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Anthropogenic impacts on sedimentation in Jiaozhou Bay, China

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Abstract In the last 150 years, China transformed its economy from a feudal system (pre-1911) to a modern market economy. During this time, policy-driven rapid development created a series of ecological and environmental problems, especially in the coastal economic regions. Although the synthetic effects are certainly identifiable, the specific effects of different policies in different developing periods have been difficult to disentangle. Here we show that the footprints of Chinese policies in the last 150 years, and their different influences on coastal environments, were archived in the temporal dynamics of sedimentation in Jiaozhou Bay. Before 1935, natural processes predominantly controlled the sedimentation in Jiaozhou Bay. After the introduction of modern economic policies in 1935, the sediment mass accumulation rate (MAR) was overwhelmingly driven by the sea areas of the bay as a result of policy-driven anthropogenic activities (i.e. saltern development, mariculture, and land reclamation). An increasing MAR at the early stage of each policy, followed by a decrease at the late stage was observed. Land reclamation in the 1990s led to a much quicker increase of MAR than the earlier saltern development. Our results demonstrated that marine exploitation, instead of natural processes, are currently regulating the ecological environments of Chinese bays.

Keywords Sedimentation · Economic policy · Jiaozhou Bay · Lead chronology

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Introduction

China ended the feudalism of the Qing dynasty in 1911 A.D., and then experienced short-term civil war in the first half of twentieth century (Wasserstrom 2015). From the 1950s, China entered the stage of a planned economy until the early 1990s. In 1995, the economic mode was adjusted to a market economy after the 5th Plenary Session of the 14th CPC Central Committee (Wu 2003). Obviously, economic development in China was closely related to policy guidance in the past 150 years. Mostly coastal areas benefitted from these policies, and gained rapid development (Lemoine et al. 2015). Meanwhile, coastal environmental and ecological systems have deteriorated, resulting in an unsustainable development especially in the last 30 years (Liu and Diamond 2005; Liang et al. 2015; Liu and Mu 2016). Although the worsening status in some bays and coastal seas of China are extensively reported (Liang et al. 2015), it is still difficult to disentangle the effects of different policies on coastal ecosystems (Yuan et al. 2016). This situation prevents governments from taking target-directed measurements to correct the problems corresponding to different economic policies used in earlier years.

We selected Jiaozhou Bay to check whether different Chinese economic policies and their environmental effects were archived in the sediment cores. Jiaozhou Bay is a semi-enclosed bay located in the southern Shandong Peninsula, China with a total area of 390 km^2. It represents one of the most developed coastal regions and has witnessed several economic policies in the past 150 years. From 1860s, the sea area of Jiaozhou Bay decreased more than one-third with the influence of anthropogenic activities (Yuan et al. 2016). About 20 % of the bay is intertidal area, which decreased ~70 % in the last half century (Yang et al. 2003). Anthropogenic activities have significantly changed the input of nutrients (i.e. N, P, and Si) into Jiaozhou Bay (Shen 2001) and resulted in the frequent red tides (Dai et al. 2007). Sediment discharges from surrounding rivers also decreased from 1950s to 1980s (Wang 1986; Wang and Gao 2007). These observations indicated that the sedimentary environments probably changed to a large degree in Jiaozhou Bay. Fortunately, there are relatively complete historical records (Ma et al. 2014; Yuan et al. 2016) in Jiaozhou Bay over the last 150 years, which would help us resolve the confounding effects of the various policies.

