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Evolution of shoals and vegetation of Jiuduansha in the Changjiang River Estuary of China in the last 30 years

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Abstract
The evolution of the shoals and vegetation plays an important role in maintaining the stability of the river regime and the estuarine ecosystem. However, the interaction between the evolution of shoals and vegetation dynamic has rarely been reported. In this study, we determined the interaction between the shoal and vegetation evolution of Jiuduansha in the Changjiang River Estuary in the last 30 years. We did this through the collection and summarization of the existing data of the regional hydrological processes, wading engineering, and vegetation, and combined it with the analysis of nautical charts and remote sensing images. During the past 30 years, the expansion of the shoals within the 0 m isobath in Jiuduansha was obvious, with an increase of 176.5%, while the expansion of the shoals within the 5 m isobath was relatively slow. The regional hydrological characteristics in the Jiuduansha area changed dramatically, especially the sediment discharges. The area of vegetation in Jiuduansha increased from 9.1 km^2 in 1990 to 65.68 km^2 in 2015, while the variations in the different vegetation types were different. The best combination of environmental factors with a significant correlation on the shoals within the 0 m isobath is the area of *Spartina alterniflora* and *Phragmites australis*. The evolution of Jiuduansha shoals was significantly affected by the variations in hydrological characteristics. Meanwhile, on a long-term scale, the expansion of the shoals could promote the regional vegetation expansions due to the suitable elevation and environmental conditions it provides. The interaction between the shoal and vegetation evolution varied in the different vegetation types and different elevations. In the future, long-term monitoring and detailed data are needed to the systematical analysis of the interaction between the hydrological processes and the evolution of the shoal and vegetation.

Key words: Jiuduansha shoals, Changjiang River Estuary, vegetation, evolution

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1 Introduction

Shoals formed by the deposition of sediments are widely distributed in muddy and sandy estuaries (Xie and Pan, 2012; Nelson et al., 2013). They usually develop with high dynamics (Bartholdy et al., 2005). Studies have shown that the location, shape, and size of shoals are related to the river runoff, sediment discharge, and ocean dynamics (van der Wal et al., 2002; Li et al., 2006) and are also sensitive to human activities such as dam construction, channel projects, and soil and water conservation (Gao et al., 2010; Li et al., 2016). At the same time, estuarine shoals are an essential part of the estuarine ecosystem and important object for the research on estuarine and coastal ecology and environment (Wei et al., 2016). Estuarine shoals have unique habitats of brackish water and sufficient nutrient inputs due to their locations. As a result, they are usually suitable places for the settlement of living organisms, such as plants, birds, and benthos (Krull and Craft, 2009; Lv et al., 2014). Therefore, studying the evolution of the estuarine shoals plays an important role not only in the river regime maintaining but also in the conservation of the estuarine ecosystem and regional economic development (Wei et al., 2016).

The evolution of geomorphology in the estuarine and coastal zone is one of the important drivers of regional ecosystem variation (D'Alpaos et al., 2016). Numerous studies have shown that the species composition and diversity in the estuary varied significantly with geomorphological evolution. This is mainly due to the variations in environmental factors, such as hydrodynamics, salinity, and elevation (Colonnello and Medina, 1998; Wu and Tong, 2017). The evolution of the estuarine shoals is also accompanied by the variations in ecosystem structure and function (Li et al., 2016). Previous studies have shown that the pattern of vegetation changed with the evolution of shoals (Huang and Zhang, 2007). In recent years, relevant researches have begun to pay attention to the effect of the geomorphological evolution of shoals on the variations of vegetation (Carey et al., 2017). However, the effects of shoal evolution on the vegetation and also the corresponding driving factors appear to vary with hydrodynamics and locations, and the relevant discussions are still insufficient.

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On the other hand, vegetation acts as an important ecosystem engineer in the estuarine and coastal ecosystem. The evolution of vegetation also has important effects on estuarine geomorphology (Kearney and Fagherazzi, 2016). Previous studies have shown that vegetation has the effects of flow velocity reducing, sediment trapping, and deposition promoting (Yager and Schmeeckle, 2013). However, most of them are limited to the relatively small spatial scales, such as patches and tidal flats, and other relatively short time scales. The effects of vegetation on the evolution of shoals on the large spatial and temporal scales have rarely been reported.

