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Spatiotemporal Characteristics of Sea Level Changes in Hangzhou Bay over the Past 40 Years

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Abstract: To investigate the spatiotemporal characteristics of sea level changes in Hangzhou Bay over the past 40 years, we collected tide gauge data from six stations within the bay. Various mathematical and statistical methods, including linear regression, empirical orthogonal function (EOF) analysis, and wavelet analysis, were employed to reveal the long-term variation patterns and spatiotemporal characteristics of sea levels in Hangzhou Bay. The results show that the overall trend of sea levels in this area is characterized by a fluctuating rise, with the rate of rise at the top of the bay (Ganpu Station) reaching 6.74 mm/year, higher than the average rise rate of 3.5 mm/year along the coastal areas of Zhejiang Province. Since the 2010s, the rate of sea level change has accelerated. There is a significant seasonal variation in sea levels, with high values occurring in summer and autumn and low values in spring and winter. The sea level in Hangzhou Bay exhibits multi-timescale periodic changes, including astronomical tides, solar activity cycles, and seasonal cycles. It is projected that the sea level will transition from a rising cycle to a declining cycle after 2026. The rise in sea level in the open sea is the main factor contributing to the rising trend of sea levels in Hangzhou Bay. The contracted river for regulation and morphological evolution of the estuary have intensified tidal wave deformation, resulting in a significant impact on local sea level changes.

Keywords: sea level; Hangzhou Bay; contracted river for regulation; wavelet analysis; EOF analysis; tidal wave deformation

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1. Introduction

Against the backdrop of global warming, the trend of sea level rise has become increasingly significant [1]. In estuarine and coastal regions, local sea level changes are more complex due to factors such as land reclamation, groundwater extraction, and major engineering projects. Sea level rise can trigger issues such as coastal erosion [2], saltwater intrusion [3], land submersion [4], and storm surges [5], posing significant challenges to coastal ecosystems and socio-economic systems.

To this end, domestic and international scholars have conducted research on sea level and tidal changes in estuarine and coastal areas. Ren Mei'e et al. [6] found that in the past 30 years, the sea level in the Yellow River, Yangtze River, and Pearl River delta regions has risen significantly. The research shows that these regions are affected by global warming and local subsidence, and the relative sea level has risen. The speed of sea level rise in each region is different, and the Pearl River Delta is one of the regions in China with the fastest relative sea level rise. Payandeh et al. [7] studied the impact of sea level rise on tidal dynamics in Barataria Bay. Sun Yanwei and Li Ying [8], using satellite altimetry data, revealed that from 1993 to 2018, the sea level along China's coast rose at a rate of 3.47 ± 0.50 mm/year, with the fastest increase observed in the East China Sea at 3.75 ± 0.55 mm/year. He Lei et al. [9] found that the average rate of sea level change in the Pearl River Delta from 1959 to 2011 was 4.08 mm/year, with evidence of an accelerating upward trend. Yang Yang et al. [10] applied wavelet analysis and EOF analysis to study the spatiotemporal characteristics of sea level changes in the East China Sea.

Hangzhou Bay is a typical strong tidal estuary of the world. The trumpet shape causes tidal wave deformation, making the changes in the sea level in Hangzhou Bay unique and more complex. Many studies have already been conducted on sea level change trends and tidal characteristics. For example, Feng et al. [11] analyzed the tide gage data in Tanxu Station to estimate that the average sea level rise in Hangzhou Bay was 4.6 mm/year 1978 to 2017. Pan Cunhong et al. [12] studied tidal characteristics and their spatiotemporal variations in Hangzhou Bay, pointing out that the narrowing of the river channel is the main reason for the changes in the tidal regime. Furthermore, Pan Cunhong and Han Zengcui [13] explored the response of tidal changes above Zhapu in the Qiantang River estuary to the narrowing of the river.

However, existing research on the effects of continuous sea level rises in the open sea, combined with increasing human activity, on the local sea level changes in Hangzhou Bay is still relatively limited. This study collected tide data from Hangzhou Bay and used statistical methods to analyze the long-term sea level change patterns and their spatiotemporal characteristics. Additionally, it explored the complex mechanisms by which large-scale sea level rises, estuarine landform evolution, and human activities impact local sea level changes in Hangzhou Bay.

2. Data Sources and Research Methods

2.1. Data Sources

Hangzhou Bay generally refers to the water area between the Zhapu section at the top of the bay and the Nanhui Zui–Zhenhai section at the mouth of the bay. It has a trumpet-shaped appearance, with the bay mouth being 98 km wide, narrowing to 16.5 km at the Zhapu section [13].

There are six tide gauge stations in the bay: Luchaogang, Daishan, and Dinghai are located at the mouth of the bay; Jinshan and Zhapu are located in the central bay; and Ganpu is located at the top of the bay. The locations of these stations are shown in Figure 1, and basic information on the data for each tidal station is shown in Table 1. To facilitate a comparison among the stations, tide data from 1980 to 2020 were used for the study, although some data are missing for certain stations: Jinshan Station (2016–2020) and Luchaogang Station (1980–1985, 2018–2020). The tide data from Jinshan and Luchaogang Stations come from the Shanghai Hydrological Station, while the other four stations' data come from the Zhejiang Provincial Hydrological Center. Annual average sea level data along the Zhejiang coast from 1980 to 2020 are sourced from the *China Sea Level Bulletin* [14]. The elevation reference used is the 1985 National Height Datum Phase I. It should be noted that the tide level data in Hangzhou Bay are all derived from revised data from Chinese national stations, avoiding errors caused by factors such as land subsidence. Therefore, the sea level we analyzed is the absolute elevation rather than the relative elevation. The principle is to determine the absolute elevation of the change in sea level by combining GPS reference station and tide gauge station data [15].

