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Complexities of China's Coast in Response to Climate Change

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Abstract: Global warming and rising sea level have been observed to exert great impacts on China's coast in the past century, including increased coastal erosion, degraded coastal ecosystems, exacerbated saltwater intrusion, and enhanced storm surges. The impacts of climate change and the adjustments of coastal systems are significantly site specific, resulting from local differences in climate change, coastal physiographic and ecological conditions, and resilience of coastal systems. Anthropogenic activities also exert increasing influences on coastal systems. Societal vulnerabilities to climate change are greatly influenced by their adaptive capacities and selective adjustment, which are greatly determined by local socioeconomic conditions, so they are also highly localized. Coastal systems do not behave linearly to climate change. The projected increasing global warming and accelerating sea level rise will undoubtedly impose more threats to coastal systems. However, it is still difficult to determine the coastal socio-ecological thresholds to climate change without full understandings of coastal physical and biological processes, and adaptation responses of coastal ecosystems and human societies.

Key words: coastal systems, climate change, sea-level rise, vulnerability, adaptive capacity, regional variability

Introduction

Fourteen administrative units are located along China mainland coast, including 8 provinces, 2 municipalities (Shanghai and Tianjin) and 2 special administrative regions (Hong Kong and Macao). Their lands adding up to 1.6×10^6 km^2, occupy only 16.8% of China's total, but foster 41.9% of national population, and produce 72.5% of China's GDP (China Mainland plus Hong Kong and Macao) [1]. The coast is, therefore, the most economically developed and heavily populated area in China. The low-lying deltas and coastal plains have, however, been assessed to be key vulnerable regions due to sea level rise [2]. Global warming and sea level rise are projected to be continuous and accelerating, and more and heavier storm-surge disasters will take place. At the same time, rapid economical development will continue and more people will be attracted to coastal regions with accelerating urbanization. Growing human activities will, therefore, undoubtedly complicate the impacts of changing climate and rising sea level on coastal systems. This study will examine the synthetical effects of climate change, sea level rise and human activities on coastal ecosystems and human societies, and their adaptation responses, followed with a discussion whether and when coastal systems will cross the critical climate thresholds thus arising irreversible degradation.

1 Regional differences in sea-level change

The average rate of sea level rise was 2.5 mm/a in the past 50 years. Local rates of sea-level changes are greatly different, considering that tectonic movements and human activities are significantly site specific, and both contribute to changes in relative sea level. The rates of relative sea level changes are more important than global sea level rise to the assessmeat of coastal vulnerabilities [1]. The rates of tectonic uplift in Qinhuangdao and eastern Shandong Peninsula are a little higher than the rate of sea level rise, inducing a slight fall in relative sea level [2−3]. Coastal plains and major river deltas are located in the tectonic-subsidence zones with a subsiding rate 1−3 mm/a, where Quaternary strata are generally 200−400 m thick. Ground subsidence of thick unconsolidated sedimentary strata is usually accelerated by additional sediment compaction due to subsurface water extraction and heavy load of lofty buildings and

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skyscrapers. In the urban of Tianjin, ground subsidence amounted to 2.7 m with an average rate of 77 mm/a in the period of 1959−1993. The average rate of ground subsidence reached 29 mm/a in Shanghai urban center during the period of 1921−1998 [1]. The rates of relative sea level rise may, therefore, be much higher than that of global warming induced sea-level rise in the tectonic subsidence provinces.

In a word, relative sea level may be rising or falling, and variations in local rates of sea level changes can be several tens of times. Also, the projected rates of relative sea level rise for the year 2050 differ greatly among three major deltas, 70−90 cm for the Yellow River Delta, 50−70 cm for the Yangtze River Delta, and 40−60 cm for the Pearl River Delta [4].