Jiuduansha is the distributary sandbar of the third-order bifurcation of the Changjiang River Estuary. Since the 1950s, Jiuduansha has experienced dramatic evolution. Many scholars have conducted extensive researches on its evolutionary characteristics, causes, and effects. Early studies believed that the formation and evolution of Jiuduansha were mainly affected by the changes in the river runoff and sediment discharge, and also the evolution of river regimes (Yang et al., 1998). Recently, the significant impact of human activities on the evolution of Jiuduansha has attracted wide attention (Li et al., 2016; Wei et al., 2016). As the largest uninhabited island in the Changjiang River Estuary, Jiuduansha is an ideal experimental site for the study of the estuarine shoal ecosystem. A large number of studies involving vegetation, fish, macrobenthos, and other biological groups have been carried out there (Yang et al., 2006; Huang and Zhang, 2007; Zhu and Sun, 2011; Lv et al., 2014). The development of related work provided a basis for studying the interaction between shoal evolution and vegetation on a long-term scale.

In this study, we determined the evolutionary characteristics of the shoals and vegetation in Jiuduansha in the past 30 years. We did this through the collection and summarization of the existing data of the regional hydrological processes, human activities, and vegetation variation, and combined it with the analysis of nautical charts and remote sensing images. We hope to reveal the long-term interaction between the evolution of estuarine shoal and vegetation under the background of high-intensity human activities, and to provide new theoretical knowledge for the effective management and protection of estuarine and coastal areas.

2 Study area and methods

2.1 *Study area*

Jiuduansha is the distributary sandbar of the third-order bifurcation of the Changjiang River Estuary, splitting the Changjiang River Estuary into the North Passage and South Passage (Fig. 1). It is mainly composed of four parts: Upper Shoal, Middle Shoal, Lower Shoal, and Jiangya Shoal. It is located in the northern subtropical zone with abundant rainfall. The average annual temperature is 15.7°C, and the average annual precipitation is about 1 145 mm. Tides are irregular semidiurnal, with an average tidal range of 2.67 m (Zhang, 2011; Wu and Gao, 2012). The sediment mainly consists of silt and clayey silt (Zhang, 2011). The main plant species in the area are native species *Phragmites australis* (Cav.) Trin. ex Steud., *Scirpus mariqueter* Tang & F. T. Wang, and the invasive species *Spartina alterniflora* Lois (Wang et al., 2013).

2.2 *Materials and methods*

We selected seven nautical charts in 1986, 1990, 1994, 2001, 2004, 2009, and 2015 as data sources. ArcMap 10.2 was used to extract the 0 m and 5 m isobaths of the Jiuduansha shoal and calculate the area within these regions of each year. At the same time, we selected six Landsat 7 TM remote sensing images in 1986, 1990, 1994, 2001, 2004, and 2009 and one Landsat 8 TM remote sensing image in 2015. We were able to extract the vegetation information and analyze the variation in the vegetation of Jiuduansha in the past 30 years using supervised classification tools in ENVI 5.2. Also, part of the information on the area of the different vegetation types was extracted from existing literature.

We collected data on the wading engineering, the split ratios of sediments and water, the sediment concentration, and the tidal current velocities in the South and North Passage in the past 30 years. Additionally, the annual runoff and sediment discharge of the Changjiang River Estuary were used to analyze the variations in hydrology and sediment conditions in the Jiuduansha area (data source: Bulletin of China River Sediment, available at www.cjh.com.cn).

We used IBM SPSS Statistics 21 to calculate the Pearson correlation coefficient between the area of the shoals, the river runoff and sediment discharge, and the vegetation area. We used the BVSTEP program in Primer 5.2.8 to carry out nonlinear regression analysis to find the best matches between the combined environmental factors and the area of the shoal. Then the RELATE program in Primer 5.2.8 was used to check whether the correlation between the factor combination and the area of the shoals was significant.

