correlation correction; slope is the rate of the trend using Sen’s slope estimation; CI95 is the 95% confidence interval of the trend; * is the 90% statistical significance level.

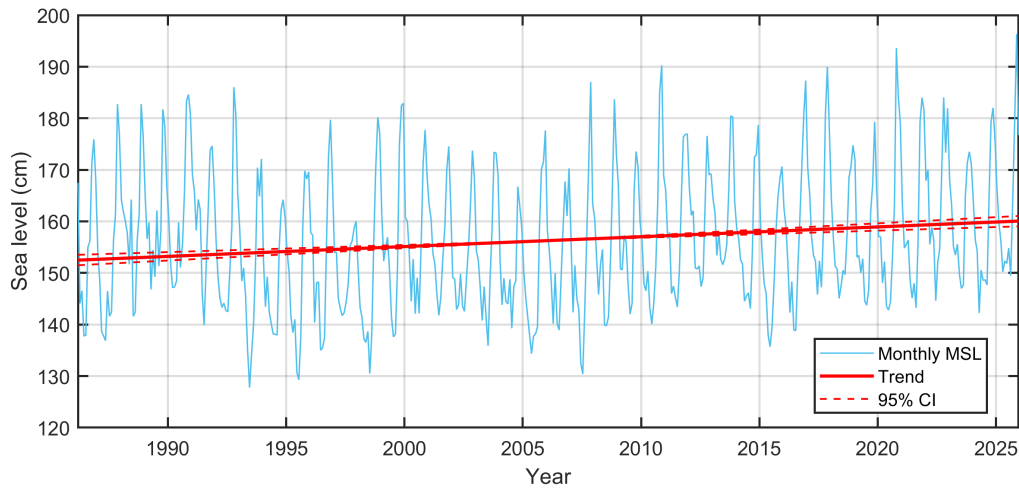


Figure 2. Long-term trends in monthly mean sea level at Quy Nhon station (1986–2025).

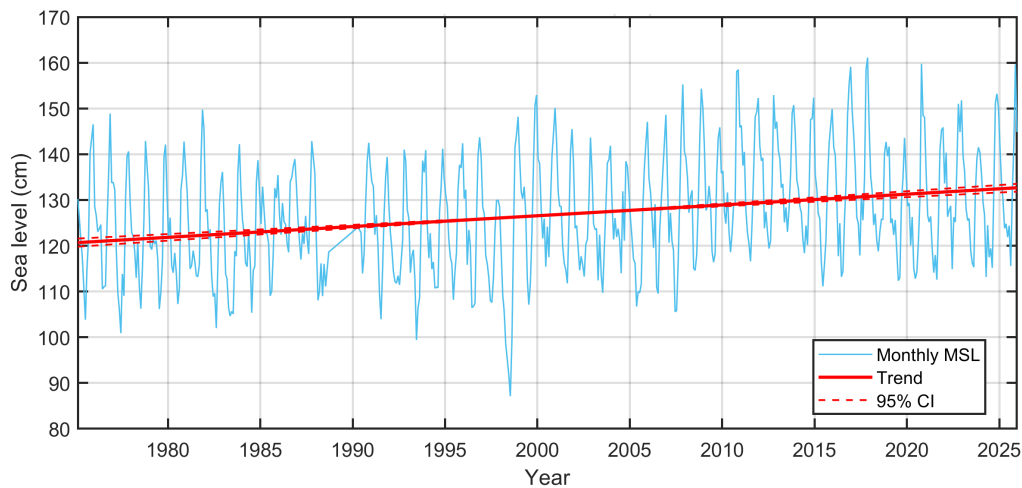


Figure 3. Long-term trends in monthly mean sea level at Cau Da station (1975–2025).

A stronger increasing trend was detected at Cau Da station during 1975–2025, with $\tau = 0.349$ and $p = 0.057$. The estimated rate of sea-level rise reached 2.36 mm yr^{-1} , with a 95% confidence interval of $2.02\text{--}2.70 \text{ mm yr}^{-1}$. Similar to Quy Nhon, the trend was significant at the 90% confidence level.

The linear trends shown in **Figures 2** and **3** are consistent with the MK–Hamed Rao and Sen’s slope results, indicating a persistent increase in relative sea level at both stations despite pronounced seasonal and inter-annual variability. The observed rate at Cau Da was approximately 24% higher than that at Quy Nhon, suggesting spatial differences in the magnitude of long-term sea-level rise along the South Central Vietnam coast.

The results demonstrate that relative sea level has risen continuously along the South Central Vietnam

coast during the last four to five decades, with the strongest increase observed at Cau Da. Although the trends are only statistically significant at the 90% confidence level, the consistency among the MK–Hamed Rao test and Sen’s slope estimates provides robust evidence of ongoing sea-level rise in the study area.

The results of the Innovative Trend Analysis (ITA) are presented in **Table 3** and **Figure 4**. Consistent with the MK–Hamed Rao and Sen’s slope analyses, the ITA method indicated increasing sea-level trends at both tidal-gauge stations. At Quy Nhon, the ITA trend indicator reached $D = 4.0 \text{ cm}$, while the regression slope between the first and second halves was $S = 0.985$. Similarly, at Cau Da, the ITA indicator was $D = 7.15 \text{ cm}$ and the corresponding slope was $S = 1.018$. In this study, the ITA (D) indicator is used as the primary indicator

of the trend direction; therefore, a positive D value in both stations indicates an overall increasing trend. The regression slope (S) serves as an additional measure of the relationship between the two sorted halves

of the time series. Therefore, the S value slightly below unity at Quy Nhon reflects the relatively weak magnitude of the increase and the influence of data variability rather than a decreasing trend.

Table 3. Trend analysis of SRL in the coastal waters of South Central Vietnam using the ITA method.

Station	Data Period	D	S	Trend Type
Quy Nhon	1986–2025	4	0.985	Increasing
Cau Da	1975–2025	7.15	1.018	Increasing

Note: D (cm) is the ITA index used to assess whether the trend is increasing ($D > 0$), decreasing ($D < 0$), or unchanged ($D \approx 0$); S is the slope of the regression line between the first and second halves of the data series.