2 Complexities of coastal systems' response to climate change

2.1 Accelerating coastal erosion

Muddy coasts, whose distribution is closely related to major river deltas, occupy nearly a quarter of China mainland coastline. The deltas can prograde seaward rapidly, given that riverine sediment supply is abundant. Annual mean vertical aggradation at tidal flats flanking the deltas can be several centimeters per year, much higher than relative sea level rising. Recently, accretion rates of tidal flats have slowed down due to obvious reduction in the sediment load of the Yangtze and Pearl Rivers, although a general prograding trend is still maintained [1, 5]. Serious coastal erosion occurs when sediment input decreases below a critical threshold or is completely cut off. The abandoned Yellow River Delta in the northern Jiangsu is exactly a typical case. The coastline has retreated 20 km landward and 1400 km^2 of the delta plain has been lost since 1855 when the Yellow River switched debouching to the Bohai Gulf in north-eastern Shandong Province [6]. Sediment starvation is, therefore, a key coastal erosion driver instead of sea level rise. In the modern Yellow River Delta, coasts can be divided into accretion or erosion according to their locations relative to the active water way. Rapid accretion takes place in the active delta lobe, while severe erosion occurs in the recently abandoned delta lobe. Coastal erosion has recently been exacerbated by the sharp reduction in sediment flux. A net negative change in area of 10.44 km^2 was once measured during the period from October 1996 to October 1997 in the modern Yellow River Delta. A threshold for sediment flux was presumably put at 245 million tons, bellow which the Yellow River Delta will turn from construction into destruction [7].

Approximately 70 percent of China's sandy coasts undergo sea water encroaching, induced by rising sea level, declining river sediment flux, bed sand mining, and/or unreasonable coastal constructions [3, 8]. A case study from the southern Shandong Peninsula based on systematic field observations along 33 km-long sandy coast over 20 years, revealed that factors of sand mining, sediment supply reduction, and sea level rise contributed 50%, 40%, and 10% to coastal erosion, respectively [8].

Summarily, coastal erosion in China is ascribed firstly to sharp reduction in riverine sediment supply, and then to rising sea level. The decrease in river sediment load can be the consequence of both climate change and human activities including reservoir construction, deforestation and reforestation, and land-use changes in drainage basins. Coastal erosion is, therefore, the consequence of both natural processes and human activities, and their different effects on coastal erosion are by far too complicated to discriminate.

2.2 Increasing saltwater intrusion

Exacerbated saltwater intrusion into estuaries and freshwater aquifers is another consequence of climate change, worsening the shortage of freshwater resource and increasing soil salinization in coastal plains. Seawater encroaching in estuaries is highly constrained with river runoff and sea level rise, especially reduction in river runoff having severer impacts on saltwater intrusion. For example, there is a close relationship between freshwater discharge at Datong Gauging Station, Anhui Province and saltwater intrusion in the Yangtze River estuary with a correlative coefficient of 0.884. When freshwater discharge drops below 7000 m^3/s, saltwater can encroach into the estuary by more than 100 km. An extreme case occurred in the winter of 1978 through the spring of 1979 revealed that Chongming Island was completely surrounded by saline water for five months when freshwater discharge reduced to 7300−8000 m^3/s [9]. The Pearl River debouches into the sea via eight waterways, and saltwater intrusion in each distributary is quite different because of their uneven freshwater discharges and varied tidal regimes. Considering one distributary under a certain tidal regime, saltwater can encroach 20−60 km more inland in dry seasons than in wet seasons [5]. Because yearly variations in river runoff are greatly influenced by climate change, further studies on saltwater intrusion should take into consideration effects of sea level rise and yearly variations of climate change in the drainage basins.

Extreme drought events may occur more frequently and intensely under the projected global warming, which will exacerbate the saltwater intrusion into estuaries. In some regions, climate change is projected to increase precipitation and river runoff, constraining saltwater intrusion in estuaries. The effects are complicated for construction of key hydrologic engineering in the drainage basins on saltwater intrusion. For example, South-to-North Water Diversion Project will reduce Yangtze River runoff, intensifying saltwater intrusion in the estuary especially during the dry seasons; while normal operation of Three Gorges Reservoir is schemed to increase water discharge by lowering the reservoir water level in the dry seasons, which will constrain the estuarine saltwater intrusion. In a word, both effects of climate change and human activities are complicated and mixed for the estuarine saltwater intrusion.

2.3 Changes in mangrove ecosystems

Mangrove forests in China have ever reached a maximum area of 250×10^3 hm^2, sharply dropped to 50×10^3 hm^2 in the 1950s, and now only remains 15×10^3 hm^2 [10]. Sharp reduction of mangrove forests in the last century is mainly linked to direct or indirect damages by human activities, like converting mangrove forests into farmland or aquaculture ponds, constructing harbors or coastal infrastructures.