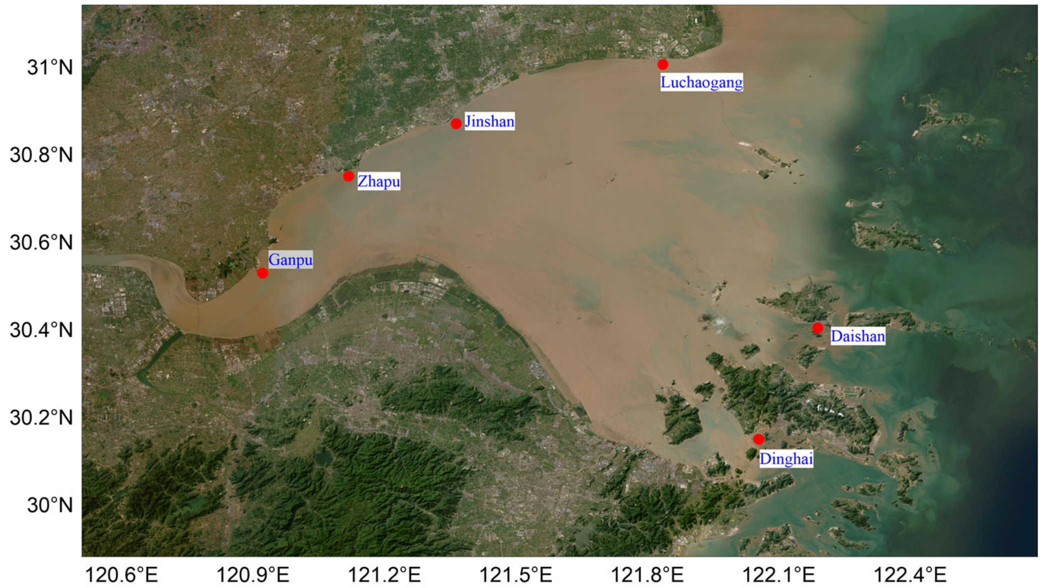

Figure 1. Location of the tidal stations.

Table 1. Basic information of the data for each tidal station.

Station	Data Time Series	Time Resolution	Data Source
Ganpu	1980~2020	hourly	Zhejiang Provincial Hydrological Center
Zhapu	1980~2020	hourly	Zhejiang Provincial Hydrological Center
Jinshan	1980~2015	hourly	Shanghai Hydrological Station
Luchaogang	1980~1991, 1995~2017	hourly	Shanghai Hydrological Station
Daishan	1980~2020	hourly	Zhejiang Provincial Hydrological Center
Dinghai	1980~2020	hourly	Zhejiang Provincial Hydrological Center

This study also collected shoreline and topographic data in Hangzhou Bay for 1959 and 2022, which were sourced from Zhejiang Institute of Hydraulics and Estuary's long-term tracking and monitoring data. The measurement accuracy is 1:50,000.

2.2. Research Methods

The statistical methods used in this study include linear regression, Empirical Orthogonal Function (EOF) analysis, and wavelet analysis.

The long-term trend analysis of sea level changes usually uses linear regression method, which uses the least squares method to find the best fitting straight line of the sea level time series. The slope of the straight line is the rate of sea level rise or fall.

The EOF analysis method is widely used in fields such as meteorology and oceanography. It can be used to decompose and understand the spatial and temporal variation characteristics of complex datasets [16,17]. By identifying the main spatial patterns of sea level change and the corresponding time series, it can well distinguish the driving mechanisms of sea level change. EOF analysis decomposes the sea level dataset into two parts, namely the spatial mode and time coefficient, as shown below

$$X = EOF_{m\times m} \times PC_{m\times n} \tag{1}$$

where m is the number of sites, n is the length of the time series, EOF is the spatial mode, and PC is the time coefficient.

Through decomposition, multiple spatial modes are obtained. The proportion of variance explained by the *k*-th mode is given by the following formula

$$\frac{\lambda_k}{\sum_{i=1}^{m} \lambda_i} \times 100\% \quad (2)$$

where λ_k is the eigenvalue corresponding to the *k*-th mode, which represents the variance explained by that mode. The higher the variance explanation rate, the more important the corresponding mode is, as it contributes significantly to the total variance.

Wavelet analysis is a time-frequency analysis tool that has significant advantages in revealing periodic patterns and the local features of complex signals. It can effectively and accurately extract trends, cycles, and abrupt changes from sea level time series [18,19]. The key to wavelet analysis is selecting an appropriate wavelet function. In this study, the complex Morlet wavelet commonly used in hydrological analysis was chosen. The calculation formula for the Morlet wavelet is as follows

$$W_f(m,n) = \frac{1}{\sqrt{m}} \int_R f(t) e^{ic\left(\frac{t-n}{m}\right)} e^{\frac{t}{m}\left(\frac{t-n}{m}\right)^2} dt \quad (3)$$

where $W_f(m,n)$ is the wavelet transform coefficient, *m* is the scale factor, and *n* is the translation parameter.

3. Results and Discussion

3.1. Long-Term Changes in Sea Level in Hangzhou Bay

The annual average sea level was obtained by averaging the hourly tidal data over the course of a year. Figure 2 shows the interannual variation in the average sea levels at various stations in Hangzhou Bay from 1980 to 2020. The long-term average sea level heights at Ganpu, Zhapu, Jinshan, Luchaogang, Daishan, and Dinghai Stations are 325 mm, 404 mm, 377 mm, 345 mm, 260 mm, and 269 mm, respectively. Spatially, the sea level gradually increases from the bay mouth to the top of the bay. The sea level at Luchaogang to Zhapu Station has increased by 59 mm, primarily due to the tidal waves propagating from the open sea into the estuary, where the narrowing of the coastline causes tidal wave reflection and energy concentration [12].