Materials and methods

Jiaozhou Bay has an average tidal range of 2.7–3.0 m (Liu et al. 2007). Recently, the bridge construction (e.g. Jiaozhou Bay Bridge) has changed the hydrodynamic conditions (Zhao et al. 2015). In order to avoid the influence of bridge construction, two stations (i.e. C4 and C3) in the southeast of Jiaozhou Bay were occupied (Fig. 1), where sediment is well-preserved. The water depths at C4 and C3 ranged between 10 m and 20 m. The sediment cores were collected using a gravity corer on 11 June 2015, and sectioned into subsamples of 0.5 cm thickness. The weights of the wet sediments were measured to calculate the water contents. After freeze drying, the sediment weights, radioactive activities of ^{210}Pb and ^{137}Cs were determined in subsamples. ^{210}Pb was measured via its granddaughter ^{210}Po. In brief, 0.6 g of sediment was digested with concentrated HNO_3 after adding an accurate ^{209}Po spike. Both ^{210}Po and ^{209}Po in solution were finally auto-deposited on an Ag-plate under specific conditions (Yang et al. 2011, 2015). The activities of Po isotopes (i.e. ^{210}Po and ^{209}Po) were counted using α-spectrometry until the counting errors were less than $\pm 1\sigma$. ^{137}Cs activities were determined by non-destructive gamma counting using a Canberra ultra-high purity germanium well detector. The counting efficiency at 661.3 keV for ^{137}Cs was calibrated using standard material from the National Institute of Metrology (No. 9MLSG) with the same geometry as the samples in the counting vial. Both ^{210}Pb and ^{137}Cs in Bq kg^{-1} dry sediment were used to calculate the ^{210}Pb-chronology and label ^{137}Cs-chronology (Tables S1-S7, and Fig. 2).

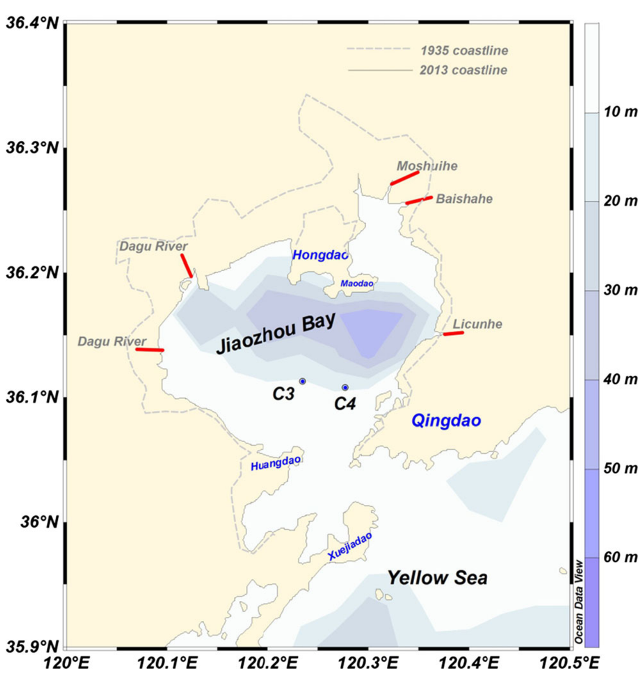


Fig. 1 Sampling coordinates in Jiaozhou Bay connected to the Yellow Sea. The coastlines in 1935 and 2013 are from Yuan et al. (2016)

The constant rate of supply model (i.e. CRS, Goldberg 1963), also called the constant flux model (i.e., CF, Robbins 1978), of ^{210}Pb-chronology was adopted in this study. ^{210}Pb in coastal seawater is derived mainly from atmospheric deposition (Baskaran 2011), and this source usually shows little inter-annual variation on the western Pacific coasts (Huh et al. 2006; Wang et al. 2014). ^{210}Pb in coastal seawater is usually scavenged into local sediments because coastal waters have very high particle concentrations, which efficiently remove atmosphere-derived ^{210}Pb and even ^{210}Pb transported from open seawater, i.e. boundary scavenged-^{210}Pb (Nozaki et al. 1997; Huh and Su 1999). Hence, the flux of ^{210}Pb at a specific site in coastal seas would, to a large extent, meet the precondition of the CRS model rather than other ^{210}Pb-chronology models (i.e. Appleby and Oldfield 1983; Sanchez-Cabeza and Ruiz-Fernández 2012). In addition, the rapid development of the economy in the past 30 years probably resulted in large variations of the sedimentation rate in Chinese coastal seas, either in cm yr^{-1} or g cm^{-2} yr^{-1}. Combining the small variability in ^{210}Pb flux and the large variability in sedimentation rate, the constant activity of ^{210}Pb in the last century does not seem to be valid for the constant activity model, constant sedimentation model, or constant flux constant sedimentation model (Sanchez-Cabeza and Ruiz-Fernández 2012). In contrast, this factor has little influence on the application of the CRS model. To further validate the CRS model, ^{137}Cs-chronology was concurrently used in the present study.

