Environ Earth Sci (2014) 71:3503–3515
DOI 10.1007/s12665-013-2740-1

ORIGINAL ARTICLE

Impacts of relative sea level rise on the shoreface deposition, Shuidong Bay, South China

Xiaoling Zhang · Zhijun Dai · Ao Chu · Jinzhou Du

Received: 4 June 2012 / Accepted: 19 August 2013 / Published online: 30 August 2013

Abstract The influence of relative sea level rise on shoreface deposition helps to elucidate changes in beach and nearshore geomorphology in response to different forcing factors. In this study, two sets of sediment samples, one from 1982 and one from 2004, from the Shuidong Bay of South China were analyzed to determine the changes in shoreface depositions. An EOF (Empirical orthogonal function) method was used to examine how these depositions changed based on the relative sea level rise. The results show that shoreface sediments of Shuidong Bay are mainly composed of sand. Fine-grained sediments are distributed in the lower shoreface/offshore area, and coarse-grained sediments are mainly found in the upper shoreface/nearshore area. Due to the altered hydrological forcing caused by relative sea level rise, the sand fraction in sediments increased from 84.7 % in 1982 to over 90 % in 2004, and the clay and silt fractions decreased from 11.8 % in 1982 to 5.6 % in 2004. Grain-size parameters in sediments in 2004 became coarser, slightly more well sorted, less skewed and had lower kurtosis than those in 1982. In addition, the shoreface deposition of Shuidong in 1982 and 2004 is distinctly different: a polarized mode was described by the first eigenfunctions, and a homogenized mode was described by the second eigenfunctions. The former means that the sediment components developed towards the two opposite poles, undergoing both coarsening and refining processes. The second mode indicates that the secondary variation in sediment components was mostly in the three intermediate-grained sand components. In the future, the Shuidong Bay shoreface may be subjected to even further erosion because of increases in the energy of the environment resulting from rapid relative sea level rise.

Keywords Shoreface deposition · Sea level rise · EOF analysis · Shuidong Bay

X. Zhang · Z. Dai (✉) · J. Du
State Key Laboratory of Estuarine and Coastal Research, East China Normal University, Shanghai 200062, China
e-mail: zjdai@sklec.ecnu.edu.cn

A. Chu
Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

Introduction

The shoreface, which is the zone of shoaling waves between the breakpoint and the edge of the inner shelf (Niedoroda et al. 1984), occurs in low to high latitude coastal settings. Shoreface deposition varies widely according to regional differences in wave climate and the type of coastal sediment (Schwartz 1982), which is wholly dominated by wave processes (Dalrymple et al. 1992). The character of preserved shoreface sedimentary successions is also determined by geology, tidal action, and relative changes in sea level (e.g., regressive and transgressive) (Riggs et al. 1995; Posamentier and Moris 2000; Dashtgard et al. 2012).

Understanding the dynamics of shoreface deposition is important for the design of shore-zone structures and the placement of sand for beach nourishment (Schwartz and Birkemeier 2004). Some studies indicate that physical attributes across the sediment–water interface of the shoreface vary systematically (Clifton et al. 1971; Schwartz et al. 1981; Short 1984). Many studies suggest that shoreface bedforms exhibit regular variation in response to differences in flow conditions and sediment size (Allen 1984; Harms et al. 1982; Rubin 1987). Moreover, hydrodynamic interpretation and shoreface depositional models have clearly shown that shore-normal zonation of the faces occurs (Komar 1976; Clifton 2006). Shoreface morphodynamic processes are also discussed in detail in the literature (Schwartz 1982; Riggs et al. 1995; Schwartz and Birkemeier 2004). However, the relative global sea level rise that has been caused by global warming during the last half of the 20th century is occurring much faster than before (Michael and Harry 2009). Sea level rise is one of the fundamental determinants of shoreline position (Tamura et al. 2003) and induces or accelerates on-going shore retreat because deeper water decreases wave refraction (Everts 1985). In addition to the coastal hydrodynamics and morphological changes (Everts 1985; Tamura et al. 2003; Sanders et al. 2010), the change in shoreface deposition is one of the important consequences of sea level rise. It is expected that rising sea levels will accelerate beach and shoreface erosion (Slott et al. 2006; Jones et al. 2007; Schlacher et al. 2008). Unfortunately, the characteristics of the shoreface deposition in response to relative sea level rise are relatively poorly understood.

Therefore, the purpose of this study is to describe the overall characteristics of bottom sediments in the shoreface of Shuidong Bay, South China, and determine how deposition patterns have changed and will continue to change with relative sea level rise. To accomplish this, two sets of sediment samples, one collected in 1982 and one collected in 2004, from Shuidong Bay, were used to examine the changes in the shoreface depositional environment over the past two decades.

Physical setting

Shuidong Bay is located in the western part of the Guangdong coast of South China (Fig. 1). There are two tidal inlets in Shuidong Bay. Bohe beach, with a gently arc-shaped configuration due to dominance of bedrock headlands, is located between the two inlets (Fig. 1) (Dai and Li 2008). Semidiurnal tides are dominant in this region, with a tide range that varies from 1.75 (neap) to 2.6 m (spring) (Chen 1991). The yearly residual current is in southwestern direction along the coast and is mainly induced by tides. However, in the offshore region, the residual current is northeastward in the summer and southwestward in the winter. The waves are mainly controlled by the monsoon, as the dominant wave direction is from the southeast or southwest greater than 82 % of the time (Chen 1996). The average wave height is 0.68 m with a mean wave period of 3.4 s. Moreover, tropical cyclones (locally called typhoons) can influence the Bay in the summer and autumn with violent winds, waves and storm surges. The river inflow and its associated sediment are negligible due to damming upstream of the Shuidong Bay.

Materials and methods

Two cruises to collect surficial sediment samples from Shuidong Bay were carried out under fair-weather conditions on November 21, 1982 and on November 30, 2004. A total of 64 sediment samples in 1982 and 23 sediment samples in 2004 were taken by a grab sampler from the top 5–10 cm of the shoreface (Fig. 1). The sample locations were determined using a differential GPS system. In addition, the 1:40,000 navigation charts of Shuidong Bay from 1967 and 2007 were digitized in an ArcGis platform and used for bathymetry data. The yearly average tide gauge data from eight stations near the Bay were collected from the Hydro-logic Yearbook of Guangdong Province. The annual statistical descriptions of wave characters for five stations were mainly collected from historical documents (Chen et al. 1999).

In the laboratory, each sample was treated with 30 % hydrogen peroxide solution for 24–28 h to eliminate organic materials, and then the analysis of each sediment sample grain size (-1 to 8 ϕ) was conducted by a sieving method with one-phi intervals (Liu and Zarillo 1989). The parameters of the mean grain size (μ), sorting coefficients (σ), skewness (SK), and kurtosis (K) were calculated based on the grain-size classes of each sample by the statistical moment method (McManus 1988). In addition, the sediments were classified according to Folk's methodology (Folk et al. 1970), and the sediment components of all samples were calculated according to the Udden-wentworth grain-size classification scheme (Wentworth 1922).