3 Results

3.1 *Evolution of shoals of Jiuduansha in the past 30 years*

In the past 30 years, the shoals within the 0 m isobath in Ji-

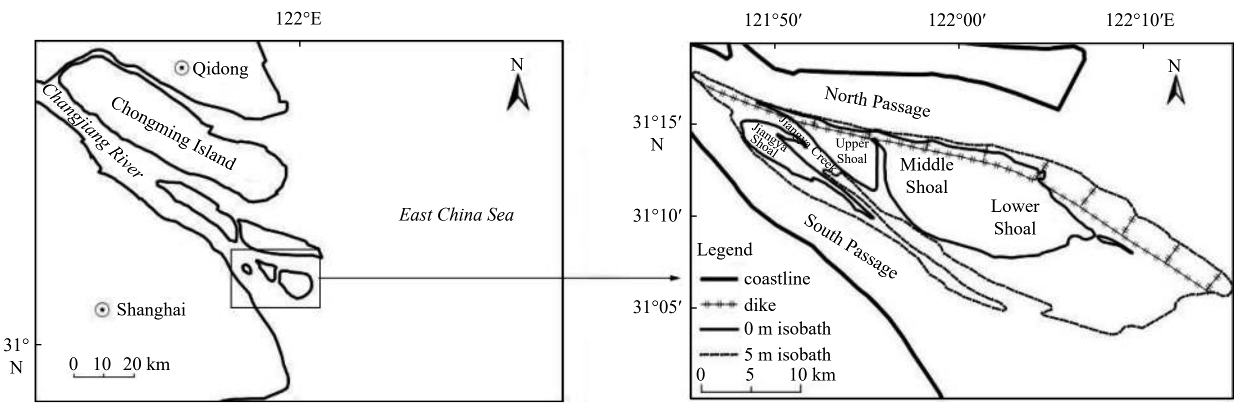

Fig. 1. Map of the study area in Jiuduansha of the Changjiang River Estuary.

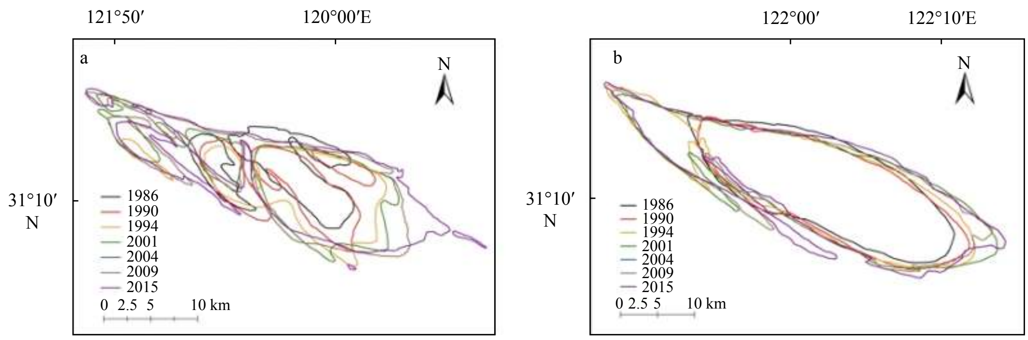

Fig. 2. Variations in the isobaths of 0 m (a) and 5 m (b) of the Jiuduansha shoals in last 30 years.

uduansha had a dramatic evolution (Fig. 2a). Before the 1990s, the Jiuduansha shoals within the 0 m isobath consisted of Upper Shoal, Middle Shoal, and Lower Shoal. By 1990, the 0 m isobath of Middle Shoal and Lower Shoal were connected. The combined Lower and Middle Shoal expanded seaward, and the Upper Shoal head moved down. During 1990–1994, the 0 m isobath of the Jiangya Shoal was connected with the 0 m isobath of the Jiuduansha shoals, and the central part of the Jiuduansha shoals still maintained seaward expansion. From 1994 to the beginning of the 21st century, the head of the Jiangya Shoal and the Upper Shoal moved seaward slightly, and the Middle and Lower Shoals were stable on the north side, and their tails continued to expand seaward. During 2001–2004, the head of the Jiangya Shoal retreated seaward, and the Jiangya Creek widened significantly. The 0 m isobaths of Upper Shoal and Middle Shoal were connected, with their northern side expanded significantly. The tails of the Middle Shoal and Lower Shoal continued to expand seaward, but a partial erosion appeared on the south side of the shoal. During 2004–2009, the northern boundary of the 0 m isobath of Jiuduansha shoals continued to expand. Jiangya Shoal, Middle Shoal, and Lower Shoal continued to expand towards the sea, while their south side eroded partially. After 2009, the northern boundary of the 0 m isobath of Jiuduansha tended to be stable, while Jiangya Shoal, Middle Shoal, and Lower Shoal continued to expand towards the sea. There was still partial erosion on the southern side of the Upper, Middle, and Lower Shoals.

During 1986–1990, the head of the 5 m isobath of Jiuduansha retreated, and the tail expanded seaward (Fig. 2b). By 1994, the 5 m isobath of the Jiangya Shoal was connected to the 5 m isobath of Jiuduansha. The head of the Upper Shoal retreated marginally, while the tail of the Middle Shoal and Lower Shoal expanded more significantly. During 1994–2001, the Middle and Lower Shoals maintained the trend, while the northern side expanded slightly. The head of the Jiangya Shoal retreated, and the tail expanded significantly. However, during 2001–2004, the northern side of the Jiangya Shoal, Middle Shoal, and Lower Shoal expanded, while the southern side experienced partial erosion. From 2004–2015, the rate of evolution of the shoals within the 5 m isobaths in Jiuduansha slowed. The northern side remained stable, the eastern side expanded seaward slightly, and the southern side partially eroded.