Results and discussion

The maximum of the ^{137}Cs specific activity in sediment cores, witnessing the highest ^{137}Cs content in the atmosphere during the 1960s, is widely used to label 1963 A.D. and validate the ^{210}Pb-chronology (Sanchez-Cabeza and Ruiz-Fernández 2012). At stations C4 and C3, ^{137}Cs clearly showed the

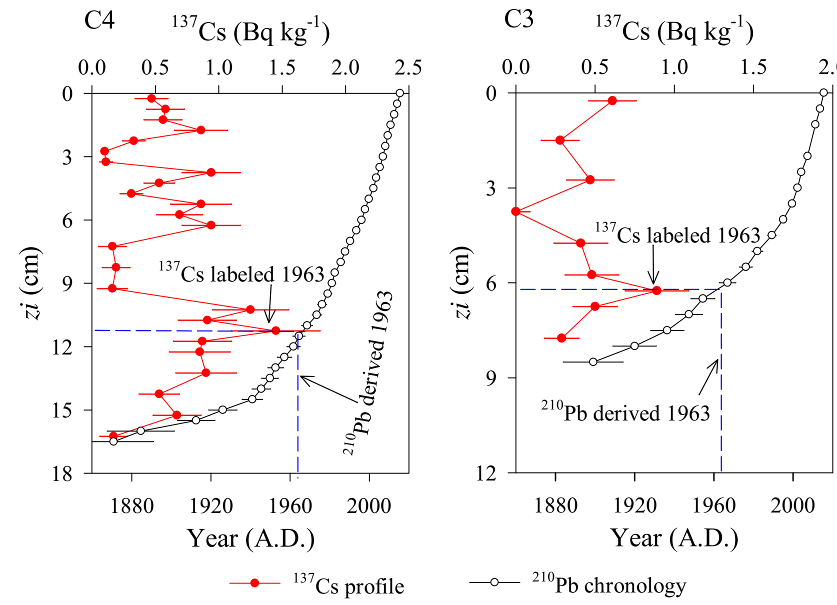


Fig. 2 Comparison between ^{137}Cs-labeled 1963 and ^{210}Pb-chronology (CRS model) in the sediment cores at C4 and C3. The consistencies between the two methods support the validity of ^{210}Pb-chronology

highest value at 11.5–12.0 cm and 6.0–6.5 cm, although it fluctuated in the cores (Fig. 2). Concurrently, ^{210}Pb-chronology confirmed 1963 A.D. was observed at 11.0–11.5 cm and 6.0–6.5 cm in C4 and C3 cores. These consistencies verified that the CRS model derived ^{210}Pb-chronologies at the two stations reflected the archived sediment mass accumulation rate (MAR) in sediments.

In the past 150 years, the MARs varied largely at stations C4 and C3 (Fig. 3). However, they showed similar patterns in most cases. Owing to the low time resolution of the MAR at C3, C4 was mainly used here to illustrate the temporal evolution of sedimentation dynamics in Jiaozhou Bay. Overall, five periods were identified based on MAR variation (Fig. 3). Before 1935, the MAR changed little with an average of 0.03 ± 0.01 g cm^{-2} yr^{-1}. From 1935, the MAR