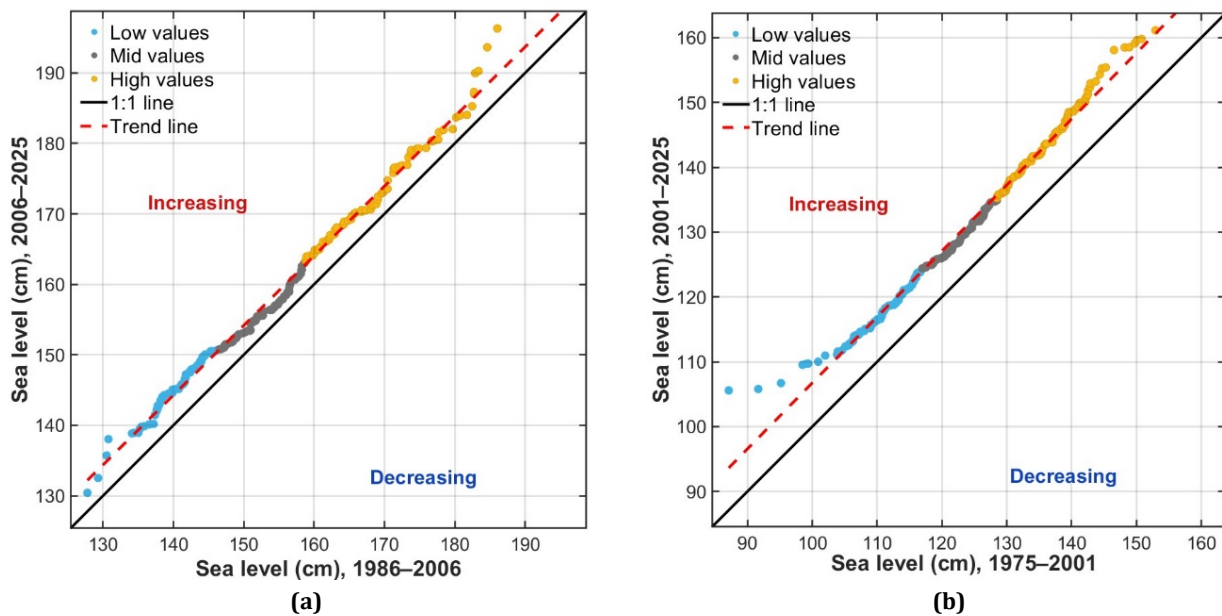


Figure 4. Sea level trends at tidal gauge stations in the coastal waters of South Central Vietnam using ITA: (a) at Quy Nhon (1986–2025); (b) at Cau Da (1975–2025).

The ITA scatter plots (Figure 4) further illustrate that most data points are distributed above the 1:1 reference line, particularly for the medium and high sea-level values. This pattern suggests that sea levels in the later half of the records were generally higher than those in the earlier half of the records. The upward displacement is more pronounced at Cau Da than at Quy Nhon, indicating a stronger long-term increase at Cau Da.

Both statistical approaches consistently indicate a long-term increase in relative sea level at Quy Nhon and Cau Da. The agreement between the MK–Hamed Rao test, Sen’s slope estimates, and ITA strengthens the robustness of the detected sea-level rise signal despite the presence of strong seasonal and interannual variability.

3.3. Relationship between Sea Level Variability and Climate Indices

The influence of ENSO phases on sea-level anomalies (SLA) is summarised in Table 4. Distinct differences were observed between El Niño and La Niña conditions at both stations. During El Niño years, mean SLA decreased by approximately 3.20 cm at Quy Nhon and 2.89 cm at Cau Da. In contrast, positive anomalies of 2.43 cm and 3.24 cm were recorded during La Niña years, respectively. The difference between the two ENSO phases reached approximately 5.6–6.1 cm, indicating a substantial modulation of coastal sea level by ENSO. Under neutral conditions, SLA remained close to zero, suggesting the absence of strong large-scale climatic forcing.

Table 4. Mean sea-level anomalies (cm) associated with El Niño, La Niña, and Neutral conditions in the South-Central Vietnamese coastal waters.

Station	El Niño	La Niña	Neutral
Quy Nhon	-3.20	2.43	0.43
Cau Da	-2.89	3.24	-0.14

Correlation analysis quantified the relationship between sea level variability and major climate indices such as ONI, PDO, and DMI. The correlation coefficients for serial autocorrelation using the effective sample size (ESS) and monthly SLA showed a significant negative correlation with both ONI and PDO at both stations (Peff < 0.01). The strongest relationship was observed for ONI, with correlation coefficients of -0.322 at Quy Nhon and

-0.316 at Cau Da (Peff < 0.001). PDO also exhibits significant negative correlations, although weaker than those for ONI ($R = -0.294$ at Quy Nhon and $R = -0.181$ at Cau Da). In contrast, correlations with DMI were weak ($|R| \leq 0.10$) and were not significant after ESS correction (Peff > 0.2), indicating only a minor influence of the Indian Ocean Dipole on monthly sea-level variability along the South Central Vietnam coast (see **Table 5**).

Table 5. Pearson correlation coefficients (R), effective sample sizes (Neff), and ESS-based significance levels (Peff) for the relationships between monthly sea-level anomalies (SLA) and the major climate indices (ONI, PDO, and DMI) in South Central Vietnam.

Station	R S, O	Peff S, O	Neff S, O	R S, P	Peff S, P	Neff S, P	R S, D	Peff S, D	Neff S, D
Quy Nhon	-0.322	<0.001	149	-0.294	<0.001	172	-0.102	0.20	158
Cau Da	-0.316	<0.001	170	-0.181	0.011	198	0.006	0.932	181

Note: S, O, P, and D denote SLA, ONI, PDO, and DMI, respectively. Peff is the significance level using the effective sample size (ESS) to account for serial autocorrelation in the monthly time series.