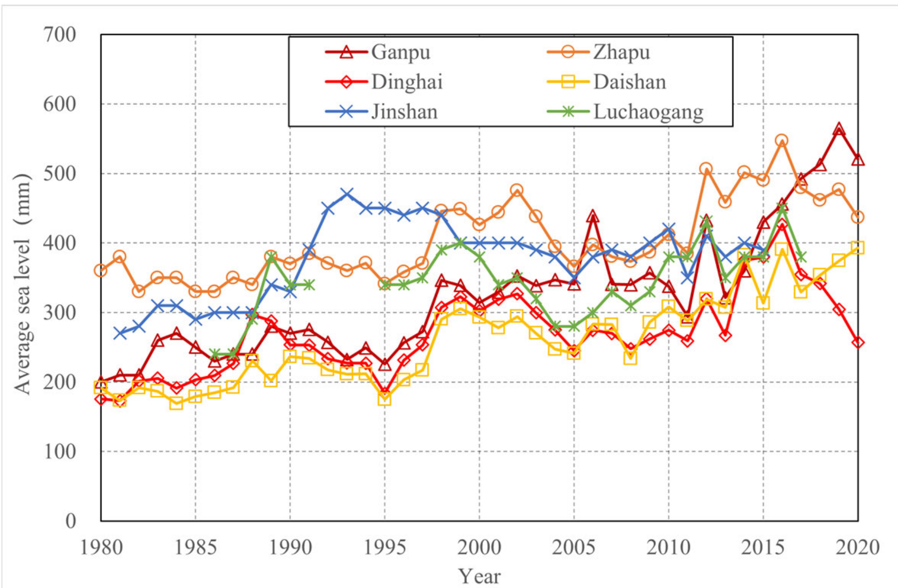

Figure 2. Average sea level changes at each station from 1980 to 2020.

The sea level at the top of the bay at Ganpu Station is anomalous, with a long-term average sea level 79 mm lower than that at Zhapu Station. The cause of this phenomenon is not fully understood, but it may be related to local topographic changes. In recent years, however, the sea level at Ganpu Station has continued to rise rapidly, exceeding that at Zhapu Station after 2017. Transversely, the average sea level at Luchaogang Station, located on the northern side of the bay mouth, is 76 mm higher than at Dinghai Station on the southern side, which is closely related to the Coriolis effect. Tidal currents entering Hangzhou Bay tend to deflect toward the northern shore, raising the tide levels on the northern side.

Figure 3 illustrates the sea level change process at Daishan Station from 1980 to 2020, along with the fitted trend line. Table 2 lists the sea level change rates and their standard deviations at various stations in Hangzhou Bay over different decades. The data reveal that over the past 40 years, all stations have shown an upward fluctuating trend in sea levels. Among them, Ganpu Station at the top of the bay has experienced the fastest average sea level rise, reaching 6.74 mm/year, far exceeding the average sea level rise rate of 3.5 mm/year along the Zhejiang coast during the same period [14]. The southern bay mouth saw a slower increase, with Daishan and Dinghai Stations recording rise rates of 4.86 mm/year and 3.49 mm/year, respectively. The slowest rise occurred at the central and northern parts of the bay, with Zhapu, Jinshan, and Luchaogang Stations showing rise rates of 3.59 mm/year, 2.75 mm/year, and 2.72 mm/year, respectively. The standard deviation of sea level changes over the years in Ganpu reached 92.25 mm/year, far higher than at other stations, indicating that the tidal level fluctuation characteristics of this station have been the most significant over the years. Compared with the results of Feng et al. [11] from 1978 to 2017, which showed a sea level rise rate of 4.07 mm/a in Hangzhou Bay, Ganpu Station's sea level rise rates at the top of Hangzhou Bay and Daishan Station's sea level rise rates at the mouth were higher, while the sea level rise rates at other stations were lower.

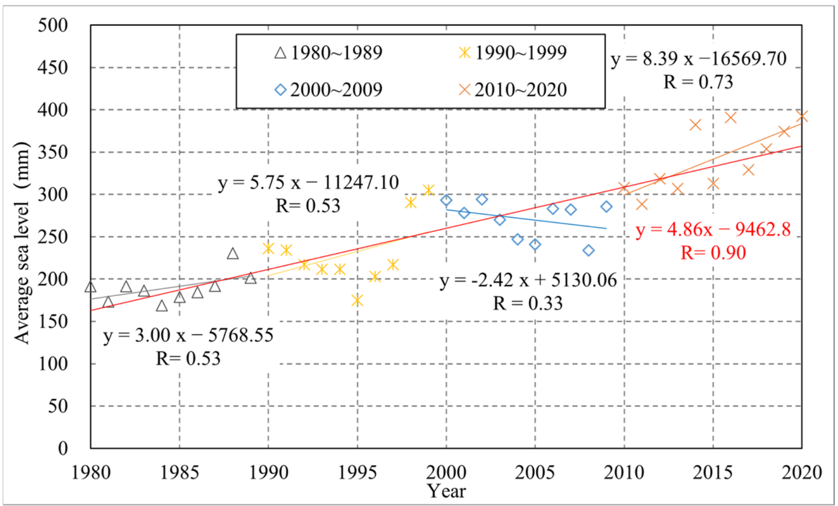

Figure 3. Average sea level change rate at Daishan Station in different years.

The sea level change rates varied across decades. In the 1980s, the sea levels generally rose steadily at all stations, with Dinghai Station showing a faster rise of 12.30 mm/year, while Zhapu Station saw a slight decrease. In the 1990s, the sea levels at most stations initially decreased before increasing, with the overall rise rate being around 5.5 to 7.5 mm/year. In the 2000s, except for Zhapu Station, which maintained a rise rate of 4.24 mm/year, other stations showed a downward trend, with rates of decline ranging from 1.5 to 9.0 mm/year. In the 2010s, except for a slight decrease at Jinshan Station from 2010 to 2015, Ganpu Station's rise rate accelerated significantly to 24.32 mm/year, followed by Daishan Station at 8.39 mm/year. The rise rates at the other three stations ranged from 2.7 to 4.0 mm/year. In addition, the standard deviation of sea level at each station has significantly increased over the past 10 years compared with the previous 30 years, indicating an amplification of sea level fluctuations. Notably, in 2016, the sea levels at Zhapu and downstream stations reached their highest point in nearly 40 years before slightly decreasing, while the sea level at Ganpu Station continued its rapid rise, reaching its peak in 2019. This may be related to the accelerated sedimentation at the Qiantang River estuary after the river's reclamation, as the changing topography has impacted water levels [20].