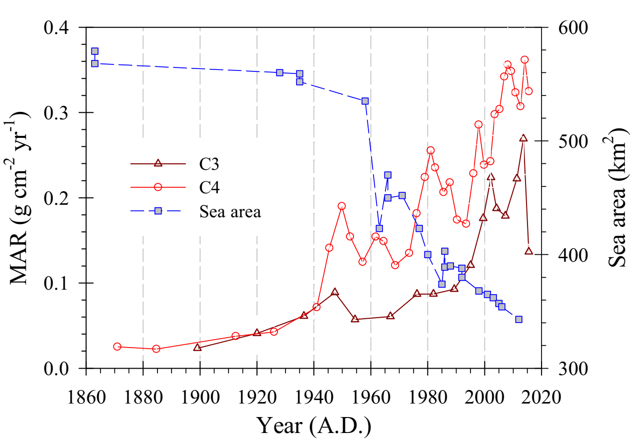


Fig. 3 Variations of sedimentation rates in g cm^{-2} yr^{-1} at stations C4 and C3 in the past 150 years, as well as the sea area of Jiaozhou Bay. The data relating to sea area are from Dai et al. (2007), Zhou et al. (2010), and Ma et al. (2014)

increased to 0.19 g cm^{-2} yr^{-1} in 1949 and then decreased to 0.12 g cm^{-2} yr^{-1} in the late 1960s. From the late 1960s to around 1990, the MAR exhibited a second round of increase and decrease, varying from 0.13 to 0.26 g cm^{-2} yr^{-1} and peaking in 1981. The third round cycling of the MAR occurred between 1990 and 2002. After this, the MAR experienced a rapid increase again. The temporal pattern revealed complicated variations of the MAR in Jiaozhou Bay rather than the monotone increasing and decreasing of the MAR in some areas (Sun et al. 2008), probably due to the influence of anthropogenic activities in addition to natural processes.

Either increase of sediment loads or decrease of sea area could result in the increase of the MARs. From the 1950s to 1980s, annual sediment discharges from seven major rivers entering Jiaozhou Bay decreased (Wang 1986; Wang and Gao 2007), indicating that the decrease of sediment loads was not the reason behind the increased MARs. However, the sea area of Jiaozhou Bay also shows an overall decrease from the 1860s to 2010s (Zheng et al. 1991; Bian et al. 2001; Wu et al. 2008; Dai et al. 2007; Zhou et al. 2010). Before 1935, the sea area showed a small decrease (from 579 to 559 km^2) (Fig. 3). After 1940, the sea area decreased; especially after 1960 when it was reduced rapidly. Interestingly, the sea area appears to show asymmetric temporal patterns compared to the MARs during the past 150 years, supporting the dominant control of sea area rather than sediment loads (Fig. 3). By analyzing the variations of the MAR with the sea area, a significant inverse correlation was observed ($r^2 = 0.93$, $p < 0.0001$, Fig. 4), indicating an exponential increase of MAR instead of a linear increase accompanying the decrease in sea area. Similar relationship was also observed at C3 (Fig. 4) with a comparable coefficient of 0.010 ± 0.003 to

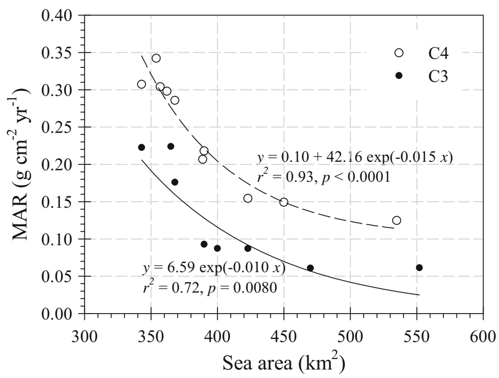


Fig. 4 Relationships between sediment mass accumulation rates at station C4, C3 and the sea area of Jiaozhou Bay

that of 0.015 ± 0.005 at C4. These results indicated that sedimentation at C4 and C3 show similar dependence on the sea area in Jiaozhou Bay.