Subsequently, an empirical orthogonal function analysis (EOF) was used to diagnose spatial variation in the grain size of shoreface sediments. EOF is a classical statistical technique, which had been widely applied to problems in meteorology, oceanography, geology, and sedimentology (James and Justin 1998; Yoo and Kim 2004). The advantages of the EOF are that any complex original data can be completely described by a relatively small set of uncorrelated variables via linear transformation, and the new variables are mutually orthogonal (Dai et al. 2008, 2010). Here, the size distribution of sediment samples from the EOF analysis is represented in the form of a matrix $S(x, \Phi)_{m \times n}$ of discrete size classes (Ramanamurty et al. 1986), where x represents the sampling station and Φ is the particle size class considered at 1 ϕ intervals from -1 to 8 ϕ. Each element of this matrix is the sample with that size class expressed as a percentage of the whole sample. To study the changes in the content of the sediment

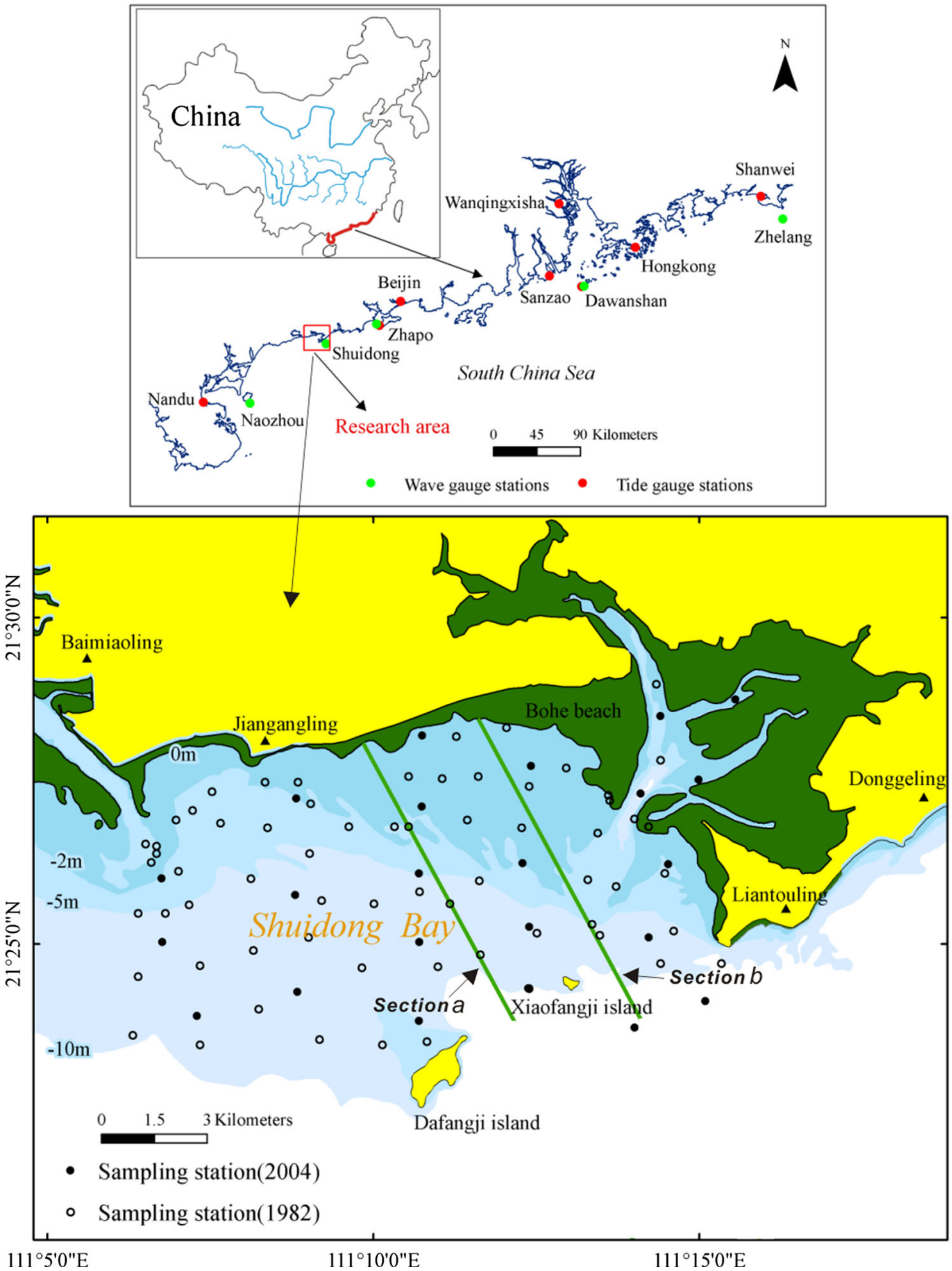

Fig. 1 Sample locations, section locations and research area

component, the data matrix $S(x, \Phi)_{m \times n}$ was changed into an anomaly matrix before EOF analysis. Therefore, the computational procedures are as described below:

$$S(x, \Phi)^T_{m \times n} \approx \overline{S(\Phi)^T} + \sum_{j=1}^{n} a_j(x) e_j(\Phi) \tag{1}$$

where $e_j(\Phi)$ are the spatial eigenfunctions, $a_j(x)$ are the corresponding temporal amplitude eigenfunctions, and n is the number of eigenfunctions in the series. Therefore, the particle size distribution of sediment samples in the study area can be quantified by a set of eigenvalues; each eigenvalue and its $e_j(\Phi)$ define the importance of the eigenfunction.

Results

Shoreface deposition characteristics

The distribution of the grain size of surface sediments usually differs significantly between locations. Figure 2 indicates that the distribution of the mean grain size (μ) in 1982 ranged from very fine (4 ϕ) to very coarse sand (0 ϕ)