Mangrove is a typical woody salt-tolerance plant, distributing along intertidal tropical and subtropical coasts. Both soil salinity and air temperature are the main habitat factors affecting the growth and distribution of mangrove forests. Especially, mean temperature of the coldest month should be above 20℃ for mangrove growing. Therefore, global warming should promote mangrove forests extending northwards and increasing their biodiversity and abundance. The present growing boundary for natural mangrove forests is at Fuding County (latitude 27°20′ N), Fujian Province, and transplanted mangroves can survive much north at Leqing County (latitude 28°25′ N), Zhejiang Province. If the mean temperature rises up 2℃, the north boundary for the natural growing mangroves will move 2.5° latitudes northwards from Fuding County to Sheng County in Zhejiang Province, and that for the transplanted mangroves will extend northwards to the Hangzhou Bay. It is worthy noting that the extremely low temperatures in autumn and winter have been observed to increase obviously throughout China, and mean temperatures for spring and summer seasons are generally decreasing along Southeast China's coast, which favors the northward invasion of mangrove forests, and increases mangrove biodiversity and abundance.

Sedimentation at mangrove lands is usually quite rapid. For example, ^{210}Pb dated sedimentation rates range from 0.41 cm/a to 1.54 cm/a for the mangrove lands at Dongzhai Harbor in Hainan, and Yingluo Harbor in the provincial boundary of Guangdong and Guangxi[11], which are higher than the rates of sea level rise. Thus, mangrove lands will not be inundated by rising sea level, given that there is enough sediment supply to maintain rapid sedimentation. However, if the rates of sea level rise exceed sedimentation rates, increased water depth and wave height will affect mangrove seeds to moor and root in the ground, and young seedlings to grow.

2.4 Changes in coral reef ecosystems

Coral reefs in China are classified into fringing reefs and atolls, with a total area of 30×10^3 km^2 [12]. Fringing reefs have been heavily destroyed due to their extensive exposure to human activities. For example, coral reefs in Hainan Island have been destroyed by 80% through coastal development and coral mining in the past half a century.

Corals tolerate a narrow temperature range between 21℃ and 29℃, but highly depending on location. The abnormal high sea surface temperature (SST) during 1997–1998 strong El Niño event caused widespread coral bleaching. China is influenced by monsoon climate with clear seasonal variations in temperature. The abnormally low temperature during winter cold waves can also induce coral bleaching, which has been reported several times in China. Global warming will increase the possibility of coral bleaching due to prolonged high SSTs in most part of the South China Sea (SCS), meanwhile will reduce occurrences of coral bleaching by cold waves in the northern SCS.

Coral reefs can grow upward at a maximum rate of 1 cm/a, much higher than the rate of sea level rise. The present sea level rise doesn't impose excessive pressure to coral reefs. Increased CO_2 concentration in the air enhances CO_2 dissolution into the surface sea, lowering the saturation of carbonate in seawater. Such badly reduce calcification rates of corals.

3 Regional differences in vulnerabilities and adaptive capacities of coastal societies

An area adds up to 144×10^3 km^2 for China's low-lying coastal lands with an elevation no more than 5 m. They are mainly distributed in three major deltas of the Yellow River, Yangtze River and Pearl River, respectively, which are the key vulnerable regions to sea level rise.

Extreme climate events like storm surges, typhoons are main causes of natural disasters in low-lying coastal regions. Statistics shows that both frequency and intensity of tropical storm surge disasters have significantly increased since the 1960s, although the frequencies of both the Northwest Pacific tropical cyclones and their landfall events over China have on average decreased (Table 1).

Regional vulnerability can be greatly reduced by adaptation. In the sea level rise scenario of 30 cm, potential area flooded under the maximum water level in Shanghai and Jiangsu without coastal defense is expected to be six times larger than that under the present coastal protection [2]. The storm surge induced by typhoon Polly in 1992 is blamed for direct loss of 9.2 billion RMB Yuan in six affected coastal city and provinces. Shanghai city bore only 0.3% of the gross economic loss, although it is naturally the most vulnerable to storm surges in the six provinces due to its lowest average elevation, which is mainly attributed to a higher level of coastal protection in Shanghai than the other provinces.