In 1986, the area of the shoals within the 0 m isobath was only 79.21 km^2, and it increased to 218.98 km^2 in 2015, with a total increase of 176.5% (Fig. 3a). Specifically, the area of the shoals within the 0 m isobath increased by 1.29 km^2/a from 1986 to 1990. The expansion rate was highest during 1990–2009, with an average expansion of 6.54 km^2/a. Since 2009, the expansion of the shoal has slowed down, with an average expansion rate of 1.72 km^2/a.

The expansion rate of the shoals within the 5 m isobath was relatively slow, with a total increase of 32.4%, from 298.31 km^2 in 1986 to 440.40 km^2 in 2015 (Fig. 3b). The average expansion rate was 5.02 km^2/a during 1986–1990. From 1990 to 2004, the expansion rate reached 7.41 km^2/a; after 2004, the expansion rate slowed down to 1.66 km^2/a.

3.2 *Variation in the hydrological characteristics in the region of Jiuduansha*

In the past 30 years, the annual river runoff of Changjiang River Estuary has shown a fluctuating trend, but the overall variation was not apparent (Fig. 4a). However, the annual sediment discharge has decreased significantly in the past 30 years, with an average rate of 340 million tons per year during 1985–2000 to 141 million tons per year during 2000–2015 (Fig. 4b).

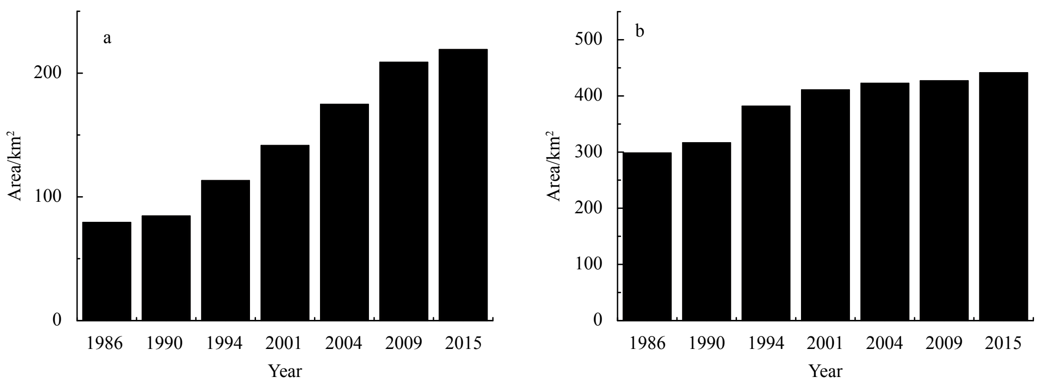

Fig. 3. Variations in the area of the shoals within the 0 m (a) and 5 m (b) isobaths of Jiuduansha during 1986–2015.

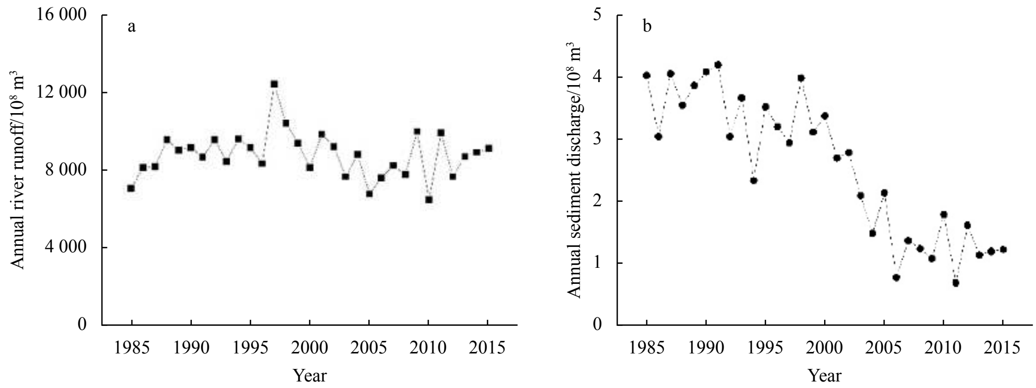

Fig. 4. Variations in the annual river runoff and sediments discharge in the Changjiang River Estuary during 1985–2015.