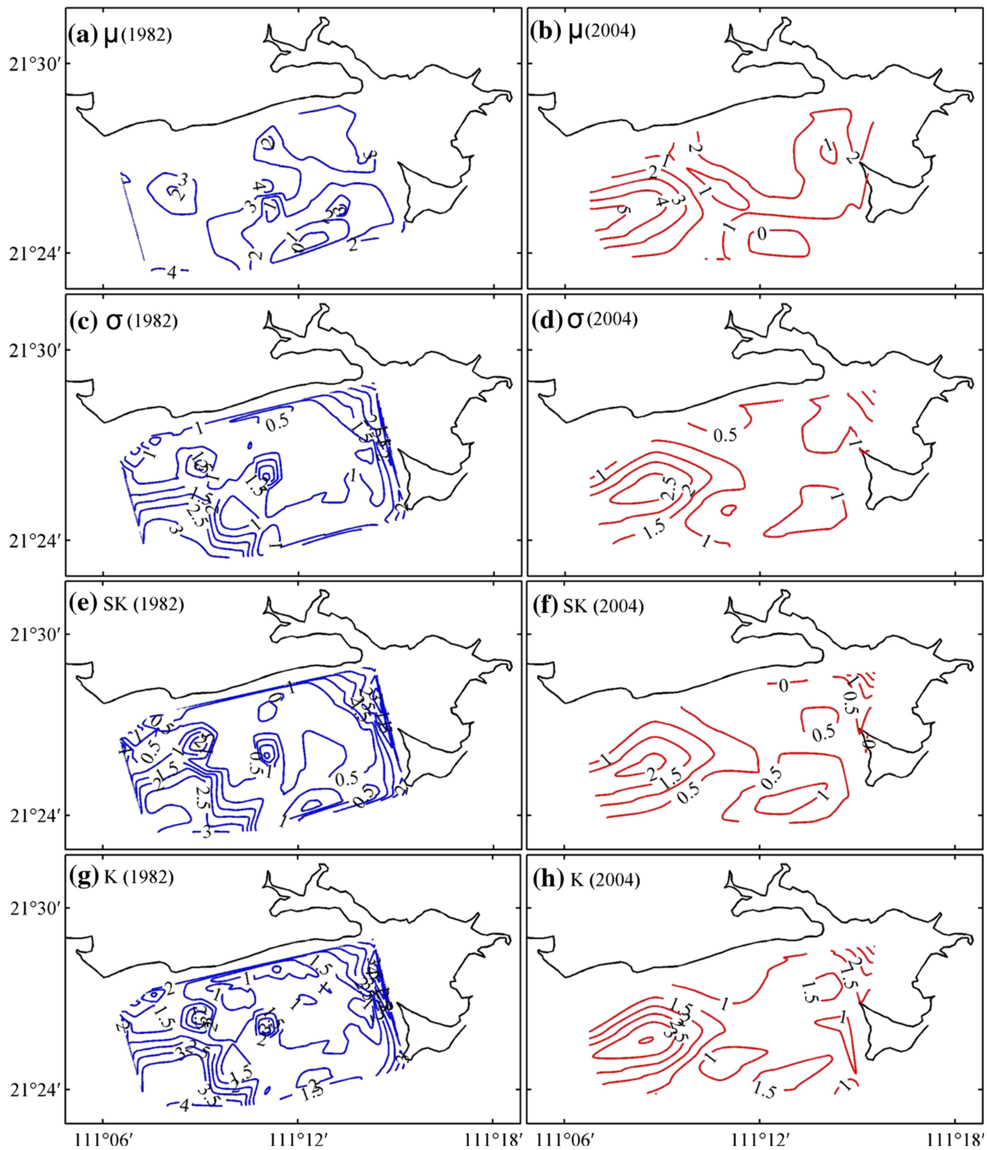

Fig. 2 Distribution of grain-size parameters

(Fig. 2). The relatively coarse fraction is located in the nearshore/upper shoreface area around the Liantouling headland, and the very fine fraction is distributed over the southwestern offshore/lower shoreface areas. This means that grain sizes become coarser from the low shoreface to the upper shoreface in 1982, as they do in 2004. However, though there was a similar distribution of the mean grain size in 2004, the range for the medium grain size in 2004 is wider than in 1982, from coarse silt (5 ϕ) to very coarse sand (0 ϕ). A shift towards land in the finer sediments of the lower shoreface from 1982 to 2004 was also observed (Fig. 2a and b). The lower shoreface that had coarse grain-size sediments in 1982, had relatively fine sediments in 2004. Moreover, it is notable that the coarse grain fraction in 2004 was consistently higher than in 1982. The mean sorting coefficient (σ) for sediments in 1982 was 1.3, which is larger than in 2004. This means that sediment sorting in 2004 was better than in 1982. Skewness in 1982 was 1.0 on average and ranged from 0.1 to 3.1. The skewness in 2004, averaging 0.8 and ranging from 0.2 to 2.7 (Fig. 2), was clearly lower than the skewness in 1982, as indicated by the increase in the ratio of the coarser-grained fraction. The (K) behaved similarly to the σ. Taken altogether, sediment in 2004 seems to be coarser, slightly better sorted, with a lower positive skew (a smaller tail of finer particles) and lower kurtosis than sediment in 1982.

The sand component accounted for more than 84 % of the sample in 1982 and for 90 % in 2004 (Table 1). This indicates that the sediment in the bay became coarser from 1982 to 2004. The related coarse components were consistent with the increase in coarse sand (Fig. 3). However, the mean clay component was 2.8 % in 1982, higher than 1.9 % in 2004, indicating decrease in clay and silt fractions from 1982 to 2004 (Fig. 3). Therefore, the changes in the

Table 1 Mean percentages of clay, silt, sand and gravel in 1982 and 2004

Dataset name	Mean clay content (%)	Mean silt content (%)				Mean sand content (%)					Mean gravel content (%)
		Very fine silt	Fine silt	Medium silt	Coarse silt	Very fine sand	Fine sand	Medium sand	Coarse sand	Very coarse sand	
1982	2.8	11.8				84.7					0.8
		0.9	0.7	3.2	7.0	39.7	21.5	15.5	4.3	3.6	
2004	1.9	5.6				90.6					1.9
		0.9	1.1	1.8	1.8	11.1	26.5	18.3	23.9	10.8	

composition of sediment before and after 2004 imply a coarsening process of the sedimentary environment, possibly due to changes in regional dynamic action.

Furthermore, based on Fig. 4, the surficial sediments of Shuidong Bay can be divided into sand, silty sand and muddy sand in 1982 and into sand, silty sand and sandy silt in 2004 (Fig. 4a and b). The distribution of the sediments in 1982 and 2004 within the triangle diagram clearly reflects differences in both the particle size and specific hydrodynamic energy conditions. Sediments in 2004 were coarser than they were in 1982, indicating that dynamic action of Shuidong Bay may have been more intense in 2004 than in 1982.

Shoreface deposition modes by EOF analysis

Table 2 shows that the valid results of EOF analysis are the first two eigenvalues, which account for approximately 80 % of the total variation. This means that they represent the vast majority of the meaningful information in the original anomaly datasets. The first eigenfunction for the eleven components of sediment composition reflects most of the variation of the anomaly matrix of the sediment datasets in different sampling periods (Fig. 5). The values of the first spatial eigenfunction of the sediment components in 1982 ranging from medium silt to very fine sand were negative, with a minimum negative anomaly of −0.83 occurring in the very fine sand component. The values of the remaining components were positive, with a maximum positive anomaly of 0.49 in the medium sand component (Fig. 5a). Moreover, the positive anomaly of the fine-grained components showed a slight decline. Therefore, the intermediate-grained components of the sediment (from segment 4 to segment 6) decreased, and the fine-grained components (segment 1 to segment 3) and the coarse-grained components (segment 7 to segment 11) of sediment were in anti-phase variation.

The associated first temporal eigenfunction clearly shows a regional differentiation in distribution, where the negative values are located in the upper shoreface area, and positive values are mainly found in the southeast in the lower shoreface (Fig. 5b). Combined with the first spatial eigenfunction, this finding suggests that the intermediate-grained components in the upper shoreface area increased with the decrease in both the fine-grained and coarse-grained components. However, the fine-grained components and the coarse-grained components increased in the southeastern area of the lower shoreface. This is consistent with the characteristics of spatial distribution of sediment components as shown in Fig. 3. Moreover, it is notable that negative values of the associated first temporal eigenfunction occurred more frequently than positive values and that the sum of all values is negative. Therefore, for the entire study area, the basic variability in sediment components in 1982 could be mostly attributed to the higher content of intermediate-grained components (from segment 4 to segment 6), followed by a reduced content of the remaining sediment components, especially in the coarse-grained ones (segment 7 to segment 10).

In comparison with 1982, the values of the first spatial EOF of the fine-grained sediment materials in 2004 (including components from clay to fine sand) were negative (Fig. 5c). Among them, the curve (Fig. 5c) of the first spatial eigenfunction of the first five components was relatively stable with values of approximately −0.005. However, there was a clear decrease from the coarse silt component to the fine sand component, with the minimum value (−0.78) for the fine sand component. In addition, the values of the first spatial EOF of the remaining sediment components (segment 8 to segment 11) were positive, with a maximum value of 0.5 located in the portion of the curve representing the coarse sand component. This indicates that the primary changes in sediment components occurred in the sand fractions and that the anomaly variation of the fine-grained components (segment 1 to segment 7) and coarse-grained components (segment 8 to segment 11) was in anti-phase compared to those in 1982 (Fig. 5d). According to the first temporal EOF, in most cases positive values were found in the lower shoreface area and negative values in the upper shoreface area. The frequency of positive values was higher than that of negative values, and the sum of all values was positive. Therefore, the trends of values of this temporal EOF indicate that the coarse-grained components increased, accompanied by a further decrease in the fine-grained components in 2004.