Table 2. Average sea level change rate and standard deviations in different years at each station (unit: mm/year; the data in parentheses are the standard deviation).

Station	1980~1989	1990~1999	2000~2009	2010~2020	1980~2020
Ganpu	5.88 (26.85)	7.54 (40.47)	4.24 (33.69)	24.32 (89.64)	6.74 (92.25)
Zhapu	−0.48 (18.86)	6.67 (36.14)	−8.92 (35.77)	4.04 (43.65)	3.59 (56.35)
Jinshan	5.17 (20.00)	5.39 (41.91)	−1.52 (15.67)	−0.86 (23.02)	2.75 (55.56)
Luchaogang	/	5.54 (26.28)	−4.97 (31.20)	2.74 (34.50)	2.72 (49.97)
Daishan	3.00 (17.24)	5.75 (39.56)	−2.42 (22.15)	8.39 (38.46)	4.86 (64.85)
Dinghai	12.30 (42.73)	6.49 (40.35)	−7.60 (28.51)	3.50 (57.47)	3.49 (58.35)

Sea level also exhibits significant seasonal fluctuations [21,22]. Figure 4 shows the distribution of average sea levels at Daishan Station from 1980 to 2020 for different months. As illustrated, the sea level rises and then falls throughout the year, reaching its peak between August and October when it is about 450~520 mm—up to 250~320 mm higher than the levels in January to March. This seasonal variation is consistent with related existing research [10,23]. Sea level changes in the North Pacific have significant seasonal characteristics, with the highest value occurring in September and the lowest value occurring in March. In terms of the seasonal variation scale, especially in the mid-latitude sea areas of the Northern Hemisphere, the specific volume of sea level changes caused by thermal expansion account for 86% of the sea level changes [23]. The minimum and maximum values of sea level in the East China Sea lag behind the extreme temperatures by one month [10]. The Hangzhou Bay area has a subtropical monsoon climate, with high temperatures and heavy rainfall in summer and mild rainfall in winter, with both rain and heat occurring simultaneously [13]. In addition to thermal expansion, various factors such as wind fields, circulation, solar radiation, rainfall, and runoff also contribute to the seasonal changes in sea level [24]. The increase or decrease in sea level caused by the monsoon along the southeast coast of China will have a certain impact on the changes in sea level [9]. The Kuroshio Current in the East China Sea affects the sea level changes in the East China Sea through exchange with the continental shelf water, while the variation in subtropical circulation affects the seasonal and interannual changes in sea level in the East China Sea through the Kuroshio Current [23]. The Yangtze River's runoff and precipitation are important factors affecting sea level changes in the East China Sea and Yellow Sea of China [25].

Additionally, during the 2010s from June to July, average sea levels at Daishan Station reached around 400 mm, which was an 80–100 mm increase compared with the same period in the previous decade. This increase is closely tied to the ongoing trend of climate warming, which has contributed to higher sea levels in these months due to more pronounced thermal expansion effects.

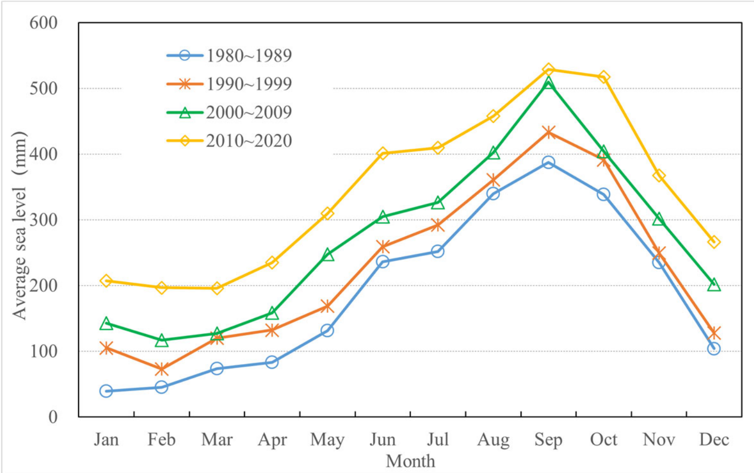

Figure 4. Average sea level at Daishan Station in different months from 1980 to 2020.

3.2. Hangzhou Bay's Sea Level Change Cycle

Wavelet analysis was used to study the periodic characteristics of sea level changes in Hangzhou Bay. The analysis was conducted on the monthly average sea level time series from 1980 to 2020 for four stations, namely Ganpu, Zhapu, Daishan, and Dinghai, which had the most complete data. The Morlet wavelet transform was applied. The selected Morlet wavelet was used to perform multi-layer wavelet decomposition on the signal, obtaining wavelet coefficients and approximation coefficients at various scales, removing low-frequency information, and obtaining the signal after trend removal.

Figure 5 shows the time-frequency distribution of the real part of the wavelet transform coefficients and the wavelet variance at Daishan Station. The black dots may be some noise in the data. The wavelet coefficients reveal oscillation centers at multiple time scales, alternating between positive and negative, indicating that the sea level changes at Daishan Station involve several periodic time scales. The first main period is at the 180~230 month scale, covering all decades with a central time scale of 212 months. This corresponds to the primary tidal astronomical cycle of 18.6 years, reflecting the changes in the moon's declination angle. The time scale of the second main period is 12 months, corresponding to the seasonal changes in a single hydrological year. The third main period is at the 100~140 month scale, with a central time scale of 112 months. This is similar to the sunspot activity cycle. There is a correlation between sunspot activity and sea level temperature, which affects sea level rise and fall [26]. The result is consistent with Wang Guodong's analysis of sea level fluctuations in the East China Sea [27], which identified three main periodic scales at 30 months, 134 months, and 230 months. Interestingly, the 2~7 year quasi-periodic events associated with the El Niño Southern Oscillation (ENSO) were not significantly observed in the Hangzhou Bay region.