Table 1. Wading engineering and variations in the hydrological characteristics in the area of Jiuduansha in the past 30 years

Year	Wading engineering	Spilt ratio of water/%		Spilt ratio of sediments/%		Sediment concentration /kg·m^{-3}		Average flooding tide current velocity/m·s^{-1}		Average ebbing tide current velocity/m·s^{-1}	
		South Passage	North Passage	South Passage	North Passage	South Passage	North Passage	South Passage	North Passage	South Passage	North Passage
1985	–	47.2 (1984)[1]	52.8 (1984)[1]	44.6 (1984)[1]	55.4 (1984)[1]	1.8845 (1982)[6]	2.8255 (1982)[6]	0.84 (1983)[7]	0.83 (1983)[7]	1.06 (1983)[7]	1.22 (1983)[7]
1990	–	46.3 (1988)[2]	53.7 (1988)[2]	46.9 (1988)[2]	53.1 (1988)[2]	–	–	–	–	–	–
1995	Deep Waterway Project (Phase I, II)[10], Nanhui Dongtan Reclamation Project[11]	47.6 (1995)[1]	52.4 (1995)[1]	54.3 (1995)[1]	45.7 (1995)[1]	–	–	–	–	–	–
2000		42.8 (2000)[3]	57.2 (2000)[3]	47.0 (2000)[3]	53.0 (2000)[3]	2.089 (2000.8)[5]	1.282 (2000.8)[5]	0.63 (2002.8)[8]	0.83 (2002.8)[8]	1.29 (2002.8)[8]	1.25 (2002.8)[8]
2005		52.2 (2005)[3]	47.8 (2005)[3]	52.8 (2005)[3]	47.2 (2005)[3]	1.121 (2005.8)[5]	0.394 (2005.8)[5]	1.26 (2005.8)[8]	0.63 (2005.8)[8]	1.41 (2005.8)[8]	1.19 (2005.8)[8]
2010	Deep Waterway Project (Phase III)[10]	59.19 (2010)[4]	40.81 (2010)[4]	61.1 (2010)[4]	39.7 (2010)[4]	0.647 (2010.8)[5]	0.501 (2010.8)[5]	0.98 (2010.8)[8]	0.75 (2010.8)[8]	1.57 (2010.8)[8]	1.34 (2010.8)[8]
2015		58.4 (2015)[4]	41.6 (2015)[4]	61.8 (2015)[4]	39.2 (2015)[4]	0.666 (2013.8)[6]	0.727 (2013.8)[6]	–	0.78 (2014.9)[9]	–	1.19 (2014.9)[9]

Note: – represents no data was found in that period. Data source: [1] Feng, 2010; [2] Xie et al., 2014; [3] Liu et al., 2008; [4] Yang et al., 2018; [5] Liu et al., 2017; [6] Yao et al., 2015; [7] Chen, 2003; [8] Lin et al., 2015; [9] Wang, 2016; [10] Wei et al., 2016; [11] Li et al., 2016.

Before 1995, there was no large wading engineering in the adjacent zone of Jiuduansha (Table 1). During 1998–2010, the area has successively carried out the construction of the Deep Waterway Project and the Nanhui Dongtan Reclamation Project (Li et al., 2016; Wei et al., 2016). In the past 30 years, the hydrological characteristics in the South and North Passages of the Changjiang River Estuary have changed dramatically. During 1985–2000, the split ratio of water in the North and South Passages did not change significantly, with that of the North Passage being slightly higher than the South Passage. However, after 2000, the split ratio of water in the South Passage exceeded the North Passage (Liu et al., 2008; Feng, 2010; Xie et al., 2014; Yang et al., 2018). The split ratio of sediment fluctuated before 2000. After 2000, the split ratio of sediment of the South Passage continued to rise and exceeded the North Passage (Liu et al., 2008; Feng, 2010; Xie et al., 2014; Yang et al., 2018). The sediment concentration in the South and North Passages decreased by 64.6% and 74.2% respectively in the past 30 years (Yao et al., 2015; Liu et al., 2017). The average ebbing tide current velocity in the North Passage did not change much, while the average ebbing tide current velocity in the South Passage has continuously increased (Chen, 2003; Lin et al., 2015; Wang, 2016). The average flooding tide current velocity of the North Passage decreased before 2005 and then increased. The variation in average flooding tide current velocity of the South Passage was not significant (Chen, 2003; Lin et al., 2015; Wang, 2016).