The decrease of the sea area in Jiaozhou Bay results mainly from coastal utilization directed by the government (Zhou et al. 2010; Ma et al. 2014). From 1863 to 1935, anthropogenic reclamation decreased only 1.42 km^2 of sea area (Fig. 5), while, in contrast, natural processes diminished the sea area by 13.7 km^2 (Ma et al. 2014). In this period, natural processes dominated the little variability in MAR. During 1935–1969, saltern development was introduced by the government, accounting for more than 80 % of the decreased sea area during this period. Correspondingly, the MAR showed a rapid increase (Fig. 3). From 1969, the economic policy surrounding Jiaozhou Bay changed into mariculture, which became the dominating factor for the decrease of sea areas during 1969–1987, following saltern development. Hence, mariculture industry, to a large extent, controlled the second increase of the MAR in Jiaozhou Bay (Fig. 3). Mariculture lasted as the main industry until the late 1990s (Liang et al. 2015). Then, tourism and the manufacturing industries quickly replaced the mariculture industry and became the pillar industries after the late 1990s (Shen 2003; Li and Jia 2006). At the same time, land reclamation became the predominant reason for the decrease of sea area as a result of population and industry expansion (Ma et al. 2014). Notably, at the later stage of each policy, i.e. 1950–1960s, 1980s, and 1990s, the MAR decreased rather than increased (Fig. 3), probably because of the end of the implementation of the old policy.

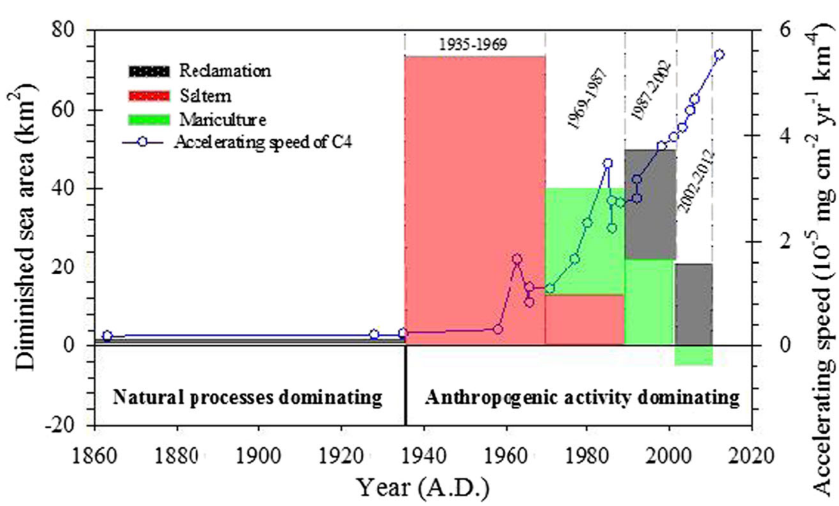
To discriminate the different speed of MAR increase induced by different sea area usage, the equation between the MAR and sea area at C4 (Fig. 4) was used to calculate the accelerating speed of MAR increase, i.e.

$$\frac{d^2y}{dx^2} = 42.16 \times (-0.015)^2 \times e^{-0.015x} \quad (1)$$

where y is the MAR, and x is the sea area.

Before 1935, the accelerating speed of MAR dominated by natural processes averaged 0.20 (in 10^{-5} mg cm^{-2} yr^{-1} km^{-4}, and the same unit hereafter) (Fig. 5). Saltern usage, on average, resulted in an accelerating speed of 0.98 from 1935 to 1969. From 1969 to 1987 and 1987–2002, the accelerating speed averaged 2.73, mainly influenced by the mariculture industry. The highest acceleration occurred after 2002, corresponding to 4.71. Overall, the influence of saltern development was a slow process, while land reclamation in the last two decades appeared to be very fast. Such a difference was attributed to the direct sediment input during reclamation. A considerable amount of the anthropogenic addition of solid material would be re-distributed in Jiaozhou Bay with tides and circulation (Zhao et al. 2015; Yuan et al. 2016). In contrast, saltern development did not introduce a sediment load increase.