Figure 6 shows the real part of the wavelet coefficients corresponding to the first three main periodic cycles at Daishan Station. From the graph, it can be observed that the real part of the coefficients for the second main period oscillates within a relatively stable range, while the amplitude of the recent positive phase of the third period has significantly increased. For the first main period, since 2005, the amplitude of both the positive and negative phases has been expanding continuously, indicating a marked increase in the interannual sea level fluctuations at the entrance of Hangzhou Bay.

The wavelet coefficients for the first and third main period reached their positive phase peaks in 2018 and 2020, respectively. Afterward, the sea level transitioned into a declining phase. According to the time coefficient curves of each main period, it is expected that the coefficients of the first and third main period will enter a negative phase around

2025~2026, and then the sea level will shift from an increasing cycle to a declining cycle. It should be noted that the periodic decline in sea level here is a characteristic of periodic changes, rather than a trend decline.

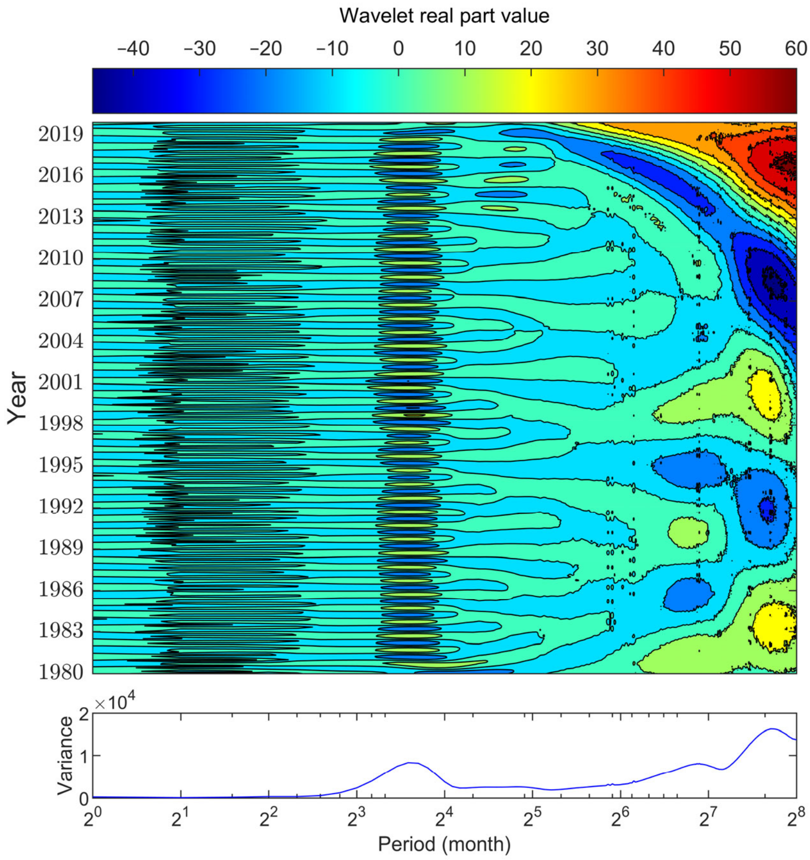

Figure 5. Time-frequency distribution and variance of the wavelet coefficients' real part for Daishan Station.

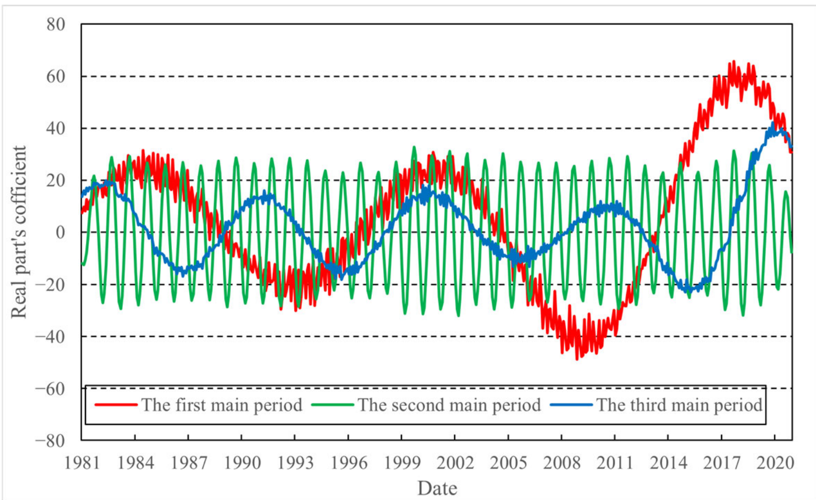

Figure 6. Variations in the wavelet coefficients' real part corresponding to different main periods at Daishan Station.

Table 3 lists the center characteristic time scales for the first three main cycles derived from wavelet transform analysis at Ganpu, Zhapu, Daishan, and Dinghai Stations. The results for the other three stations are similar to those of Daishan Station, which include the following time scales: a short-term scale of 12 months, a medium to long-term scale of 100~119 months, and a long-term scale of 202~212 months. These time scales reflect various periodic influences on sea level fluctuations, with the 12 month cycle linked to seasonal changes, the 100~119 month cycle related to solar activity such as sunspots, and the 202~212 month cycle associated with long-term tidal and astronomical cycles.

Table 3. Time scale of the first, second, and third periods in Hangzhou Bay's tidal stations (unit: months).

Station	The First Main Period	The Second Main Period	The Third Main Period
Ganpu	206	12	100
Zhapu	212	12	118
Daishan	212	12	118
Dinghai	202	12	119

3.3. Analysis of the Causes of the Rising Trend of Sea Level in Hangzhou Bay

3.3.1. Impact of Rising Sea Levels in Offshore Areas

The rising sea level in the open sea is a major factor contributing to the overall upward trend in sea levels in Hangzhou Bay. According to the IPCC's Sixth Assessment Report, global sea levels rose by 0.20 m between 1901 and 2018. The *China Sea Level Bulletin* [14] indicates that the average rate of sea level rise along the Zhejiang coast from 1980 to 2023 was 3.5 mm per year. This rise in sea level along the Zhejiang coast inevitably causes corresponding changes in the sea level of Hangzhou Bay.