To further test the low-frequency variability, 12-month moving averages were applied to SLA, ONI, and DMI, while a 24-month moving average was applied to PDO. The resulting correlation coefficients remained relatively high, ranging from -0.39 to -0.46 for SLA-ONI and from -0.31 to -0.50 for SLA-PDO. However, filtering by moving averages significantly increased the serial autocorrelation, reducing the effective sample size to only 3–8 independent observations. Consequently, the ESS-corrected significance levels (Peff = 0.25–0.99) were not significantly different. Therefore, they should be considered as descriptive evidence of lower-frequency covariability rather than independent statistical relationships.

Overall, monthly correlation analyses by ESS-corrected significance levels indicate that ENSO is the dominant large-scale climate mode associated with sea-level variability along the South Central coast of Vietnam, with PDO having a weaker but negligible influence, while the contribution of DMI is dismissed. The identified re-

lationships from the smoothed series should be interpreted qualitatively because the moving-average filtering significantly reduced the effective sample size (Neff = 3–8), resulting in insufficient samples to test the significance of the statistical.

Additional evidence for the dominant role of ENSO at interannual timescales is provided by the EMD analysis presented in the following section.

3.4. EMD Decomposition of Sea-Level Variability and Its Relationship with Climate Drivers

Results of the EMD decomposition for Quy Nhon and Cau Da are presented in **Figures 5** and **6**, respectively. The sea-level anomaly series was decomposed into several intrinsic mode functions (IMFs) representing variability at different temporal scales, including seasonal (IMF2), interannual (IMF3–IMF4), decadal (IMF5), and long-term trend (Residual) components.

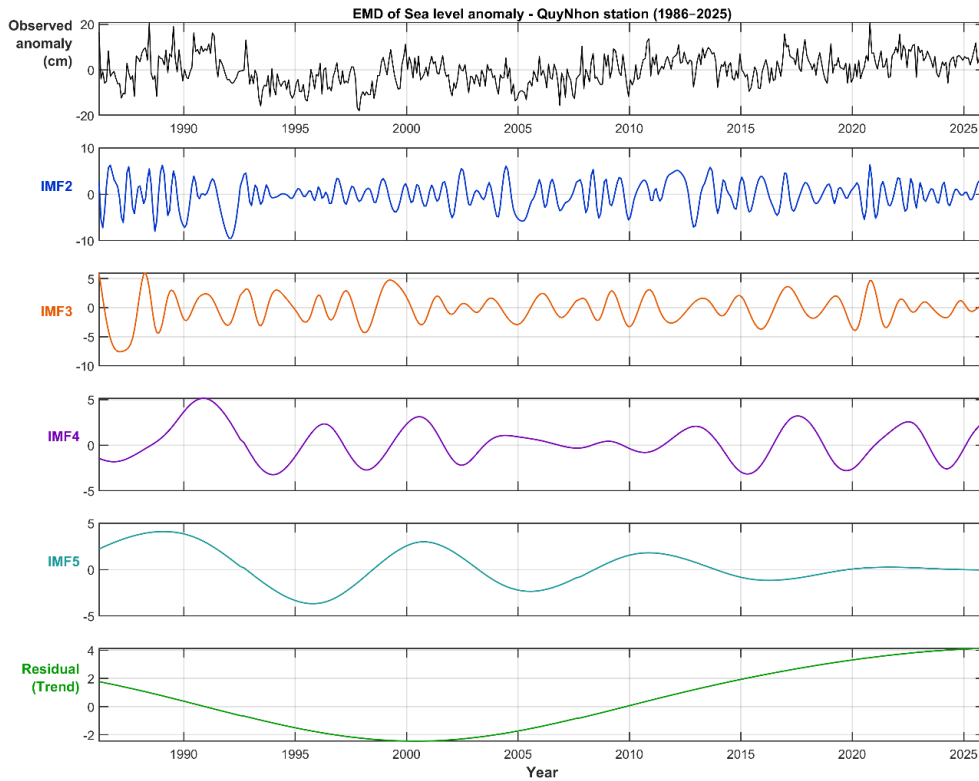


Figure 5. The seasonal (IMF2), interannual (ENSO-band, IMF3 and IMF4), decadal (IMF5), and long-term trend components of sea-level variability at Quy Nhon station (1986–2025) using EMD decomposition.

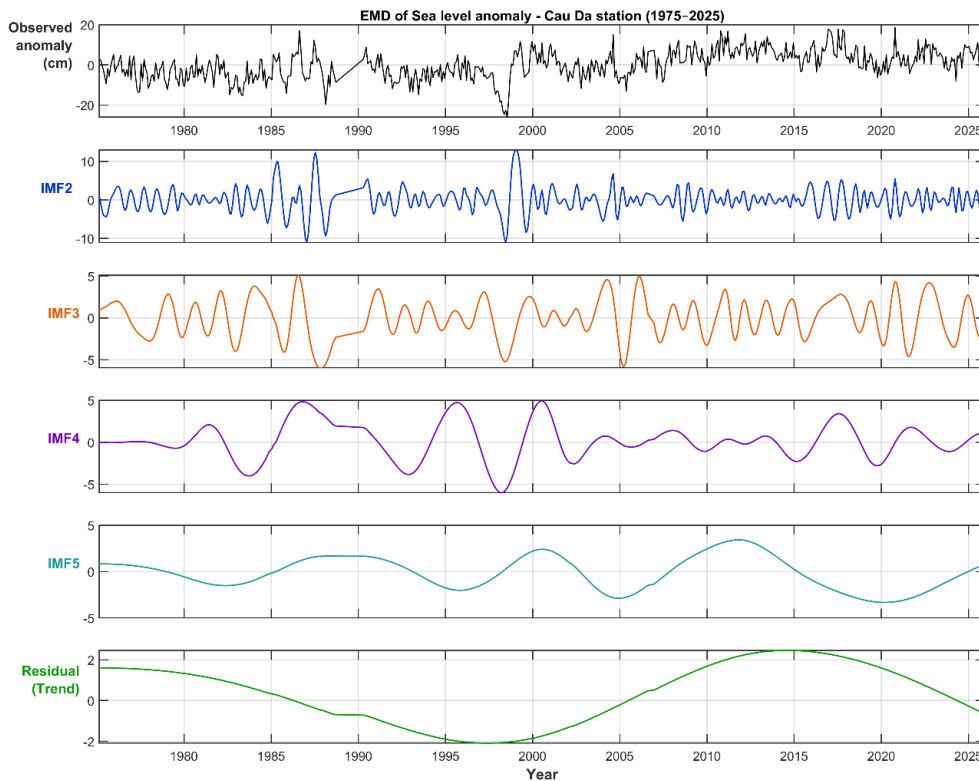


Figure 6. The seasonal (IMF2), interannual (ENSO-band, IMF3 and IMF4), decadal (IMF5), and long-term trend components of sea-level variability at Cau Da station (1975–2025) using EMD decomposition.