Fig. 5 Impacts of Chinese policies on the variations of sediment mass accumulation rates in Jiaozhou Bay



The close relationships between the MAR increase and sea area decrease in Jiaozhou Bay proved that economic policies, to a large extent, dominated the sedimentary dynamics over the past 150 years. The sediment MAR quickly increased especially in the last 30–40 years accompanying the rapid development of economy surrounding Jiaozhou Bay. The increase of MAR would enhance the siltation in the inner bay, and then weaken the circulation in Jiaozhou Bay (Yuan et al. 2016). Consequently, the exchange of nutrients and pollutants between Jiaozhou Bay and Yellow Sea could be suppressed. Thus, the MAR increase may be responsible for the enhanced eutrophication observed in Jiaozhou Bay.

Conclusions

Chinese policies on the utilization of coastal seas in order to develop the economy exerted considerable influence on coastal environments in the twentieth century, especially in the last 40–50 years. The sediments in Jiaozhou Bay archived the environmental impacts of these policies. High temporal resolution research on bay sediments would provide an objective passage for understanding the interactions between intensive anthropogenic activity and coastal environmental evolution in China or even other developing countries.

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References

Appleby PG, Oldfield F (1983) The assessment of ^{210}Pb data from sites with varying sediment accumulation rates. Hydrobiologia 103:29–35

Baskaran M (2011) ^{210}Po and ^{210}Pb as atmospheric tracers and global atmospheric ^{210}Pb fallout: a review. J Environ Radioact 102:500–513

Bian S, Hu Z, Feng A, Xia D (2001) An exploration on the natural morphology and the siltation and erosion development of the Jiaozhou Bay in recent 130 years. J Oceanogr Huanghai Bohai Seas 19: 46–53. (in Chinese with English Abstract)

Dai J, Song J, Li X, Yuang H, Zheng G, Li N (2007) Environmental changes reflected by sedimentary geochemistry in recent hundred years of Jiaozhou Bay, North China. Environ Pollut 145:656–667

Goldberg ED (1963) Geochronology with ^{210}Pb. In: Radioactive dating. Proceedings of a Symposium. International Atomic Energy Agency, Vienna, pp. 21–131

Huh C-A, Su C-C (1999) Sedimentation dynamics in the East China Sea elucidated from ^{210}Pb, ^{137}Cs and ^{239,240}Pu. Mar Geol 160:183–196

Huh C-A, Su C-C, Shiau LJ (2006) Factors controlling temporal and spatial variations of atmospheric deposition of ^{7}Be and ^{210}Pb in northern Taiwan. J Geophys Res 111:D16304. doi:10.1029/2006JD007180

Lemoine F, Poncet S, Ünal D (2015) Spatial rebalancing and industrial convergence in China. China Econ Rev 34:39–63

Li C, Jia Z (2006) Study on urban leading industry and its selection. J Qingdao Univ Sci Technol (Soc Sci) 22:5–10

Liang S, Pearson S, Wu W, Ma Y, Qiao L, Wang XH, Li J, Wang X (2015) Research and integrated coastal zone management in rapidly developing estuarine harbours: a review to inform sustainment of functions in Jiaozhou Bay, China. Ocean Coast Manag 116:470–477

Liu J, Diamond J (2005) China's environment in a globalizing world. Nature 435:1179–1186

Liu X, Mu R (2016) Public environmental concern in China: determinants and variations. Glob Environ Chang 37:116–127

Liu X, Li X, Zhang J, Wei H, Ren J, Zhang G (2007) Nutrient dynamics in Jiaozhou Bay. Water Air Soil Pollut Focus 7:625–643

Ma L, Yang X, Qi Y, Liu Y, Zhang J (2014) Oceanic area change and contributing factor of Jiaozhou Bay. Sci Geogr Sin 34:365–369 (in Chinese with English Abstract)