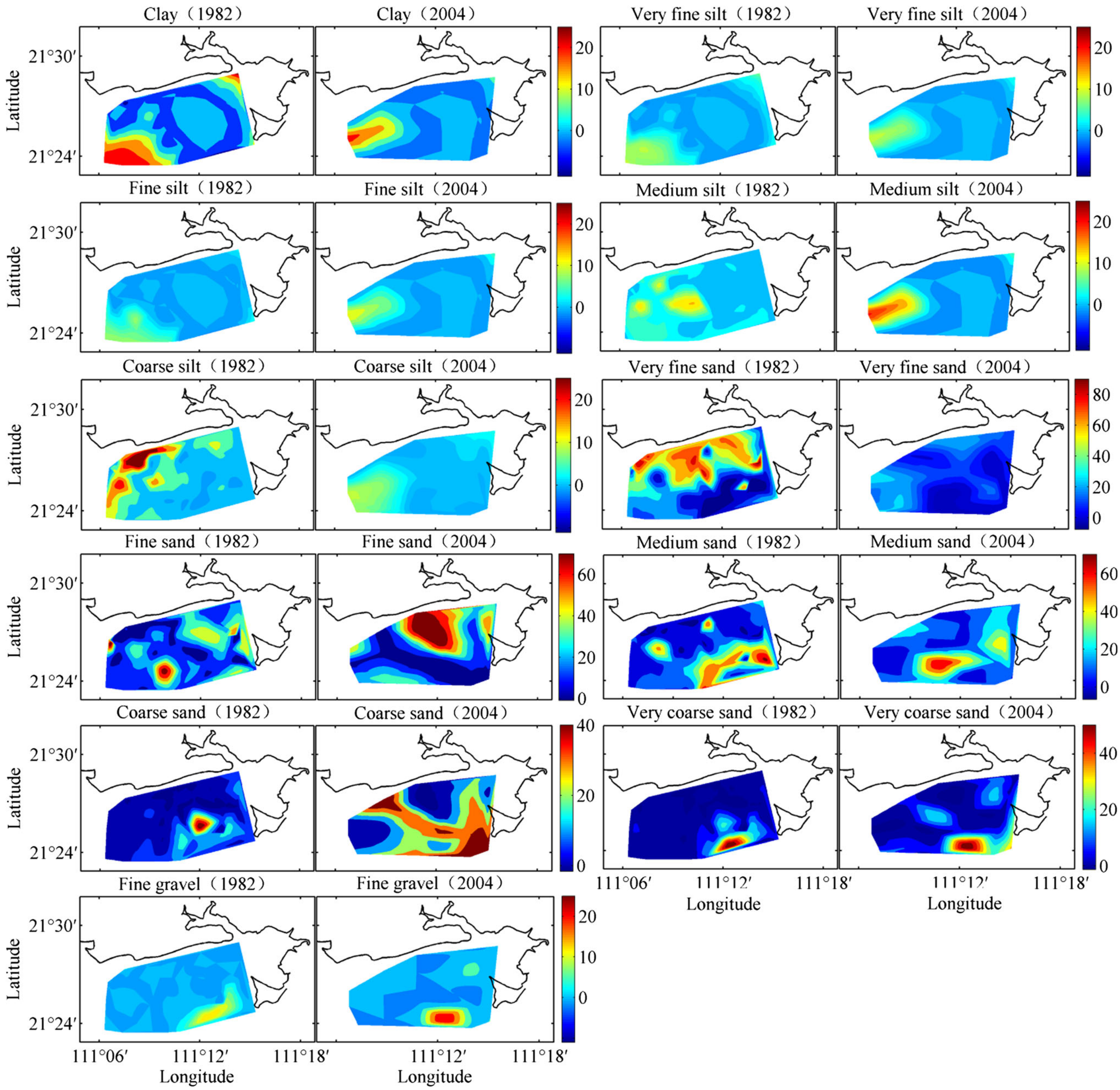

Fig. 3 Spatial distribution of sediment components

Obviously, there was a coarsening process from 1982 to 2004. Furthermore, the first eigenfunctions in 2004 indicate a decline in intermediate-grained components (from segment 4 to segment 7) and an especially sharp decrease in the very fine sand component. Thereafter, the sediments changed towards the two opposite poles, including both coarsening and refining processes. In other words, comparing the first eigenfunction of the sediment components in 1982 with the same value in 2004 shows polarized deposition environments in Shuidong Bay.

The second eigenfunction for both datasets, accounting for approximately 19 % of the total variation, reveals the secondary variation of the anomaly matrix of sediment components (Table 2). As shown in Fig. 6a, negative anomalies in 1982 only occurred in the fine sand (segment 6) and very fine sand (segment 7) components, with a minimum of −0.91 occurring for very fine sand. The remaining sediment components were characterized by positive anomalies. Among them, the maximum positive anomaly of 0.25 was observed in the medium sand component, but the first four and the last components fluctuated only slightly (<0.05). The spatial distribution (Fig. 6b) of the associated second temporal eigenfunction was more complex than that of the first spatial eigenfunction,

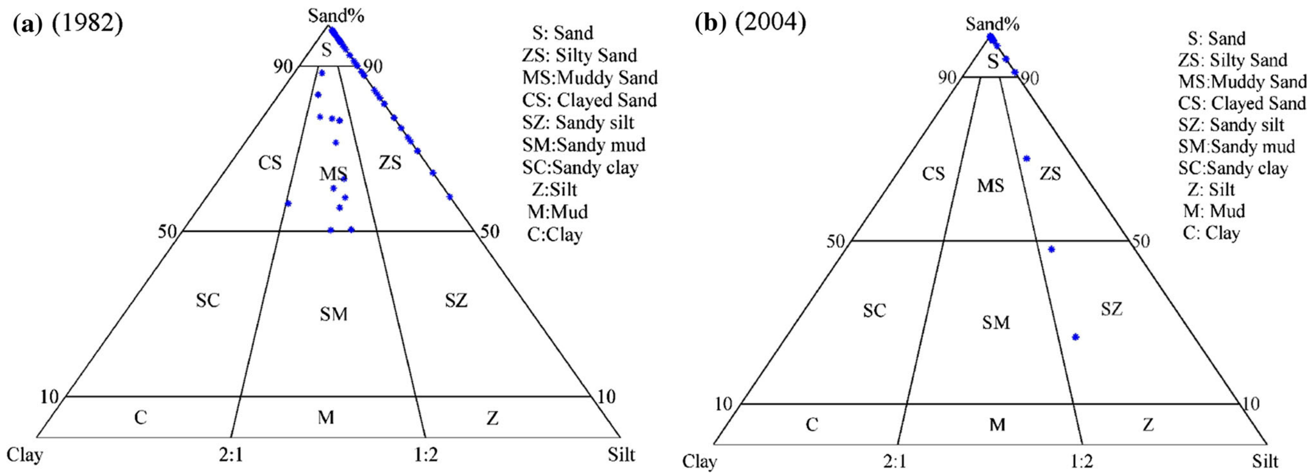

Fig. 4 Distribution of the surficial sediment samples from Shuidong Bay based on Folk's triangle diagram. **a** 1982, **b** 2004

Table 2 Eigenvalues and percent dominance of valid eigenfunctions

Sediment constituents (1982)				Sediment constituents (2004)			
Mode	Eigenvalue	Percent dominance (%)	Accumulative percent dominance (%)	Mode	Eigenvalue	Percent dominance (%)	Accumulative percent dominance (%)
1	1,023.3	64.5	64.5	1	883.1	58	58
2	305.9	19.3	83.8	2	288.3	18.9	76.9