IMF2 clearly represents the seasonal cycle, characterised by annual oscillations with relatively stable amplitudes over time. The dominant periods were 1.02 years at Quy Nhon and 1.07 years at Cau Da. This mode reflects the influence of the monsoon system, coastal circulation, and seasonal meteorological forcing on regional sea-level variability, accounting for approximately 31.5–35.1% of the total variance.

IMF3 and IMF4 represent interannual variability with periods ranging from approximately 2 to 7 years, consistent with the characteristic ENSO frequency band. The dominant periods of IMF3 were 2.13 years at Quy Nhon and 2.37 years at Cau Da, contributing 13.5–14.6% of the total variance. IMF4 exhibited a dominant period of 5.33 years at both stations and explained approximately 10–13% of the variance. The amplitudes of IMF3 ranged from about –6 to +5 cm, while those of IMF4 varied between –5 and +4 cm, indicating substantial temporal fluctuations. Strong oscillation phases occurred during the late 1980s, late 1990s, 2009–2011, and after 2015, corresponding closely to major ENSO events documented across the Pacific basin. These results suggest that ENSO is one of the primary drivers of interannual sea-level variability along the coast of Central Vietnam.

IMF5 represents lower-frequency variability at decadal timescales. The dominant period was approximately 10.67 years at both Quy Nhon and Cau Da, with amplitudes ranging from –3 to +3 cm and contributions

of about 8–9% of the total variance. The presence of this mode suggests the influence of basin-scale climate variability, particularly Pacific Decadal Oscillation (PDO)-like processes, as well as regional oceanic dynamics, in modulating sea-level fluctuations at decadal timescales.

The residual component represents the long-term sea-level evolution after removing seasonal, interannual, and decadal oscillations through EMD decomposition. At Quy Nhon, the residual showed a slight decline until around 2000, followed by a persistent increase during 2000–2025. A similar pattern was observed at Cau Da, with a decreasing tendency before the late 1990s and a marked rise thereafter. Despite some differences in temporal evolution, both stations reveal a clear long-term increase in sea level during the early twenty-first century, consistent with the ongoing sea-level rise observed along the Vietnamese coast and global oceans.

Overall, the EMD analysis indicates that sea-level variability along the South Central Vietnam coast results from the superposition of seasonal, interannual, decadal, and long-term components. The correlation analysis further demonstrates that ENSO is the dominant driver of interannual variability, whereas PDO mainly contributes to decadal-scale fluctuations.

To further identify the climatic drivers of sea-level variability at different temporal scales, correlation analyses were conducted between the EMD-derived intrinsic mode functions (IMFs) and major climate indices (ONI and PDO) (Table 6).

Table 6. Correlations between EMD-derived sea-level variability components and large-scale climate indices (ONI and PDO).

Station	R (IMF3, ONI)	R (IMF4, ONI)	R (IMF34, ONI)	R (IMF5, PDO)	Rp (IMF34, ONI)
Quy Nhon	–0.42	–0.35	–0.52	–0.39	–0.43
Cau Da	–0.36	–0.29	–0.45	–0.30	–0.43

Note: R denotes the Pearson correlation coefficient, whereas Rp denotes the partial correlation coefficient between the combined interannual sea-level variability component (IMF34) and the Oceanic Niño Index (ONI) after removing the effects of the Pacific Decadal Oscillation (PDO) and Dipole Mode Index (DMI). All reported correlations are statistically significant at $p < 0.001$.

At both stations, the interannual components represented by IMF3 and IMF4 exhibited negative correlations with ONI. The correlation between IMF3 and ONI reached –0.42 at Quy Nhon and –0.36 at Cau Da, indicating that ENSO explains a substantial portion of the 2–7-year sea-level variability. Similarly, IMF4 also showed moderate negative correlations with ONI (–0.35

at Quy Nhon and –0.29 at Cau Da), suggesting that ENSO-related variability extends into lower-frequency oscillations beyond the classical ENSO band. When IMF3 and IMF4 were combined (IMF34), the correlation with ONI increased markedly, reaching –0.52 at Quy Nhon and –0.45 at Cau Da. These stronger relationships imply that ENSO influences sea level through multiple interannual

timescales and that the combined signal captures ENSO-driven variability more effectively than either mode individually.

The decadal-scale component (IMF5) showed negative correlations with PDO, with coefficients of -0.39 at Quy Nhon and -0.30 at Cau Da. Although weaker than the IMF34–ONI relationship, these results indicate that PDO contributes to longer-term sea-level fluctuations in the South Central Vietnam coastal region. The lower correlation values also suggest that PDO is likely one of several factors governing decadal variability.

To isolate the ENSO signal from the effects of other climate modes, a partial correlation analysis was performed between IMF34 and ONI while controlling for PDO. The resulting partial correlation coefficients remained relatively strong (-0.43 at both stations), only slightly lower than the corresponding ordinary correlations. This finding demonstrates that ENSO exerts an independent and robust influence on interannual sea-level variability, whereas PDO plays a secondary role in modulating the observed relationship.

Overall, the results indicate that ENSO is the dominant driver of interannual sea-level variability along the South Central Vietnam coast, while PDO contributes primarily to lower-frequency decadal fluctuations. The stronger correlations obtained using the combined IMF34 component further support the interpretation that sea-level responses to ENSO are distributed across multiple interannual timescales rather than being confined to a single oscillatory mode.