3.3 *Evolution of the vegetation in Jiuduansha*

In 1990, the vegetation of Jiuduansha only existed in the Upper Shoal. By 1995, the vegetation appeared in the Upper Shoal, Middle Shoal, and Lower Shoal (Fig. 5). Between 1995 and 2000, the vegetation of Jiuduansha expanded significantly in the Middle and Lower Shoals, while vegetation in the Upper Shoal did not vary a lot. During 2000–2005, vegetation in the northern side of the Upper Shoal, and the northern and southern sides of Middle and Lower Shoals expanded obviously. Vegetation also appeared in the Jiangya Shoal in this period. From 2005 to 2015, the vegetation in Jiuduansha continued to expand, especially in the southern side of Jiangya Shoal, the northern side of Upper Shoal, and the eastern side of the Middle and Lower Shoals.

The area of the vegetation in Jiuduansha has increased from 9.1 km^2 in 1990 to 65.68 km^2 in 2015 (Fig. 6). The expansion rate was slightly slower during 1985–1995, with an average rate of 1.77 km^2/a. This value increased from 1995 to 2010, reaching 2.83 km^2/a. After 2010, the expansion slowed once again, with an average rate of 1.80 km^2/a.

Variations in the area of the different vegetation types during 1987–2015 were significantly different (Table 2). *Scirpus mariqueter* firstly settled in Jiuduansha in the 1980s. Its area showed an increasing trend before 2002 and decreased after this year. After the 1990s, the *Phragmites australis* began to develop and continued to expand in the past 30 years. By 2013, its area accounted for 32.08% of the total vegetation area in Jiuduansha.

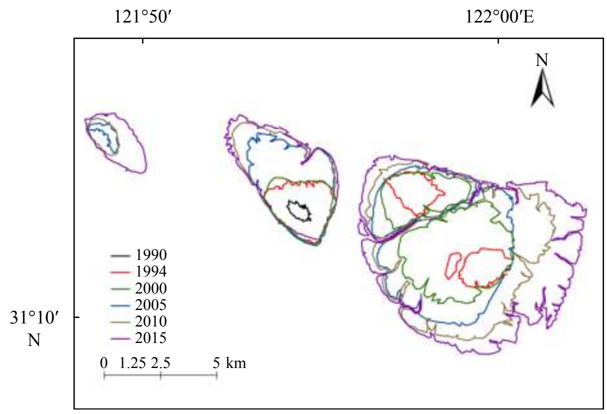

Fig. 5. Variation in the distribution characteristics of the vegetation in Jiuduansha during 1990–2015.

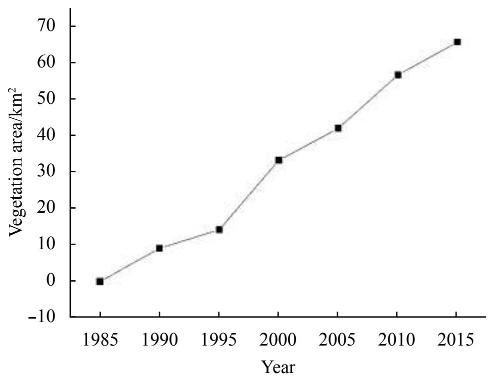

Fig. 6. Variation in the area of the vegetation in Jiuduansha during 1985–2015.

Since the end of the last century, *Spartina alterniflora* has expanded rapidly in Jiuduansha, with an expansion rate of 2.04 km^2/a. By 2015, its area accounted for 53.93% of the total vegetation area in Jiuduansha.

3.4 *Correlations between the vegetation, shoal, and hydrological characteristics*

There were significant positive correlations between the total vegetation area and the shoals within 0 m isobath, 5 m isobath, the area of *Spartina alterniflora* community, and the area of *Phragmites australis* community (Table 3). The positive correlation between the area of *Spartina alterniflora* and *Phragmites australis* was significant. Both, in turn, were also positively correlated to the area of the shoals within the 0 m isobath and the 5 m isobath, and the total vegetation area significantly. There was no significant relationship between the area of *Scirpus mariqueter* and the area of the shoals, annual runoff, sediment discharges and the area of other vegetation types. In addition, there was an extremely significant positive correlation between the area of shoals within the 0 m isobath and within the 5 m isobath.

The best combination of environmental factors with a significant correlation on the area of the shoals within 0 m isobath is the area of *Spartina alterniflora* and the area of *Phragmites australis* (r=0.966, P<0.05) (Table 4). Environmental factors that have a significant effect on the area of the shoals within the 5 m isobath were not found.