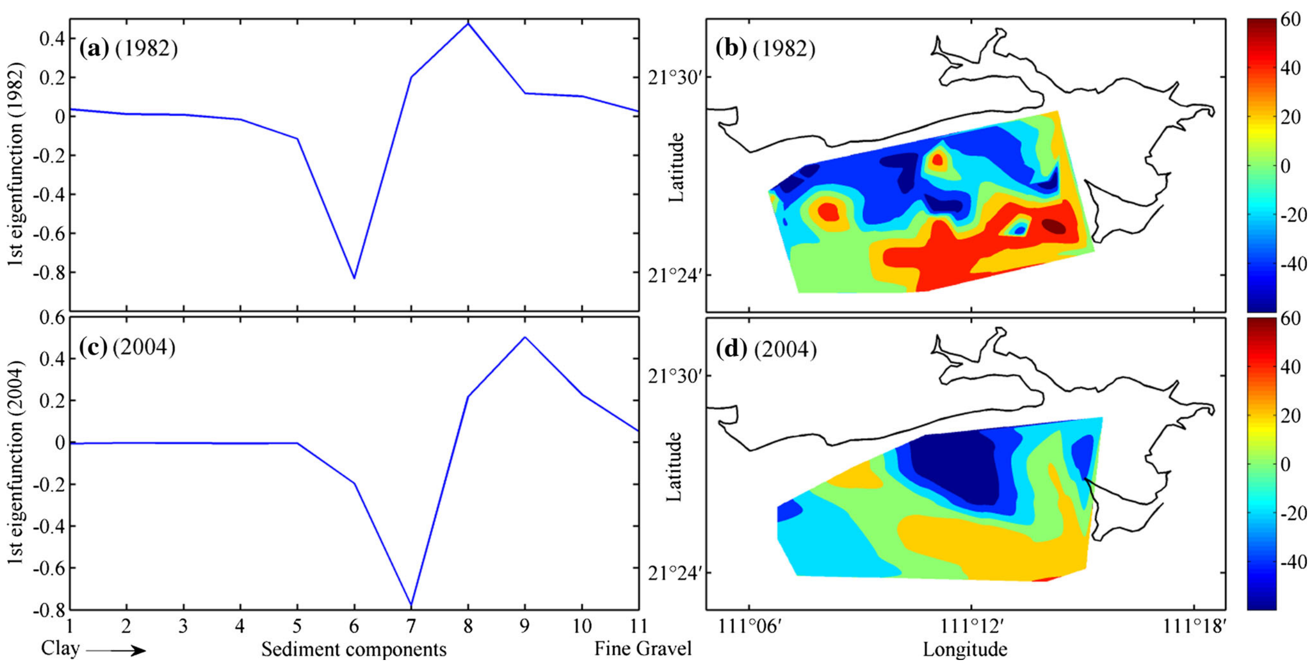

Fig. 5 The first eigenfunction (**a**, **c**) and spatial distribution of the first eigenfunction's weightings (**b**, **d**). The numbers of transverse axis of (**a**, **c**) represent sediment components: *1* clay, *2* very fine silt, *3* fine silt, *4* medium silt, *5* coarse silt, *6* very fine sand, *7* fine sand, *8* medium sand, *9* coarse sand, *10* very coarse sand, and *11* fine gravel

indicating that the patches of negative values are usually surrounded by areas with positive values. In addition, the frequency of positive values was greater than that of negative values, and the sums are positive. This implies that the secondary changes in sediment components over the entire study area are characterized by a decrease in the

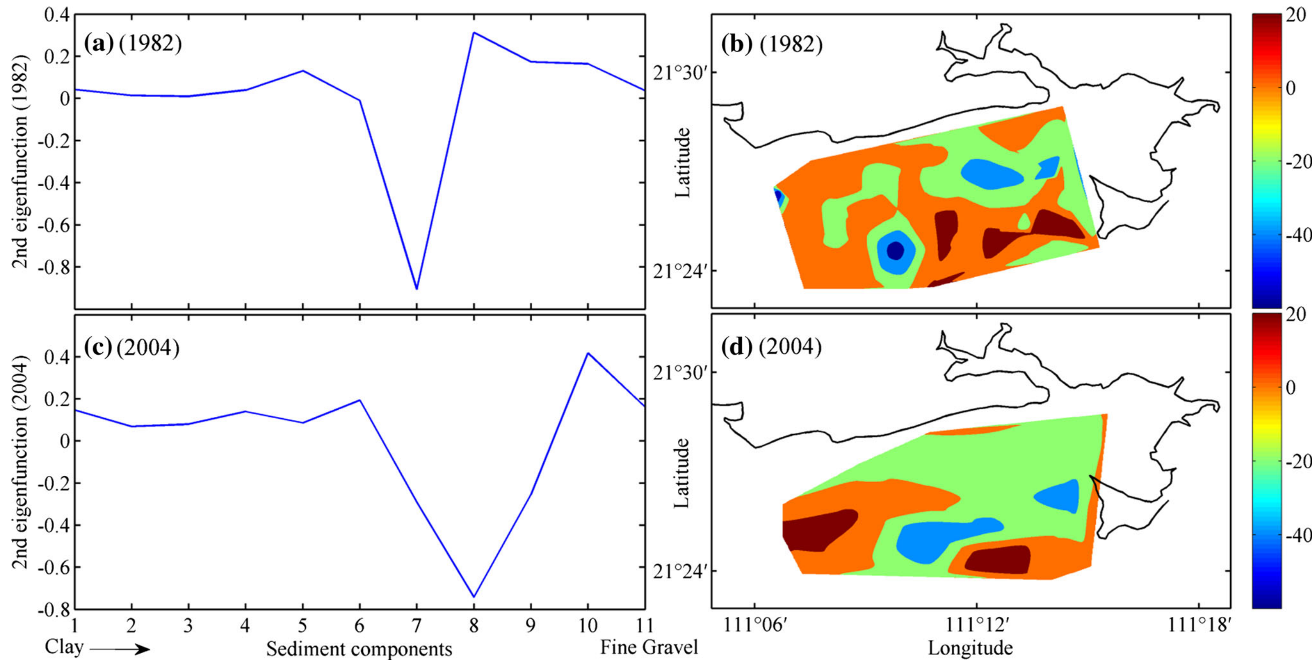

Fig. 6 The second eigenfunction (**a**, **c**) and spatial distribution of the second eigenfunction's weightings (**b**, **d**). The numbers of transverse axis of (**a**, **c**) represent sediment components: *1* clay, *2* very fine silt, *3* fine silt, *4* medium silt, *5* coarse silt, *6* very fine sand, *7* fine sand, *8* medium sand, *9* coarse sand, *10* very coarse sand, and *11* fine gravel

intermediate-grained components (from segment 6 to segment 7).

In 2004, the curve of the second spatial eigenfunction for the sediment components from clay to very fine sand changed little, followed by a sharp drop from very fine sand to coarse sand components (from positive anomaly to negative anomaly). It then climbed rapidly upward again (from negative anomaly to positive anomaly). Taking the spatial distribution and the results of the associated second temporal eigenfunction together, the variation in depositional environment of Shuidong Bay in 2004 could be an increase in fine to coarse sand sediment and a decrease in the remaining components. Compared with 1982, in 2004, the first six and the last two components of sediments decreased, and the middle three sediment components increased. This means that the sediments became more homogeneous with a better sorting coefficient.

Discussion

The effects of wave action on shoreface deposition

It could be argued that the two cruises may not represent fair-weather conditions because the sediment deposition may have been affected by the occasional typhoons that passed over the region during the study period. The sampling depth in this study was 5–10 cm, which should be associated with a time-scale on the order of 1–10 years (Gao and Collins 1992). This means that the distribution of grain-size sediment reflects variation in dynamic processes (Friedman 1979). Although the sediments of the shoreface can be affected by occasional storm actions, they should recover based on subsequent wave action.

Second, previous studies have indicated that with increasing storm influence, sand beds can be deposited in the lower shoreface and become increasingly prevalent towards the landward-end of the upper shoreface. However, our study region shows no such effect, with both the lower and upper wave-dominated shorefaces characterized by intensely bioturbated silty and sandy mud that represents fair-weather deposition (Dashtgard et al. 2012). Therefore, the variation in grain-size parameters in the sediments of Shuidong Bay from 1982 to 2004 appears to reflect fair-weather conditions.

In addition, in storm-affected shorefaces that are predominantly erosional, the grain sizes coarsen from the lower to the upper shoreface (Roy et al. 1994). Such variation in grain sizes from storm action was not found in our data. Overall, the sediment samples collected in this study area most likely represent fair-weather wave conditions. Further studies could be carried out in relation to shoreface successions with sedimentological and ichnological analyses, which are better at distinguishing the differences in sediment deposition from storm events and fair weather.