3.5. Independent Effects of ENSO, PDO and IOD on Sea Level Variability in the Coastal Waters of South Central Vietnam

To further quantify the independent influence of ENSO on sea-level variability, partial correlation analyses were performed between monthly sea-level anomalies (SLA) and the Oceanic Niño Index (ONI) after removing the effects of the Pacific Decadal Oscillation (PDO), the Dipole Mode Index (DMI), and both climate indices simultaneously (**Table 7**).

Table 7. Partial correlation analysis of interannual sea-level variability and ENSO after removing PDO and DMI influences in the coastal waters of South Central Vietnam.

Station	Rp (ONI)	Rp (ONI/PDO)	Rp (ONI/DMI)	Rp (ONI/PDO, DMI)
Quy Nhon	-0.322	-0.219	-0.319	-0.221
Cau Da	-0.316	-0.269	-0.317	-0.268

Note: Rp (ONI) denotes the Pearson correlation coefficient between sea-level anomalies (SLA) and the Oceanic Niño Index (ONI). Rp (ONI/PDO), Rp (ONI/DMI), and Rp (ONI/PDO, DMI) denote partial correlation coefficients between SLA and ONI after controlling for the effects of Pacific Decadal Oscillation (PDO), Dipole Mode Index (DMI), and both PDO and DMI, respectively. All correlations are statistically significant ($p < 0.001$).

Pearson analysis showed significant negative relationships between SLA and ONI at both Quy Nhon ($R_p = -0.322$) and Cau Da ($R_p = -0.316$) ($p < 0.001$), as described in Section 3.3.

After controlling for PDO, the correlation coefficients decreased to -0.219 at Quy Nhon and -0.269 at Cau Da. The decrease was more pronounced at Quy Nhon, suggesting that part of the observed ENSO-related sea level variability is shared with lower-frequency Pacific climate variability represented by PDO. In contrast, removing the influence of DMI produced almost no change in the ENSO–sea-level relationship. The correlation coefficients remained nearly unchanged at -0.319 for Quy Nhon and -0.317 for Cau Da, indicating that DMI

contributes little to the observed ENSO-related sea level variability in the study area.

When the effects of both PDO and DMI were simultaneously removed, the partial correlation coefficients were -0.221 at Quy Nhon and -0.268 at Cau Da. These values were nearly identical to those obtained after controlling for PDO alone, confirming that PDO accounts for a substantial proportion of the shared variance between ENSO and sea-level variability, whereas the contribution of DMI is comparatively weak.

Overall, the partial correlation results demonstrate that ENSO maintains a significant association with interannual sea level variability after accounting for the effects of PDO and DMI. The stronger reduction observed

after removing PDO indicates that part of the ENSO–sea-level relationship is modulated by Pacific decadal variability, particularly at Quy Nhon, whereas the influence of DMI appears comparatively weak.

To further investigate the temporally dependent

response of sea level variability to large-scale climate forcing, lagged correlation analyses were performed between monthly SLA and ONI, PDO, and DMI indices over lags from –24 to +24 months (**Table 8**). Positive lags indicate that the climate index leads the SLA.

Table 8. Maximum lagged correlation coefficients (R), effective sample size (Neff), and ESS-corrected significance levels (Peff) between monthly sea-level anomalies (SLA) and major climate indices (ONI, PDO, and DMI) in the coastal waters of South Central Vietnam.

Station	Climate Index	Lag of Strongest Correlation	R	Neff	Peff	Significant
Quy Nhon	ONI	1	–0.338	146	<0.001	TRUE
Quy Nhon	PDO	1	–0.327	169	<0.001	TRUE
Quy Nhon	DMI	1	–0.103	158	0.197	FALSE
Cau Da	ONI	4	–0.413	170	<0.001	TRUE
Cau Da	PDO	2	–0.207	198	0.003	TRUE
Cau Da	DMI	–20	0.117	169	0.131	FALSE

Note: Positive lag values indicate that the climate index leads SLA, whereas negative lag values indicate that SLA leads the climate index. R is the maximum Pearson correlation coefficient within the examined lag range (–24 to +24 months). Neff is the effective sample size, and Peff is the significance level corrected for serial autocorrelation using the effective sample size approach. Statistically significant correlations (Peff < 0.05) are indicated by TRUE.

For ONI, significant negative lagged correlations were identified at both stations. The strongest relationship occurred when ONI led SLA by 1 month at Quy Nhon ($R = -0.338$, $P_{\text{eff}} < 0.001$) and 4 months at Cau Da ($R = -0.413$, $P_{\text{eff}} < 0.001$). Compared with the zero-lag analysis (**Table 5**), the magnitude of the correlation increased slightly at both stations, particularly at Cau Da, which found regional sea level anomalies responding to ENSO with a short delay of approximately 1–4 months.

For PDO, significant but weaker negative lagged correlations were also observed. The strongest correlations occurred when PDO led SLA by 1 month at Quy Nhon ($R = -0.327$, $P_{\text{eff}} < 0.001$) and 2 months at Cau Da ($R = -0.207$, $P_{\text{eff}} = 0.003$). These lag periods were shorter than those determined for ONI, and the corresponding correlation coefficients were generally lower, suggesting that PDO had a weaker lagged effect on regional sea level variability.

In contrast, DMI found no statistically significant lagged relationship with SLA at either station over the lag range. Although the strongest correlations occurred at a lag of 1 month at Quy Nhon ($R = -0.103$, $P_{\text{eff}} = 0.197$) and –20 months at Cau Da ($R = 0.117$, $P_{\text{eff}} = 0.131$), neither of these relationships was statistically significant. Therefore, these individual peaks are unlikely to represent physically meaningful delayed responses.

Overall, the lagged correlation analysis showed that ENSO exhibited the strongest and most consistent

delayed association with monthly sea level anomalies in the South Central Vietnam coastal region, with sea level responses occurring approximately 1–4 months after ONI changes. PDO showed a weaker lagged relationship, while no robust lagged influence of DMI was detected. These findings complement the zero-lag and partial correlation analyses, further supporting ENSO as a dominant large-scale climate driver of interannual sea-level variability in the study area.