Figure 7 shows the relationship between the sea level at Daishan Station at the bay mouth and the sea level along the Zhejiang coast from 1980 to 2020, with a correlation coefficient of 0.94. For Zhapu Station in the central bay, the correlation coefficient is 0.92; for Ganpu Station at the top of the bay, it is 0.87. These results indicate a generally strong correlation between the sea levels in Hangzhou Bay and those along the Zhejiang coast. However, the correlation is slightly lower at Ganpu Station at the bay's top, suggesting that local factors may influence the sea level changes more significantly in that area.

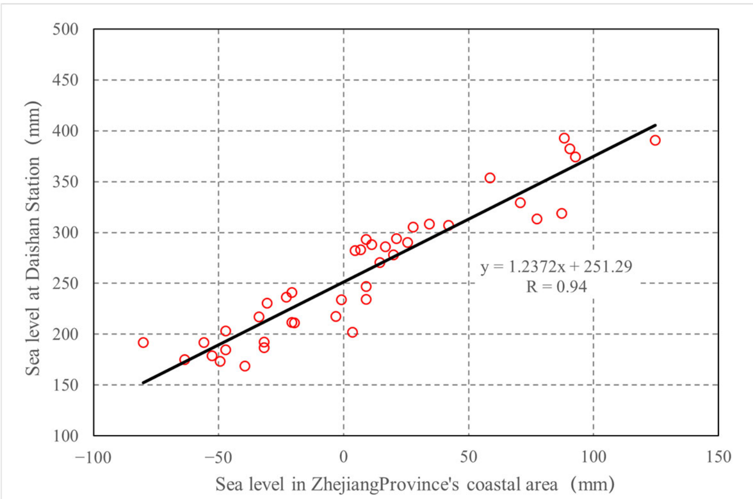

Figure 7. The correlation between Daishan Station and sea level in Zhejiang Province's coastal area from 1980 to 2020.

3.3.2. Impact of River Channel Narrowing

Hangzhou Bay has a funnel-shaped topography, with the width narrowing from approximately 100 km at the bay entrance to 16.5 km at the Ganpu section, and the bed's elevation rising from −10 m to −5 m, as shown in Figure 8. Due to the narrowing of the coastline and the rise in the riverbed's elevation, tidal waves experience various changes, such as refraction and deformation, as they enter the estuary.

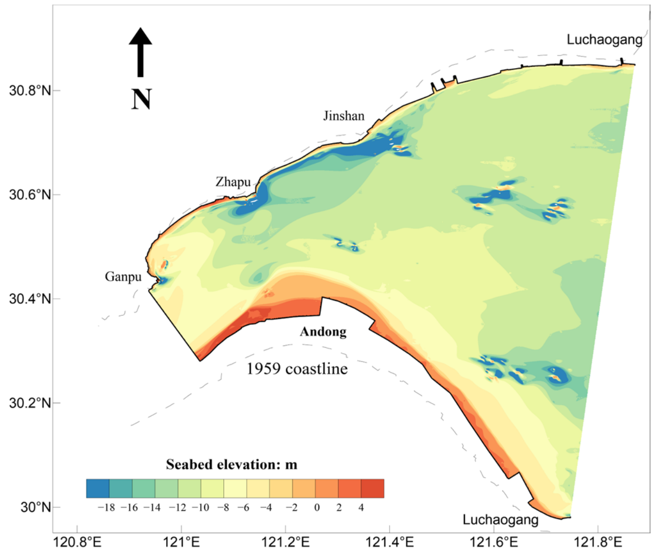

Figure 8. Seabed morphology in Hangzhou Bay (2022).

Since the 1960s, the cumulative reclamation of approximately 2 million acres in the Qiantang River Estuary has caused the Ganpu section to narrow by about 3.5 km [13]. These boundary changes inevitably intensify tidal deformation [28–30] and the evolution of the estuarine morphology [31,32]. Figure 9 illustrates the sedimentation and erosion dynamics in Hangzhou Bay from 1959 to 2022, showing an overall trend of sedimentation in the bay, with the sedimentation rate increasing further upstream. The average sedimentation rate in the Ganpu to Zhapu river section is 3.87 cm/year, due to reduced tidal inflow caused by the narrowing of the coastline, which leads to sediment accumulation on the seabed.

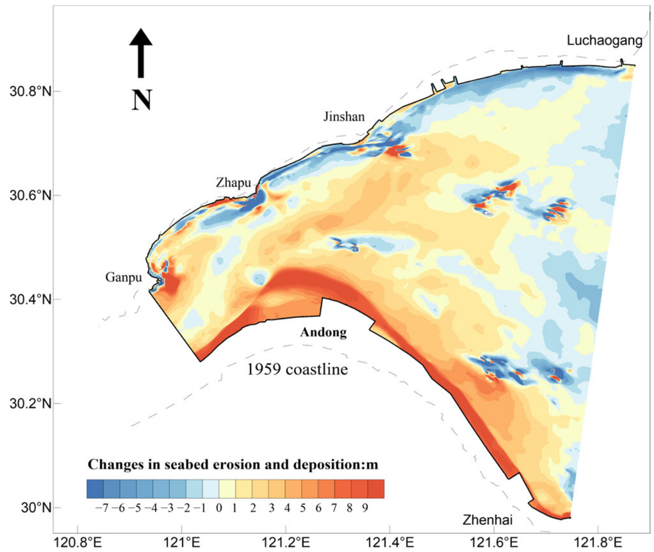

Figure 9. Changes in seabed erosion and deposition in Hangzhou Bay from 1959 to 2022.