Relative sea level change of South China Sea in recent decades

As shown in Fig. 7, the relative sea level of the South China Sea has risen by 72 mm at a rate of 2.4 mm year^{-1} over the past 30 years (1978–2007), which is slightly higher than the worldwide average. Further analysis of the relative sea level change was carried out at the main tide gauge stations close to the study area (Fig. 8). Sea level rise is observed along Guangdong coast, although there are some differences in yearly fluctuations at different stations (Fig. 8). According to a linear regression, the average yearly rates vary from 1.1 to 3.8 mm year^{-1} (Table 3). Moreover, the data suggest that the average relative sea level rise may have been faster along the Guangdong coast over the last 30 years than it was previously, as indicated by comparing the rise at the same station in the different periods. This implies an intensified impact of sea level rise on coastal zones, such as at the Zhapo station, which registered an average rise of 2.0 mm year^{-1} from 1959 to 2010, but a rise of 2.3 mm year^{-1} from 1980 to 2010. These findings are consistent with previous research (Wu et al. 2006; Shi et al. 2008). Hence, this data series is appropriate to assess sea level rise along the south Chinese coast, including the Shuidong Bay. The nearest tide station to Shuidong Bay is Zhapo station, which has more than 50 years of tide level records. Here, it is assumed that the sea level rise in Shuidong Bay is consistent with that at Zhapo station. Therefore, the rate of sea level rise in the bay is approximately 2.0 mm year^{-1} and has accelerated in the last 30 years. Higher sea level leads to landward shifting of the wave break point. Generally, a 50 cm increase in sea level could result in approximately a 500 m landward migration of the wave break point if beach gradient is less than 1 ‰ (Ji et al. 1993). The frequency and intensity of waves breaking on the beach may therefore increase, especially during storm surges. Therefore, a rising sea level in Shuidong Bay could result in intense wave action along the nearshore area, which could lead to beach erosion and coarser sediments along the shoreface.

Changes in waves in response to relative sea level rise

The changes in sea level in South China Sea because of global warming may also play a significant role in modifying the local coastal sedimentary environment, which may alter the regional hydrodynamic system and lead to morphodynamic adjustments. Wave energy is directly proportional to the square of the wave heights, and the propagation velocity of wave energy is directly proportional to the square root of water depth (Everts 1985). Hence, when offshore water depth doubles, wave energy increases four fold, and the propagation velocity of the wave energy increases by 1.4 times. Therefore, the resulting intensity of wave action increases 5.6 times. Similarly, the wave energy is also directly proportional to the wave period (Everts 1985). This implies that the longer the wave period, the stronger the wave energy. As shown in Table 4, both the average wave height and the wave periods of the main wave gauge stations located along the South China coast have increased over the past several decades. This suggests that the intensity of wave energy has increased along the South China coast. For instance, the average height of the remarkable wave height (mean of the 10 highest waves) and the mean wave period at the Shuidong station increased by 35 and 29 %, respectively,

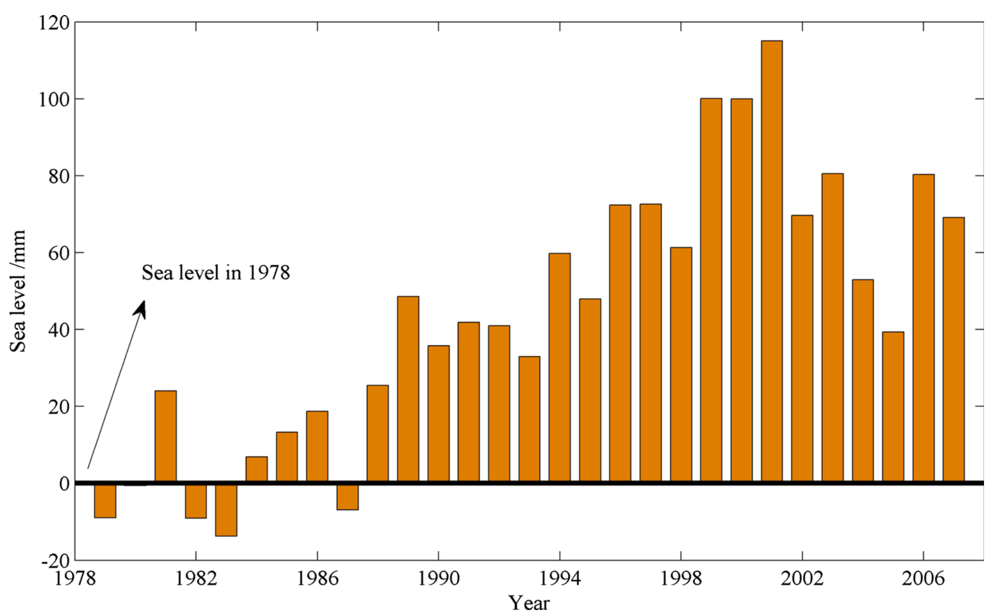

Fig. 7 Relative sea level change in the South China Sea based on a 1978 baseline

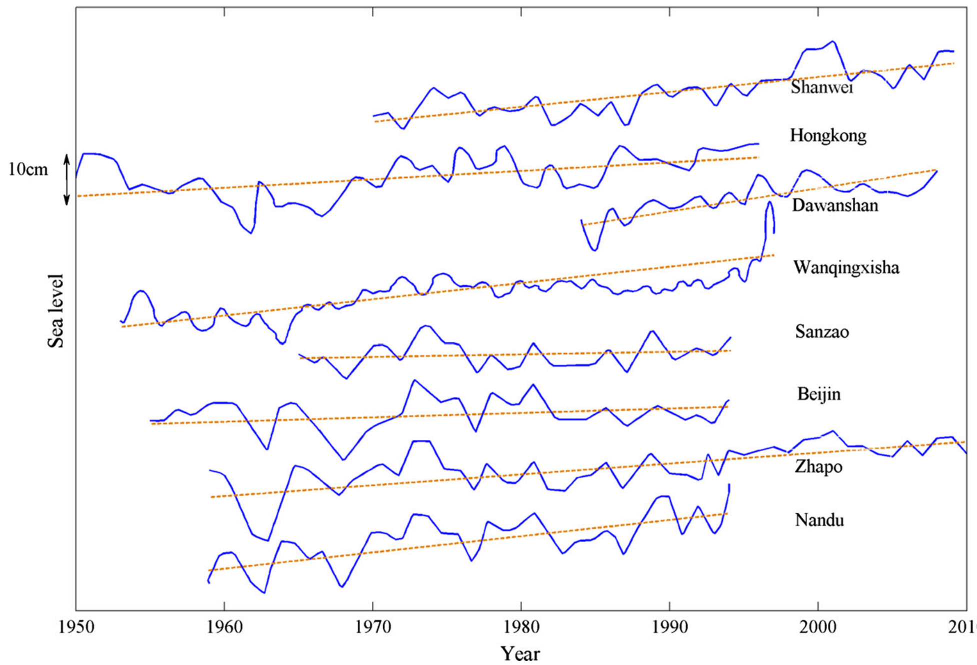

Fig. 8 Trends in sea level at the primary tide gauge stations located in Guangdong, South China

Table 3 The rising trends of relative sea level (RSL) of main tide gauge stations

Stations	Latitude (N)	Longitude (E)	The observation period (year)	Years	RSL annual rate (mm a^{-1})
Shanwei	22°46′	115°22′	1970–2009	39	+2.5
Hongkong	22°18′	114°10′	1950–1996	46	+1.6
Dawanshan	21°56′	113°43′	1984–2008	24	+3.8
Wanqingxisha	22°42′	113°30′	1953–1997	44	+2.2
Sanzao	22°02′	113°24′	1965–1994	29	+1.1
Beijin	21°48′	112°01′	1955–1994	39	+1.3
Zhapo	21°35′	111°49′	1959–2010	51	+2.0
Zhapo	21°35′	111°49′	1980–2010	30	+2.3
Nandu	20°52′	110°11′	1959–1994	35	+2.8

from 1984 to 2005 (Table 4). This result could entail a 4 % increase in the wave energy in the region. Thereafter, the sediment in the bay became coarser from 1982 to 2004, due to the remarkable increase in wave energy. The samples from 1982 were 84.7 % sand, which were significantly less than the 90 % sand in the 2004 samples (Table 1). Similarly, the mean clay component of 2.8 % in 1982 was higher than the 1.9 % in 2004 (Table 1).

The associated maximum wave heights also increased over the sampling period. Furthermore, the increase in water depth due to sea level rise may have resulted in a landward shift in the breaking point, raising the tidal level, especially at high tide. Such a shift enhances the tidal current velocity by reducing the bottom friction and amplifies the effects of wave action and tidal currents on the beach. Higher sea levels would also lead to more frequent and intense storm surges. In summary, changes in climate intensify the regional hydrodynamic condition of waves, tidal currents and storm surges, changing the sedimentary environment from low energy to a relatively high energy one over recent decades (1982–2004).