Although correlation, lagged correlation, and partial correlation analyses revealed different aspects of the relationship between sea level and individual climate regimes, they did not quantify their combined impact. Therefore, multiple regression was applied to assess the relative contributions of ENSO, PDO, and DMI acting immediately.

Multiple regression analysis further quantified the relative contributions of ENSO, PDO, and DMI to interannual sea-level variability (**Table 9**). The combined climate predictors explained 22–25% of the observed low-frequency variance ($\text{Adj. } R^2 = 0.22\text{--}0.25$). At Quy Nhon, PDO exhibited the largest standardised regression coefficient ($\beta = -0.36$), exceeding that of ENSO ($\beta = -0.19$), whereas at Cau Da, ENSO was clearly the dominant predictor ($\beta = -0.42$). The contribution of DMI was weak at both stations and statistically insignificant at Cau Da. Multicollinearity diagnostics indicated negligible collinearity among the climate predictors, with max-

imum VIF values of 1.40–1.43 and minimum tolerance values of 0.70–0.71 (**Table 9**), supporting the robustness

and interpretability of the standardised regression coefficients.

Table 9. Multiple regression analysis of interannual sea-level variability and large-scale climate drivers (ONI, PDO, and DMI) in the coastal waters of South Central Vietnam.

Station	β ONI	p ONI	β PDO	p PDO	β DMI	p DMI	Adj. R^2	Max VIF	Min T
Quy Nhon	-0.19	<0.001	-0.36	<0.001	-0.09	0.029	0.25	1.43	0.70
Cau Da	-0.42	<0.001	-0.09	0.038	0.04	0.235	0.22	1.40	0.71

Note: β represents the standardised regression coefficient. ONI, PDO, and DMI denote 12-month, 24-month, and 12-month moving-average filtered climate indices, respectively. Adj. R^2 indicates the proportion of interannual sea level variance explained by the combined climate predictors. Maximum VIF denotes the largest variance inflation factor among the predictors, whereas Minimum T represents the smallest tolerance value (Tolerance = $1/\text{VIF}$). Low VIF and high tolerance values indicate negligible multicollinearity among the predictors.

Overall, the regression results indicate that both ENSO and PDO play important roles in regulating interannual sea level variability along the South Central Vietnam coast. ENSO exerts the strongest influence at Cau Da, whereas PDO contributes more substantially at Quy Nhon. The influence of DMI is comparatively weak and spatially inconsistent. These findings are broadly consistent with the partial correlation and EMD analyses, highlighting the dominant role of Pacific climate variability in modulating regional sea level variability.

4. Discussion

4.1. The Long-Term Sea-Level Rise from Complementary Trend-Detection Methods

The MK-HR test combined with Sen's slope estimator indicates a persistent increase in relative sea level at both Quy Nhon and Cau Da during the observational period. Estimated rates of sea-level rise ranged from 1.91 mm yr^{-1} at Quy Nhon to 2.36 mm yr^{-1} at Cau Da, with both trends significant at the 90% confidence level. The positive Sen's slopes and positive Kendall's τ values suggest that sea level has generally increased over the past several decades despite substantial interannual variability. Although the confidence intervals of Sen's slopes are clearly positive, the MK-HR test only shows marginal statistical significance because the Hamed–Rao correction accounts for the compatible positive series correlation in sea level records. This correction increases the variance of the MK statistic, leading to a more conservative significance test while leaving the estimated trend magnitude (Sen slope).

These rates are lower than the global mean sea-

level rise reported from satellite altimetry since the early 1990s (approximately $3\text{--}4 \text{ mm yr}^{-1}$), indicating that local relative sea-level trends along the South Central Vietnam coast likely reflect the combined influence of regional oceanographic processes and potential vertical land motion, in addition to global mean sea-level rise. Previous reports have also indicated differences in local and global trends of sea level in the Western Pacific and the South China Sea due to the impact of climate-driven ocean circulation changes. The ITA results provide additional evidence for this increasing tendency. Most data points were distributed above the 1:1 reference line, and positive D values were obtained at both stations (4.0 cm at Quy Nhon and 7.15 cm at Cau Da), indicating that sea levels during the second half of the records were systematically higher than those during the first half. The agreement between MK-HR, Sen's slope, and ITA is particularly important because these methods are based on different statistical principles. While MK-HR evaluates monotonic trends after accounting for serial correlation and Sen's slope quantifies the trend magnitude, ITA provides a non-parametric graphical assessment without requiring assumptions regarding data distribution. The consistent identification of increasing sea levels by these independent approaches increases confidence that the detected trends represent genuine long-term changes rather than methodological artifacts.

The estimated trend at Cau Da (2.36 mm yr^{-1}) was approximately 24% larger than that at Quy Nhon (1.91 mm yr^{-1}). Similarly, the ITA indicator D was almost twice as large at Cau Da. These results imply spatial variability in relative sea-level change along the South Central Vietnam coast. Several factors may contribute

to these differences. Local coastal geometry, variations in wind-driven circulation, river discharge, and vertical land motion may affect the magnitude of observed sea-level trends. Such regional differences highlight the importance of using multiple long-term tidal-gauge records when assessing coastal sea-level change.

Although the tide-gauge data analysed in this study represent relative sea level, the contribution of VLM could not be directly quantified due to the lack of continuous GNSS observation data at the Quy Nhon and Cau Da stations. To provide regional context, nearby Global Coastal VLM estimates were considered^[59], located approximately 290–320 km from the study sites, showing a relatively small GIA component of about $+0.28$ to $+0.33$ mm yr⁻¹, whereas the reported total VLM ranged from -2.61 to -3.24 mm yr⁻¹. However, nearly 90% of the total VLM at these reference locations was attributed to non-GIA processes, which are often characterised by strong spatial heterogeneity. Because the distance between the nearest reference points and the tidal stations under study is quite far, they cannot represent the VLM for correcting the sea level trend observed at the station. Consequently, the trends reported in this study should be understood as relative sea-level changes, reflecting the combined effects of oceanic processes and potential VLM, rather than absolute oceanic sea-level rise. Future studies are needed to integrate GNSS observations at the same location and InSAR measurements, and site-specific VLM estimates are needed to better separate these contributions.