4 Discussion

4.1 *Relationship between the evolution of the shoals and the hydrological characteristics*

According to the results of this study, in the past 30 years, the expansion of the shoals in Jiuduansha was visible, especially in the shoals within 0 m isobath. The geomorphological evolution is dramatic and complicated. However, it can be roughly divided into two stages: stage one, from 1985 to 1995, variations in river regime, hydrological factors were the main driving force controlling the evolution of the Jiuduansha shoals. Under high river runoff, the head of the Jiuduansha shoals retreated and moved down, and the tail of the shoal naturally expanded seaward. The split ratio of water in the North Passage was higher than that in the South Passage, while the split ratio of sediment in the North Passage declined continually. These combining forces resulted in the shoal's erosion on the northern side and deposition on the southern side. The second stage of the 30-year evolution occurs

Table 2. Variations in the area of the different vegetation types in Jiuduansha during 1987–2015

	1987[1)]	1991[1)]	1997[1)]	2002[1)]	2006[1)]	2008[1)]	2013
Phragmites australis	0	1.81	3.78	8.11	16.04	17.96	20.10
Spartina alterniflora	0	0	1.09	7.39	18.68	22.34	33.81
Scirpus mariqueter	6.91	9.26	13.40	18.83	15.90	16.71	8.75

Note: Data source: [1)] Liu et al., 2009.

Table 3. Correlations between the area of the shoals, vegetation and the annual runoff, sediment discharge

	M0	M5	RF	SED	VA	SA	PA	SCA
SCA	0.386	0.620	−0.343	−0.240	0.379	0.143	0.361	1.000
PA	0.989**	0.902**	−0.266	−0.986**	0.982**	0.969**	1.000	
SA	0.961**	0.820*	−0.164	−0.983**	0.962**	1.000		
VA	0.992**	0.917**	−0.164	−0.965	1.000			
SED	0.981**	0.868**	0.226	1.000				
RF	−0.236	−0.112	1.000					
M5	0.921**	1.000						
M0	1.000							

Note: M0 represents the area of the shoals within the 0 m isobath, M5 the area of the shoals within the 5 m isobath, RF river runoff, SED sediment discharge, VA the total area of the vegetation, SA the area of *Spartina alterniflora*, PA the area of *Phragmites australis*, and SCA the area of *Scirpus mariqueter*. * A significant correlation between the factors; ** an extreme correlation between the factors.

Table 4. Significance of correlations between the area of Jiuduansha shoals and environmental factors

	Combination	*P*	*r*
Area of shoal within the 0 m isobath	4, 5	0.001	0.966
Area of shoal within the 5 m isobath	3, 4	0.073	0.916

Note: Environmental factors: 1, sediment discharge; 2, river runoff; 3, the total area of vegetation; 4, the area of *Spartina alterniflora*; 5, the area of *Phragmites australis*; and 6, the area of *Scirpus mariqueter*.

during 1995–2015. The evolution of Jiuduansha in this stage was mainly affected by regional wading engineering. The construction of the Deep Waterway Project started in 1998 guarded the head of the Jiangya Shoal and the northern boundary of Jiuduansha. This resulted in the stability and expansion of the northern side of the shoals (Liu et al., 2010). The Deep Waterway Project also changed the split ratio of water and sediment in the North and South Passages (Xie et al., 2014). The split ratio of water in the South Passage exceeded the North Passage after 2000. As a result, regional hydrodynamics increased significantly on the southern side of Jiuduansha. Meanwhile, affected by the operation of the Three Gorges Dam, the sediment concentration in the South Passage has been greatly reduced. Additionally, the construction of the Nanhui Dongtan Reclamation Project absorbed a large amount of sediment in the South Passage. These reduced the sediment concentration in the water area of the southern side of Jiuduansha, resulted in frequent erosion of the southern side of the shoals of Jiuduansha in recent years. At the same time, the Nanhui Dongtan Reclamation Project changed the current direction in the South Passage, which also promoted the erosion of the southern side of the Jiuduansha (Hu et al., 2013). Moreover, the increase of the regional hydrodynamics caused by the continuous erosion and expansion of the Jiangya Creek after 2000 may be another important factor causing the erosion of the southern side of the Jiuduansha (Gao et al., 2010).