The spatial distribution of shoreface sediment has been affected by these changes in the sedimentary environment. Generally, high wave energy not only enlarges the wave action of incipient motion of sediment particles, causing deeper water sediments and shallow water coarser sediments to be resuspended and moved landward and seaward, but also expands the range of the surf zone (Schwartz 1982; Yang 1997) resulting in a more active sediment created by wave-induced turbulence and convolution. Moreover, the landward migration of the wave break point due to sea level rise makes the original shallow water sediments highly mobile, causing sediments in that area to be coarser and more well sorted. In addition, the larger tidal range and stronger tidal current velocity may lead to stronger bottom shear stress on the seabed and consequent changes in

Table 4 Statistics of average wave height (m) and wave period (s) of main wave gauge stations in different periods located in Guangdong coast

Stations	Positions	The observation period (year)	The average wave height $H_{1/10}$ (m)	The average wave period (s)	The maximum wave height (m)
Zhelang	115°34′ 22°34′	1962–1971	0.93	3.6	7.5
		1971–1990	1.40	4.2	9.5
		2000–2009	1.50	4.4	9.0
Dawanshan	113°43′ 21°56′	1984–1986	1.14	6.0	12.0
		2001.4–2002.3	1.20	5.5	–
Zhapo	111°49′ 21°35′	1959.9–1960.4	0.30	2.2	4.6
		2008.1–2008.12	0.98	3.9	8.0
Shuidong	111°19′ 21°24′	1984.1–1984.12	0.76	3.5	4.4
		2005.1–2005.12	1.03	4.5	8.5
Naozhou	110°37′ 20°51′	1960–1971	0.91	3.7	9.8
		1996–2002	0.97	4.1	9.7

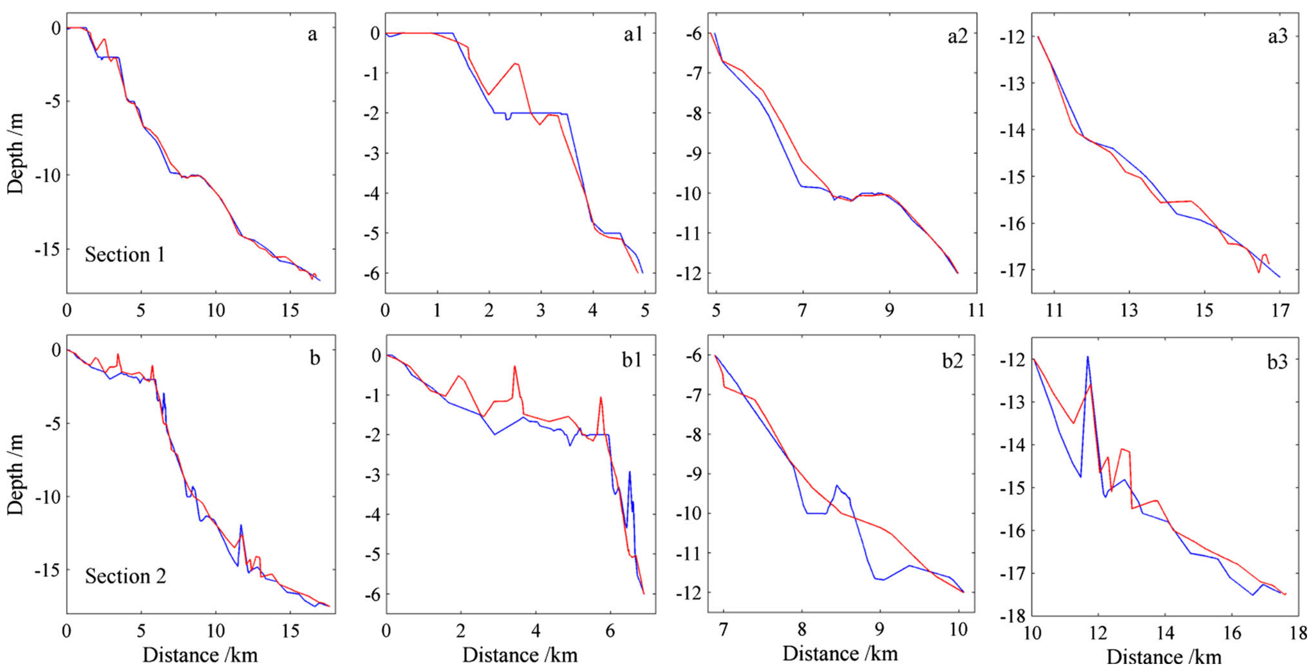

Fig. 9 The response of coastal sections to sea level rise (*Blue solid line* indicates the coastal sections in 1967 and *red solid line* indicates ones from 2007)

sediment transition and deposition. The increasing storm surges in a warming climate carry enormous energy and may also play an increasingly important role in sediment transport. Under the effects of hydrodynamic interactions, the shoreface sediments of Shuidong Bay in 2004 experienced two significant changes: a polarization in sediment size and a homogenization relative to the data from 1982 (the former was the more important effect).

Morphological changes in response to sea level rise

As shown in Fig. 9, the coastal profiles indicated that accretion mainly occurred at a depth of approximately 2 m and between 7 and 12 m (Fig. 9). The morphological variations were consistent with the grain-size distributions in sediments of the shoreface due to changes in sediment transport process. With a relative rise in sea level along South China, waves may arrive closer to the shore before breaking and accelerate shoreline retreat. In addition, fine-grained sediments were resuspended and moved seaward, where the eroded sediment was deposited around at approximately 2 m. Hence the grain size in sediments near the shoreline was coarser, with medium grain sizes from the previous 2 ϕ in 1982 to 1 ϕ in 2004 (Fig. 2a and b).

In addition, in the related deeper zone below 12 m, fine-grained sediment could be moved landward and settle on the lower shoreface due to the coupling of sea level rise and wave action (Bruun 1962). The medium grain size in sediments of the lower shoreface ranged from 3 to 4 ϕ in 1982 and from 4 to 5 ϕ in 2004 (Fig. 2a and b). Moreover, it is notable that the fine grain fraction (e.g., silt) of the lower shoreface in 2004 increased compared to 1982 (Fig. 3). This could lead to accretion in the lower shoreface at depths of 7–12 m due to fine-grained sediment getting transported landward from related deeper zones.

Conclusions

This paper examined changes in shoreface deposition based on sets of Shuidong Bay shoreface sediment samples collected in 1982 and 2004, and on related hydrodynamic data from South China. The main results can be summarized as follows:

(1) Shoreface deposition in Shuidong Bay is mainly composed of sand. There is an obvious increase in the sand fraction, from 84 % in 1982 to more than 90 % in 2004. There were also corresponding decreases in fine-grained sediment, including clay and silt fractions. Moreover, changes in the grain-size parameters of the sediments suggested that shoreface deposition in 2004 was coarser and slightly more well sorted and had lower positive skewness and lower kurtosis than those in 1982.

(2) Changes in the shoreface deposition showed two distinct modes in the two sampling years (1982–2004). A polarized mode was described by the first eigenfunctions, and a homogenized mode was described by the second eigenfunctions. The former means that the sediment components developed towards the two opposite poles ($<2\ \phi$ and $>6\ \phi$), undergoing both coarsening and refining processes. The second mode indicates that the secondary variation in sediment components was mostly in the three intermediate-grained sand components (0–3 ϕ).

(3) A rise in relative sea level rise of approximately 2 mm year^{-1} was observed in Shuidong Bay over the past several decades. Higher sea levels alter the regional hydrodynamic system by enhancing wave energy, increasing of wave height and period and magnifying tidal energy through higher tides of greater current velocities. Due to sea level rise and the associated changes in hydrodynamic forcing factors, the wave break point may migrate landward and result in more storm surges. Overall, the Shuidong Bay is exposed to a higher energy environment than it was before.