4.2. ENSO as the Dominant Driver of Interannual Sea-Level Variability

The results consistently indicate that ENSO is the primary large-scale climate driver of interannual sea-level variability along the South Central Vietnam coast. Both the composite analysis of ENSO phases and the correlation analysis between SLA and the ONI reveal a coherent inverse relationship between regional sea-level fluctuations and tropical Pacific climate variability. This finding suggests that a substantial fraction of sea-level variability in the study area is associated with interannual climate forcing originating from the Pacific Ocean.

The results of a composite analysis between SLA at

tide-gauge stations (Quy Nhon, Cau Da) and the ONI index provide further evidence of ENSO impacts on coastal sea level. During El Niño events, the mean sea level decreased by approximately 2.9–3.2 cm at Cau Da and Quy Nhon, whereas positive anomalies of 2.4–3.2 cm were observed during La Niña events. The difference between the two ENSO phases reached approximately 5.6–6.1 cm, indicating a pronounced modulation of regional sea level by ENSO. These anomalies are comparable to, or even exceed, the magnitude of several years of long-term sea-level rise, emphasizing the importance of ENSO in controlling climate variability that influences sea level fluctuations in shaping short- to medium-term.

Pearson correlation analysis based on monthly SLA series data revealed a statistically significant negative relationship between SLA and ONI at both Quy Nhon ($R = -0.322$, $P_{eff} < 0.001$) and Cau Da ($R = -0.316$, $P_{eff} < 0.001$). These results suggest that positive ONI anomalies associated with El Niño conditions often coincide with lower sea levels. Conversely, negative ONI anomalies during La Niña are associated with higher sea levels. Although the correlation coefficients are at a moderate level, their statistical significance after correcting for series autocorrelation using effective sample size confirms that ENSO is an important large-scale climate driver of sea level variability in the South Central Vietnam coastal region.

The physical mechanism underlying this relationship is primarily linked to changes in the Walker circulation and the redistribution of upper-ocean heat and mass across the tropical Pacific. El Niño conditions weaken the climatological trade winds, limiting the westward transport and accumulation of warm surface waters. As a result, sea level decreases over the western Pacific and extends into the South China Sea. In contrast, La Niña conditions strengthen the trade winds and enhance the westward transport of warm water, resulting in elevated sea levels in the western Pacific basin and adjacent marginal seas, including the coastal waters of Vietnam.

The present findings are consistent with numerous previous studies conducted in the South China Sea and the western Pacific region. Several authors have reported that ENSO is the primary source of interannual sea-level variability in the South China Sea, explaining a large proportion of observed sea-level fluctuations through changes

in basin-scale wind stress, ocean circulation, and thermoclinic effects^[26, 31, 35–38]. Studies based on satellite altimetry and tide-gauge observations have shown that sea level in the western tropical Pacific typically decreases during El Niño events and rises during La Niña events, with amplitudes often reaching several centimeters to 10 cm in some regions. Similar ENSO-related sea-level responses have also been documented along the Vietnamese coast^[40], the Sumatra Sea and the Java Sea^[35–38], where interannual sea-level variability is strongly associated with changes in Pacific climate conditions. Therefore, the results obtained in this study reinforce previous evidence showing that ENSO is the primary large-scale climate factor influencing interannual sea level variability in the coastal waters of South Central Vietnam, although other regional and local oceanographic processes also contribute to the observed variability.

4.3. Contributions of PDO and IOD to Sea-Level Variability

Although ENSO emerged as the primary climate driver of sea level variability in the South Central Vietnam coastal region, the results indicate that the PDO also contributes to sea level variability. In contrast, the influence of the IOD appears relatively weak. Evidence from the correlation analysis, EMD decomposition, partial correlation analysis, and multiple regression suggests that PDO primarily modulates sea level variability at decadal timescales, whereas IOD explains only a limited proportion of the observed variability.

Pearson correlation analysis showed statistically significant negative relationships between monthly SLA and PDO at both Quy Nhon ($R = -0.294$, $P_{eff} < 0.001$) and Cau Da ($R = -0.181$, $P_{eff} = 0.011$). Although these correlations are weaker than those found for ENSO, they indicate that PDO contributes to sea level variability in the study area. The EMD analysis further demonstrated that the decadal scale component (IMF5; approximately 10.7 years) was negatively correlated with PDO at both stations, supporting the interpretation that PDO primarily modulates lower-frequency sea level variability, particularly at Quy Nhon.

The role of PDO is further supported by the partial correlation analysis. After removing the influence

of PDO, the ENSO–sea level correlation weakened from -0.322 to -0.219 at Quy Nhon and from -0.316 to -0.269 at Cau Da. The larger reduction at Quy Nhon suggests that PDO shares part of the variability associated with ENSO, indicating a stronger modulation of sea level by Pacific decadal variability at this station. In contrast, removing the influence of DMI produced almost no change in the ENSO–sea-level relationship, confirming that the contribution of the Indian Ocean Dipole to sea-level variability in the study area is relatively weak.

In contrast, the influence of IOD should be considered negligible in the study area. The correlations between monthly sea level anomalies and the DMI index were very weak and statistically insignificant at both Quy Nhon ($R = -0.102$, $P_{eff} = 0.20$) and Cau Da ($R = 0.006$, $P_{eff} = 0.932$). Furthermore, removing the DMI signal produced only minor changes in the ENSO–sea level relationship, indicating that IOD contributed little to sea level variability in the South Central Vietnam coastal region.

Several studies have reported that PDO influences sea level indirectly through its interaction with Pacific trade winds, ocean circulation, and ENSO-related processes. In contrast, the influence of IOD on the South China Sea is generally weaker because the study area is more directly connected to the Pacific climate system than to the Indian Ocean.

4.4. Spatial Differences in Climate Controls on Sea-Level Variability

The results indicate that the response of sea level to large-scale climate forcing is not spatially uniform along the South Central Vietnam coast. Although both stations are influenced by ENSO and PDO, the relative importance of these climate modes differs between Quy Nhon and Cau Da.