Nozaki Y, Zhang J, Takeda A (1997) ^{210}Pb and ^{210}Po in the equatorial Pacific and the Bering Sea: the effects of biological productivity and boundary scavenging. Deep-Sea Res II 44:2203–2220

Robbins JA (1978) Geochemical and geophysical applications of radioactive lead isotopes. In: Nriagu JO (ed) Biochemistry of lead in the environment. Elsevier, Amsterdam, pp. 85–393

Sanchez-Cabeza JA, Ruiz-Fernández AC (2012) ^{210}Pb sediment radiochronology: an integrated formulation and classification of dating models. Geochim Cosmochim Acta 82:183–200

Shen Z (2001) Historical changes in nutrient structure and its influence on phytoplankton composition in Jiaozhou Bay. Estuar Coast Shelf Sci 52:211–224

Shen L (2003) Tourist industry and three tourist markets in Qingdao. Coast Eng 22: 95–102. (in Chinese with English Abstract)

Sun X, Peng P, Song J, Zhang G, Hu J (2008) Sedimentary record of black carbon in the Pear River estuary and adjacent northern South China Sea. Appl Geochem 23:3464–3472

Wang H (1986) Natural environment of Jiaozhou Bay. Coast Eng 5:18–24 (in Chinese with English Abstract)

Wang Y, Gao S (2007) Deposition rates of multiple temporal and spatial scales in Jiaozhou Bay, Shandong peninsula. Quat Sci 27: 787–796. (in Chinese with English Abstract)

Wang Z, Yang W, Chen M, Lin P, Qiu Y (2014) Intra-annual deposition of atmospheric ^{210}Pb, ^{210}Po and the residence times of aerosol in Xiamen, China. Aerosol Air Qual Res 14:1402–1410

Wasserstrom JN (2015) Chinese revolutions: Twentieth century. In: International Encyclopedia of the Social & Behavioral Sciences, 2nd edn. pp 515–519.

Wu L (2003) China's planned economy reconsidered and reassessed. Contemp China Hist Stud 10:37–46 (in Chinese with English Abstract)

Wu Y, Xin H, Wu L, Li W (2008) The satellite investigation on the 2006 water area and coastline length of the Jiaozhou Bay and their historical evolution. Coast Eng 27:15–22

Yang S, Chen Q, Zhu J, Zhang J (2003). Computation of storage capacity for tidal water of semiclosed bays where the intertidal zone is partly embanked-taking Jiaozhou Bay as an example. Mark Sci 27: 43–47. (in Chinese)

Yang W, Huang Y, Chen M, Qiu Y, Li H, Zhang L (2011) Unusually high ^{210}Po activities in the surface water of the Zhubi coral reef lagoon in the South China Sea. Sci Total Environ 409:4612–4617

Yang W, Guo L, Chuang C-Y, Santschi PH, Schumann D, Ayranov M (2015) Influence of organic matter on the adsorption of ^{210}Pb, ^{210}Po, and ^{7}Be and their fractionation on nanoparticles in seawater. Earth Planet Sci Lett 423:193–201

Yuan Y, Song D, Wu W, Liang S, Wang Y, Ren Z (2016) The impact of anthropogenic activities on marine environments in Jiaozhou Bay, Qingdao, China: a review and a case study. Region Stud Mar Sci. doi:10.1016/j.rsma.2016.01.004

Zhao K, Qiao L, Shi J, He S, Li G, Yin P (2015) Evolution of sedimentary dynamic environment in the western Jiaozhou Bay, Qingdao, China in the last 30 years. Estuar Coast Shelf Sci Part B 163:244–253

Zheng Q, Wu L, Zhang X, Sun Y, Pan J (1991) A remote sensing study of Jiaozhou Bay I. Measurement of total area and coastal line. Oceanol Limnol Sin 22:193–199

Zhou C, Li G, Shi J (2010) Coastline change of Jiaozhou Bay over the last 150 years. Period Ocean Univ China 40: 99–106. (in Chinese with English Abstract)