Here, the annual averages of high and low tide levels were extracted from the highest and lowest tide level of each rising and falling tide cycle based on years of hourly tide data. Figure 10 shows the changes in the average high tide and low tide levels at Ganpu and Zhapu Stations, as well as their trend lines. From 1980 to 2020, the average high tide levels at Ganpu and Zhapu Stations rose at rates of 1.4 mm/year and 1.6 mm/year, respectively.

During the same period, Ganpu's low tide level increased by 2.9 mm/year, while Zhapu's low tide level showed a decrease at a rate of 2.4 mm/year. These differences are attributed to both the narrowing of the river and the continuous sedimentation of the Hangzhou Bay seabed. The river's narrowing due to reclamation causes intensified tidal reflection and the enhancement of standing wave effects, leading to a rise in high tide levels and a drop in low tide levels. Meanwhile, the limited water depth at the Ganpu section (about 6 m) allows seabed sedimentation to raise the low tide level, which increases the shallow water partition and has resulted in a rising low tide trend at Ganpu over the past 40 years. In contrast, at Zhapu Station, the deeper water depth means that sedimentation has not yet significantly impacted the low tide level, which has caused an increase in tidal range, limiting the overall rise in sea level at this station.

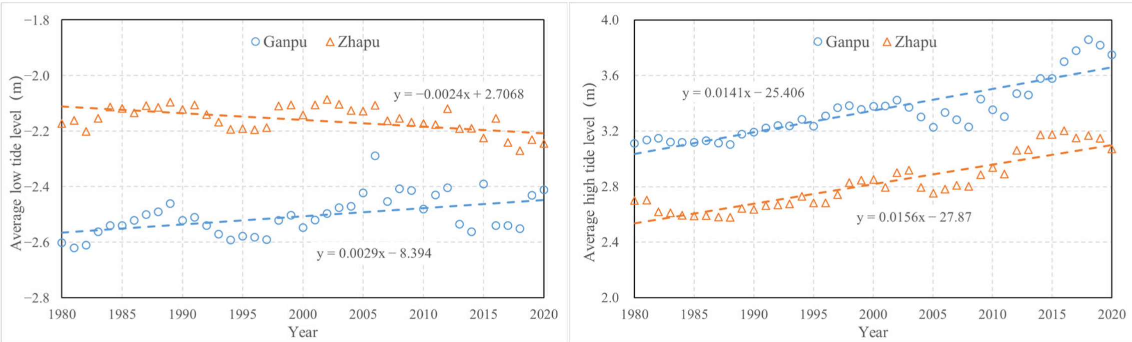

Figure 10. Changes in average high and low tide levels in Ganpu and Zhapu Stations from 1980 to 2020.

This evidence demonstrates the significant impact of river channel narrowing and estuarine morphological evolution on local sea level changes in the estuary. Given the ongoing sedimentation trend in Hangzhou Bay, it is likely that the impact will extend further downstream in the future.

3.4. EOF Mode Analysis of Sea Level in Hangzhou Bay

Empirical Orthogonal Function (EOF) analysis was applied to the average sea level time series from 1980 to 2020 at Ganpu, Zhapu, Daishan, and Dinghai Stations in Hangzhou Bay. This analysis provided the spatial modal distribution of sea level changes and the corresponding temporal variation coefficients. Table 4 lists the spatial model coefficients and weight coefficients derived from the EOF analysis for each station. The first two modes, referred to as EOF1 and EOF2, contribute 86.8% and 9.0% of the variance, respectively, with a cumulative contribution of 95.8%. These first two modes effectively represent the trend of sea level changes in Hangzhou Bay. Figure 11 shows the temporal coefficients corresponding to the first two spatial modes.

Table 4. Spatial modal coefficients and variance contribution rates of EOF analysis at each station in Hangzhou Bay.

Spatial Modes	Ganpu	Zhapu	Daishan	Dinghai	Variance Contribution (%)
The first mode	4.34	2.54	2.50	3.08	86.8
The second mode	−4.28	2.68	3.88	0.66	9.0

The variance contribution of EOF1 is 86.8%, which explains the primary information about sea level changes. All stations show a positive phase distribution, indicating that the sea level changes (whether rising or falling) are synchronized across the stations. The temporal coefficient curve for this mode has shown a fluctuating upward trend over the past 40 years. Notably, there were periods of rapid increase in the temporal coefficients over 1995–2000 and 2011–2016, with stable periods in 1980–1987 and 2002–2010. This corresponds well with the overall upward trend of sea level fluctuations.

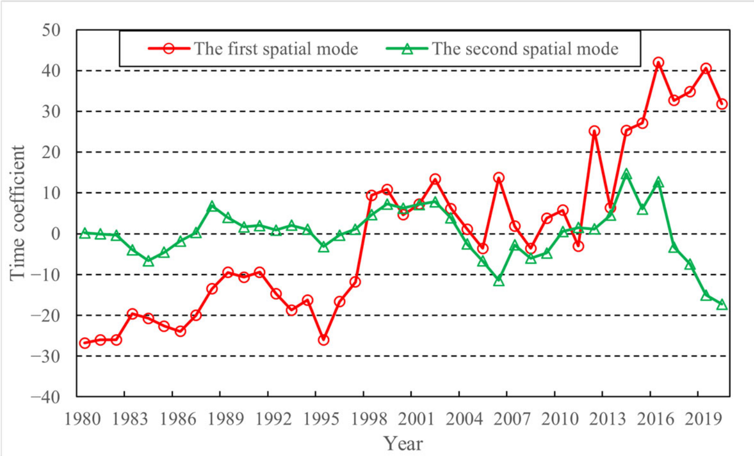

Figure 11. Time coefficient changes corresponding to spatial modes of EOF analysis at each station in Hangzhou Bay.

Correlating the temporal coefficient of this mode with the sea level data from the Zhejiang coastline over the years (Figure 12) revealed that the correlation coefficient is as high as 0.95. This indicates that EOF1 primarily reflects the contribution of sea level changes along the Zhejiang coast to the sea level changes in Hangzhou Bay and has been the main factor driving the overall sea level trend in the bay.