Adaptive capacities are greatly depended on the regional socio-economic conditions. Developed regions have capacity and necessity to construct high level coastal protection. It was evaluated that Shanghai should invest 1.2 billion RMB Yuan to strengthen coastal infrastructures defending the sea level rise in the period of 2000−2050 [13]. The adaptation cost is about 0.0005%−0.0049% of Shanghai's GDP, much lower than the reasonable cost/protection—GDP ratio of 1% suggested by IPCC. In the Pearl River Delta, adaptation cost for defending sea level rise should be 0.0003%−0.026% of Guangdong's GDP, also below the reasonable cost/protection level. It is, therefore, feasible for developed regions to take effective counter-measures coping with sea level rise.

It is worthy noting that adaptation cost to sea level rise is much heavier for developing regions than developed regions. Guangxi Province is one of eight key vulnerable coastal provinces in China. If the seawalls along 851 kmlong shoreline were all upgraded to Guangxi's 1992 Standard for Coastal Protection (1992-GSCP), 1.6 billion RMB Yuan should be invested. Given that the seawall standardized project were carried out in ten years from 2000 to 2010, annual average investment should be 0.16 billion RMB Yuan, accounting for 0.078% of Guangxi's GDP. The proportion of protection cost to GDP in Guangxi is about several times higher than those of Shanghai and Guangdong, although the 1992-GSCP is much lower than the coastal protection standard in Shanghai and Guangdong. It is shown that developing regions bear more brunt of sea-level rising impacts than developed regions. Therefore, evaluating the vulnerabilities and thresholds of climatic variations of individual coastal systems need to integrate the resilience of coastal systems, human selective adaptations and their increasing adaptive capacities following the economic development and technological progresses.

4 Conclusions

Regional differences are significant for impacts of climate change and sea level rise on China's coast. Global

Table 1 Statistics on the tropical-cyclone (TC) activities and storm-surge disasters in China from 1950 to 2004 ①

Period	TC activities in NW Pacific: Total / times	landfall in China / times	Landing percentage /%	Tropical storm surge disasters / times	Probability for landed TCs inducing disasters / %	Extreme storm surge disasters/ times	Annual average property loss /10^8 RMB Yuan	Deaths
1950−1959	262	97	37.02	15	15.46	1	< 1	> 5665
1960−1969	354	97	27.40	23	23.71	3	≈ 1	> 16821 ②
1970−1979	332	89	26.81	22	24.72	1	2−4	831
1980−1989	324	94	29.01	29	30.85	6	5−10	1546
1990−1999	304	86	28.29	39	45.35	7	121	3292
2000−2004	133	40	30.08	20	50.00	3	76.6	237
total	1709	503	29.43	148	29.42	21		

① data sources from www.typhoon.gov.cn and www.coi.gov.cn/hyzh/ernn/index.html

② including injuries

warming might increase coral bleaching occurrences due to the strengthening of abnormally high surface sea temperature (SST) in the southern South China Sea (SCS), but decrease occurrences of coral bleaching due to the weakening of abnormally low temperature in the northern SCS. Saltwater intrusion in estuaries is related with both sea level rise and river-runoff reduction. It will be exacerbated by increasing sea level rise and intensifying drought events, while also be substantially mitigated by increasing freshwater discharge due to increasing precipitation in some river basins. Thus, it bears some uncertainties to assess climate change impacts on the saltwater intrusion. Some key water conservancy projects constructed in the river basins exacerbate the saltwater intrusion, but others mitigate its occurrence. Coastal erosion is accelerated by rising sea level, but abundant sediment supply can greatly mitigate coastal erosion, or even force coast prograding seaward. Accelerating sea level rise and increasing storm surges undoubtedly exert increasing pressures on the coastal flood protection in China's key vulnerable regions. Human adaptation measures will greatly mitigate the climate impacts. Adaptive capacities are gradually going up with economic development and technical advancement. The coastal zones suffer both climate and non-climate impacts, and influences of natural processes and human activities. All these external and internal factors intervene each other to exert compound influences on coastal systems. So far it is too difficult to determine any climate threshold for China's coastal systems.

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