Acknowledgments This study was supported by the Funds for Ministry of Science and Technology of China (SKLEC: 2010RCDW03), the National Science Foundation in China (Contract number: 41376097; 40771200), and New Century Excellent Talents in University of China. We are also very grateful for editor and two anonymous reviewers for their constructive suggestions to improve previous manuscript.

References

Allen JRL (1984) Sedimentary structures: their character and physical basis. Developments in sedimentology 30. Elsevier/North Holland, Amsterdam, p 663

Bruun P (1962) Sea level rise as a cause of shore erosion. J Waterways Harbor Division, ASCE 88:117–130

Chen ZS (1991) Application of correspondence analysis to discriminate dynamic depositional environmental in Shuidong Bay, Western Guangdong Province. Trop Oceanol 10(1):55–62 (In Chinese with English abstract)

Chen ZS (1996) Characteristics of modern sedimentary environment and sediment transport patterns in Shuidong Bay, Western Guangdong Province. Trop Oceanol 15(3):6–13 (In Chinese with English abstract)

Chen ZS, Xia DX, Wang JW (1999) The Book of China Bay (Bays of Guangdong Province), No. 9, 10. Oceanography publishing Press, Beijing, China (In Chinese with English abstract)

Clifton HE (2006) A re-examination of facies models for clastic shorefaces. Facies Models Revisited. In: Posametier HW, Walker RG (eds) Special Publication No, 84, SEPM (Society for Sedimentary Geology), Tulsa, USA, pp 293–337

Clifton HE, Hunter RE, Phillips RL (1971) Depositional structures and processes in the non-barred high energy nearshore. J Sediment Petrol 41:651–670

Dai ZJ, Li CC (2008) Morphodynamic processes of arc-shaped coast in South China. East China Normal University Press, Shanghai

Dai ZJ, Chen JY, Du JZ, Zhang XL (2008) Seasonal changes of sandbar behavior in Nanwan Beach, South china. J Coast Res 24(5):1209–1216

Dai ZJ, Liu JT, Lei YP, Zhang XL (2010) Patterns of sediment transport pathways on a headland bay beach-Nanwan beach, South China: a case study. J Coast Res 26(6):1096–1103

Dalrymple RW, Zaitlin BA, Boyd R (1992) Estuarine facies models: conceptual basis and stratigraphic implications. J Sediment Petrol 62:1130–1146

Dashtgard SE, MacEachern JA, Frey SE, Gingras MK (2012) Tidal effects on the shoreface: towards a conceptual framework. Sed Geol 279:42–61

Everts CH (1985) Effect of sea level rise and net sand volume change on shoreline position at Ocean City, Maryland US Environmental Protection Agency Report, Washington DC (1985), pp 67–97

Folk RL, Andrews PB, Lewis DW (1970) Detrital sedimentary rock classification and nomenclature for use in New Zealand. NZ J Geol Geophys 13(4):937–968

Friedman GM (1979) Address of the retiring president of the International Association of Sedimentology: differences in size distributions of populations of particles among sands from various origins. Sedimentology 26:3–32

Gao S, Collins M (1992) Net sediment transport patterns inferred from grain-size trends, based upon definition of "transport vectors". Sed Geol 80:47–60

Harms JC, Southard JB, Walker RG (1982) Structures and sequences in clastic rocks. Society of Economic Paleontologists Short Course 9:2.1–2.55

James FT, Justin R (1998) Source-transport inversion: An application of geophysical inverse theory to sediment transport in Monterey Bay, California. J Geophys Res 103(C1):1275–1283

Ji ZX, Jiang ZX, Zhu JW, Yang GS (1993) Impacts of sea level rise on coastal erosion in the Changjiang Delta and North Jiangsu Coastal Plain. Acta Geographica Sinica 48(6):516–526

Jones AR, Gladstone W, Hacking NJ (2007) Australian sandy-beach ecosystems and climate change: ecology and management. Aust Zool 34:190–202

Komar PD (1976) Beach processes and sedimentation. Prentice Hall, Englewood Cliffs

Liu JT, Zarillo GA (1989) Distribution of grain sizes across a transgressive shoreface. Mar Geol 87:121–136

McManus J (1988) Grain size determination and interpretation. In: Tucker M (ed) Techniques in Sedimentology. Blackwell, Oxford, pp 63–85

Michael DB, Harry HR (2009) Drowning of the Mississippi Delta due to insufficient sediment supply and global sea-level rise. Nat Geosci 2:488–491. doi:10.1038/NGEO553

Niedoroda AW, Swift DJP, Hopkins TS, Ma CM (1984) Shoreface morphodynamics on wave-dominated coasts. Mar Geol 60:331–354

Posamentier HW, Moris WR (2000) Aspects of the strata architecture of forced regressive deposits. Sedimentary Responses to forced regressions. In: Hunt D, Gawthorpe RL (eds) Special Publication, 172, Geological Society of London, London, UK, pp 19–46

RamanaMurty TV, Veerayya M, Murty CS (1986) Sediment-size distribution of the beach and nearshore environes along the central west coast of India: an analysis using EOF. J Geophys Res 91(C7):8523–8536

Riggs SR, Cleary WJ, Snyder SW (1995) Influence of inherited geologic framework on barrier shoreface morphology and dynamics. Mar Geol 126:213–234

Roy PS, Cowell PJ, Ferland MA, Thom BG (1994) Wave-dominated coasts. In: Carter RWG, Woodroffe CD (eds) Coastal Evolution: Late Quaternary Shoreline Morphodynamics. Cambridge University Press, Cambridge, pp 121–186

Rubin DM (1987) Cross-Bedding, bedforms, and paleocurrents. Society of Economic Paleontologists and Mineralogists, Concepts in Sedimentology and Paleontology 1:187

Sanders CJ, Smoak JM, Naidu AS, Araripe DR, Patchineelam SR (2010) Mangrove forest sedimentation and its reference to sea level rise, Cananeia, Brazil. Environ Earth Sci 60(6):1291–1301

Schlacher TA, Schoeman DS, Dugan J, Lastra M, Jones A, Scapini F, McLachlan A (2008) Sandy beach ecosystems: key features, management challenges, climate change impacts, and sampling issues. Mar Ecol 29:70–90

Schwartz ML (ed) (1982) The encyclopedia of beaches and coastal environments. Hutchinson Ross, Stroudsburg, p 940

Schwartz RK, Birkemeier WAB (2004) Sedimentology and morphodynamics of a barrier island shoreface related to engineering concerns, Outer Banks, NC, USA. Mar Geol 211:215–255

Schwartz RK, Hobson RD, Musialowski FR (1981) Subsurface facies of a modern barrier island shoreface and relationship to the active nearshore profile. Northeast Geol 3(3–4):283–296

Shi XJ, Chen TG, Yu KF (2008) Sea-level changes in Zhujiang Estuary over last 40 years. Mar Geol Quat Geol 28(1):127–134

Short AD (1984) Beach and nearshore facies: southeast Australia. In: Greenwood B, Davis RA (eds) Hydrodynamics and Sedimentation in Wave-Dominated Coastal Environments. Mar Geol 60:261–282

Slott JM, Murray AB, Ashton AD et al (2006) Coastline responses to changing storm patterns. Geophys Res Lett 33(18) doi:10.1029/2006GL027445

Tamura TT, Masuda F, Sakai T, Fujiwara O (2003) Temporal development of prograding beach-shoreface deposits: the Holocene of Kujukuri coastal plain, eastern Japan. Mar Geol 198:191–207

Wentworth CK (1922) A scale of grade and class terms for clstic sediments. J Geol 30(5):377–392

Wu T, Kang JC, Wang F, Zheng YM (2006) The new progresses on global sea level change. Adv Earth Sci 21(7):730–736

Yang SL (1997) Multi-factor analysis of the annually cyclic erosion-deposition of the Changjiang River deitaic. Acta Geographica Sinica 452(2):123–130

Yoo C, Kim S (2004) EOF analysis of surface soil moisture field variability. Adv Water Resour 27:831–842