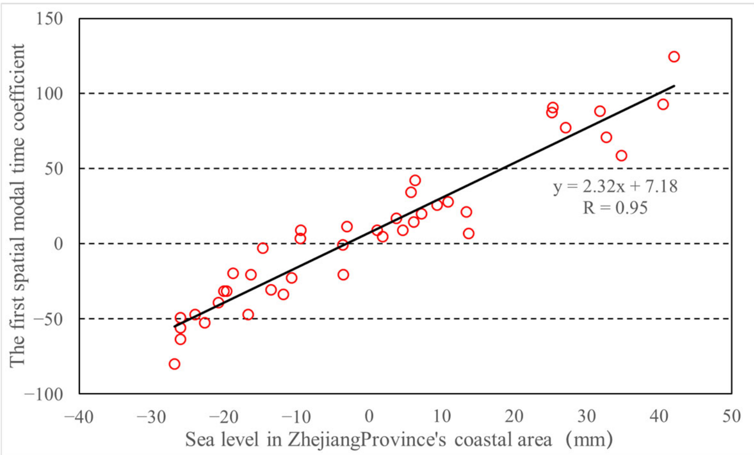

Figure 12. The correlation between sea level and the first spatial mode's time coefficient in Zhejiang Province's coastal area from 1980 to 2020.

The spatial coefficients at each station differ, with Ganpu Station at the bay's top showing the largest spatial coefficient (4.34), while the other three stations' coefficients are relatively similar, ranging from 2.5 to 3.08. This is consistent with the earlier analysis in Section 3.2, which discussed the impact of river channel narrowing and estuarine morphological evolution. Against the background of rising sea levels along the Zhejiang coast, tidal wave deformation within the estuary amplifies the sea level rise rate at the bay's top (Ganpu). Compared with downstream stations like Zhapu, the local sea level changes at Ganpu are more sensitive to the rising sea level trend in the open sea.

The variance contribution of EOF2 is 9.0%, serving as a supplement to the first spatial mode. The temporal coefficient for this mode oscillates around zero and exhibits distinct periodic fluctuations, with an increasing amplitude trend since the 21st century. According to the wavelet analysis, the primary period of the temporal coefficient for this mode was found to be around 12~13 years. This mode mainly reflects the contribution of periodic sea level fluctuations, such as the astronomical tide cycle and sunspot cycles, to the sea level changes in Hangzhou Bay [26].

The spatial coefficient for Ganpu is negative, with a maximum value of −4.34, while the other three stations have positive spatial coefficients ranging from 0.66 to 3.88. This suggests that the trend at Ganpu Station (the bay's top) differs from the other stations under this spatial mode. The sea level curve shows that between 2016 and 2020, Ganpu's sea level rose by 65 mm, while the other stations predominantly showed a decrease during this period. This difference is also due to the location of Ganpu near the upstream area, which is significantly affected by high-intensity river regulation projects in the Qiantang River. These projects have altered the tidal type, leading to an increase in the shallow water's tidal amplitude, which has caused the temporal coefficient of this mode to be less significant at Ganpu compared with other stations [12].

4. Conclusions

This study used sea level data from six stations in Hangzhou Bay (Ganpu, Zhapu, Jinshan, Luchaogang, Daishan, and Dinghai) between 1980 and 2020 to analyze the spatiotemporal variations in sea level in the Hangzhou Bay area. The study also explored the impacts of sea level rise along the Zhejiang coastline, river channel narrowing, and estuarine morphological changes on local sea level variations in Hangzhou Bay. The main understandings are follows.

1. The sea level in Hangzhou Bay gradually rises from the bay mouth towards the inner bay, with the northern side of the bay being higher than the southern side. Over the past 40 years, there has been a noticeable upward trend in sea level fluctuations. The fastest rise occurred at Ganpu Station in the upper bay, with a rate of 6.74 mm/year, which exceeded the 3.5 mm/year rise rate along the Zhejiang coastline during the same period. The rise rate is slower at the bay mouth, and even slower in the central bay. Seasonal variations in sea level are significant, with the highest values observed in the summer and autumn, and the lowest values in the spring and winter.
2. The sea level in Hangzhou Bay exhibits periodic variations at different time scales. These include a long-term scale of 202 to 212 months, a medium-long scale of 100 to 119 months, and a shorter scale of 12 months, each corresponding to distinct cyclical influences. The 202~212 month cycle corresponds to the astronomical tidal cycle, the 100~119 month cycle is linked to solar activity, and the 12 month cycle reflects seasonal changes. Among these, the astronomical tidal cycle is the most prominent. The quasi-periodic ENSO (El Niño Southern Oscillation) event, typically associated with a 2~7 year cycle, does not have a noticeable impact in the Hangzhou Bay region. Moreover, it is projected that the sea level will transition from a rising cycle to a declining cycle after 2026.
3. The rise in sea level in the open ocean has led to an overall upward trend in the sea level of Hangzhou Bay. The narrowing of the river channel and the sedimentation trend in Hangzhou Bay have intensified tidal wave deformation, with the most significant impact observed at Ganpu Station in the upper bay, where the local sea level rise rate far exceeds that at other stations. The variance contribution rate of the first EOF mode is 86.8%, which primarily reflects the influence of changes in the open ocean sea level on the sea level variations in Hangzhou Bay, making it the main

driving factor for sea level changes in the bay. The variance contribution rate of the second EOF mode is 9.0%, which mainly reflects the contribution of periodic sea level fluctuations to the changes in Hangzhou Bay's sea level.

In conclusion, the rise or fall in sea level in Hangzhou Bay is primarily driven by large-scale changes in the open ocean sea level. The response of the bay's internal areas to the rising sea level shows clear spatial differences. Factors such as the narrowing of the river channel and the sedimentation in Hangzhou Bay also have a significant impact on local sea level changes. Therefore, it is essential to further deepen our understanding of the mechanisms by which human activities and estuarine geomorphological evolution affect sea level changes in the estuarine region, and to continue monitoring sea level changes.

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