Partial correlation analysis shows that ENSO remains significantly associated with sea-level variability after removing the effects of PDO and DMI. However, the reduction in correlation strength differs markedly between the two stations. At Quy Nhon, the SLA–ONI correlation decreases from -0.39 to -0.18 after controlling for PDO, suggesting that a substantial portion of the observed ENSO-related variability is modulated by low-frequency PDO fluctuations. In contrast, the correlation

at Cau Da decreases only from -0.46 to -0.38 , indicating that ENSO retains a strong and independent influence even after PDO-related variability is removed.

The multiple regression analysis further supports this spatial contrast. At Quy Nhon, PDO exhibits the largest standardised regression coefficient ($\beta = -0.36$), exceeding the contribution of ENSO ($\beta = -0.19$), indicating that decadal Pacific variability plays a major role in shaping local sea-level fluctuations. Conversely, ENSO is the dominant predictor at Cau Da ($\beta = -0.42$), whereas the contribution of PDO is comparatively weak ($\beta = -0.09$). These results suggest that sea-level variability in the northern part of the study area is more strongly modulated by low-frequency Pacific climate variability, while the southern sector responds more directly to interannual ENSO forcing.

The observed spatial differences may be related to regional variations in coastal geometry, shelf circulation, and the transmission of climate signals from the western Pacific into the South China Sea.

Although the observed relationships are physically consistent with previous studies, the current analysis relies primarily on statistical associations between sea-level anomalies and large-scale climate indicators. Other processes, including wind stress, atmospheric pressure, steric effects, ocean circulation, river flow, and regional monsoon variability, may also contribute to sea-level variability in the South Central Vietnam coastal region. Previous studies have also emphasised that long-term sea level variability reflects the combined influence of large-scale climate oscillations and regional atmospheric impacts rather than a single controlling mechanism^[60]. Therefore, the mechanisms discussed here should be considered as plausible physical interpretations rather than direct evidence of a causal relationship. Future studies integrating atmospheric, hydrodynamic, and thermodynamic observations are needed to further clarify the mechanisms linking large-scale climate change to regional sea level change.

5. Conclusions

This study investigated the characteristics, long-term trends, and climatic drivers of sea-level variability

along the South Central Coast of Vietnam using long-term tidal gauge observations from the Cau Da and Quy Nhon stations. The results indicate that relative sea level has increased at rates of approximately $1.91\text{--}2.36\text{ mm yr}^{-1}$ during 1975–2025, as consistently identified by the Hamed–Rao modified Mann–Kendall test, Sen’s slope estimator, and Innovative Trend Analysis (ITA). The long-term trends presented in this study represent relative sea-level change derived from tide-gauge observations and should not be interpreted as purely oceanic sea-level rise because the effects of vertical land motion were not explicitly quantified.

Sea-level variability in the study area occurs across multiple temporal scales, including seasonal, interannual, decadal, and long-term components. EMD decomposition revealed that the seasonal mode (IMF2) accounts for the largest proportion of total variability, whereas the interannual (IMF3–IMF4) and decadal (IMF5) components are closely associated with large-scale climate variability.

ENSO was identified as the dominant large-scale climate mode associated with interannual sea-level variability. During El Niño events, mean sea level decreased by approximately 3 cm, whereas La Niña events were associated with sea-level increases of about 2–3 cm. Correlation coefficients between SLA and ONI ranged from -0.39 to -0.46 , and the IMF3–IMF4 components exhibited strong relationships with ENSO, supporting its dominant association with interannual sea-level fluctuations in the region.

PDO was also found to be significantly associated with multiyear to decadal sea-level variability. The IMF5 component showed negative correlations with PDO, while correlation, partial-correlation, and multiple-regression analyses consistently demonstrated that PDO acts as an important modulator of regional sea-level variability, particularly at Quy Nhon. In contrast, the influence of the Indian Ocean Dipole (IOD) was comparatively weak, with low correlation and regression coefficients indicating a secondary role relative to Pacific climate variability.

Partial-correlation and multiple-regression analyses further indicated that ENSO and PDO represent the principal large-scale climate modes associated with sea-

level variability along the South Central Coast of Vietnam. However, their relative influences vary spatially. ENSO exerts a stronger influence at Cau Da, whereas PDO contributes more substantially at Quy Nhon, highlighting spatial heterogeneity in regional sea-level responses to large-scale climate forcing.

This study still has several limitations that need to be considered. The analysis is based on two long-term tide gauge stations, and the observed sea-level data were not corrected for vertical land motion due to the lack of suitable geodetic observations. In addition, although ENSO, PDO, and DMI exhibited significant associations with sea-level variability, these climatic indicators only explain approximately 22–25% of the interannual variation, suggesting that other regional and local processes may also contribute. Future studies integrating additional tide gauges, satellite observations, geodetic measurements, and atmospheric-oceanographic variables will further improve understanding of the physical processes governing sea-level variability along the Vietnamese coast.

Overall, this study improves the understanding of the statistical relationships between large-scale climate variability and regional sea-level variability and provides physically plausible interpretations of the underlying mechanisms along the South Central Vietnam coast. Despite the limitations noted above, the findings provide a valuable scientific basis for future sea-level projections, coastal flood-risk assessments, and climate-change adaptation strategies in the region.

Author Contributions

Writing—original draft preparation, S.H.P.; writing—review and editing, S.H.P. and T.T.-D.; data collection and processing, T.V.N. and N.V.D. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Water level data at Cau Da station can be accessed by contacting the Institute of Oceanography. Water level data from 1986 to 2025 at the Quy Nhon station can be accessed by contacting the Vietnam Meteorological and Hydrological Information and Data Center.

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Conflicts of Interest

The authors declare no conflict of interest.

AI Use Statement

During the preparation of this manuscript, the authors used Google Translate and Google Grammar solely for language refinement. No AI tools were used for data analysis, interpretation, or generation of scientific content. All outputs were critically reviewed and edited by the authors. The authors take full responsibility for the integrity and accuracy of the work.

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