The results of the correlation analysis in our study showed that the variation of sediment discharge has a significant correlation with the area of the shoal. This is consistent with previous studies (Gao et al., 2010). Sediment discharge is an important source of the sediment required for the expansion of the estuarine shoal. Especially, the response of the seaward part of the estuarine shoal to the sediment discharges are sensitive (Jay and Simenstad, 1996). In the past decade, the sediment discharges have declined significantly, which could lead to the decrease in the expansion rate of the shoals. Although the correlation between the river runoff and the area of the shoal in our study is not significant, the results in our study and the previous research showed that the hydrodynamic factors of the South and North Passages could have a significant effect on the morphological evolution of the shoal (Wei et al., 2016).

4.2 *Interactions between the evolution of shoal and vegetation*

Studies have shown that regional vegetation area and composition will change significantly with the evolution of shoal (Huang and Zhang, 2007). In this study, the area of vegetation increased significantly while the Jiuduansha shoals experienced rapid expansion. Our study showed that there is a significant positive correlation between the area of the shoal and vegetation. Previous studies have shown that the expansion of vegetation requires stable substrate conditions (Zhu et al., 2012). The stable siltation of tidal flats during the evolution of the shoals can provide suitable conditions for the settlement of vegetation, which in turn, can promote the expansion of the vegetation. Previous studies on the succession and distribution of the vegetation in Jiuduansha have also shown that the rate of vegetation expansion is faster in Middle and Lower Shoals with the faster expansion than Upper Shoal with the slower expansion (Shi et al., 2007). This suggested that on a long-term scale, the development of the shoal may promote the regional vegetation expansion.

The results of nonlinear regression analysis showed that there was a significant correlation between the variation in the area of the shoals within the 0 m isobath and the vegetation area. Conversely, there was no significant relationship between the area of the shoals within the 5 m isobath and the vegetation area. This suggested that the correlation between the evolution of the shoals within 0 m isobath and the expansion of the vegetation could be stronger. Numerous studies have shown that elevation is the most important habitat factor for shaping the structural characteristics of the vegetation in the estuarine and coastal ecosystem. As the elevation increases, the stresses of hydrodynamic, salinity, and other environmental factors on vegetation gradually reduce (Silvestri et al., 2005). Due to the specific elevation conditions required for the growth of the different plant communities, the vegetation in the estuarine area often exhibits obvious zonation patterns (Kemp et al., 2004). Therefore, a key factor driving the expansion of vegetation in the long-term evolution of shoals may be the area within the 0 m isobath, since it is most suitable for vegetation growth.

The dominant vegetation in Jiuduansha changed from *Scirpus mariqueter* in the 1990s, to *Spartina alterniflora* and *Phragmites australis* in 2015. This variation in vegetation composition was due in part to the artificial introduction of *Spartina alterniflora* in the Middle shoal of Jiuduansha at the end of the last century. Studies have shown that *Spartina alterniflora* is more competitive in the Jiuduansha region than the native species *Scirpus mariqueter* (Shi et al., 2007). On the other hand, the variation of the tidal flat elevation during the evolution of shoal could be another important reason for the evolution of vegetation. *Spartina alterniflora* and *Phragmites australis* were proved to be more suitable for growing in the high tidal flat than *Scirpus mariqueter* (Chen, 2003). As a result, our study showed that the variation in the area of shoals, especially the 0 m isobath, was significantly positively correlated with the area of *Spartina alterniflora* and *Phragmites australis*. The relationship between the area of the shoals and the area of *Scirpus mariqueter* community was not significant. This suggested that the effects of the evolution of shoal on vegetation could vary in the different vegetation types.

Previous studies have reported that vegetation has an essential influence on the geomorphology in the estuarine and coastal areas (Anisfeld et al., 2016). Vegetation can weaken regional hydrodynamics, capture suspended sediments, increase sediment deposition, and promote tidal flat development (Mariotti and Fagherazzi, 2010; Mudd et al., 2010). These combined factors can promote the expansion of the shoal. The results of linear and nonlinear regression analysis also showed that the effects of the different vegetation types on the evolution of the shoals are different. Previous studies have pointed out that *Spartina alterniflora* and *Phragmites australis* have a stronger ability to promote siltation than *Scirpus mariqueter* (Chen et al., 2001). These suggested that the contribution of the different vegetation types on the evolution of the shoal is different on a long-term scale.

5 Conclusions

This study determined the effects of the evolution of the estuarine shoals on their vegetation on a long-term scale. It emphasized that the evolution of shoal is not only affected by the changes of hydrology, sediment factors, and human activities but, additionally, the dynamic of vegetation. In the future, effective long-term monitoring and more detailed data are needed to systematically analyze the interaction between the hydrological processes, shoal evolution, and variation of vegetation.

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