

Sea-Level Changes, Human Impacts and Coastal Responses in China¹

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ABSTRACT

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The rate of sea-level rise during the past hundred years has been 2-3 mm/year along China's coasts; sea level will probably continue to rise in the future. The process has decreased wave winnowing of submerged coastal sediment but enhanced erosion by waves breaking on the upper beaches. Following the rise of sea level, river-channel slopes have been reduced, decreasing fluvial sediment discharges to the ocean. Human impacts through diverting river discharge and constructing dams in the lower reaches of rivers for fresh water supplies have also upset coastal processes.

Paucity of coastal sediment supply is a world-wide phenomenon which, when combined with the frequency of storm surges and El Niño events to strengthen hydrodynamics, invariably results in beach erosion and the landward retreat of sand barriers along the coastal zone. Overpumping of groundwater and overloading by constructions on the delta plain and lowland coast have had serious effects: the average rate of relative sea-level rise is 24.5-50.0 mm/year in TianJing, the old Yellow River delta area along the Bohai Sea, 4.5-5.5 mm/year in the modern Yellow River delta, and 6.5-11.0 mm/year in the Shanghai area of the Changjiang River mouth. These rates are much higher than the mean annual rate of 1.4 mm/year. Under the circumstances saltwater intrusion has been changing river water salinity and fresh water quality. Storm surges often cause the lowland coast to be inundated and flooded. All such effects are ultimately the result of human activities.

ADDITIONAL INDEX WORDS: *China, coastal erosion, human impact.*

SEA-LEVEL CHANGES IN THE PAST 100 YEARS

The earliest systematic analysis of recent sea-level changes in China was by EMERY and YOU (1981) based on tide-gauge records of eight stations. A later paper by EMERY and AUBREY (1986) discussed relative sea-level changes in China in greater detail using both simple regression analysis and eigen analysis of the records from thirteen stations together with analysis of local environment conditions. Similar work by Chinese scientists (e.g. WANG, 1986), and detailed studies in recent years have improved the knowledge of sea-level changes in several regions of China (ZHAO *et al.*, 1990; CHEN, 1991; WANG *et al.*, 1991). Since then, more comprehensive and more reliable accounts of relative sea-level changes for the whole of China have been published (REN, 1993, 1994; SHI and YAN, 1994).

It is generally estimated that global sea-level rise over the past 100 years has been 1-2 mm/year (SCOR WORKING GROUP 89, 1991); that is, a total 10-25 cm rise estimated by IPCC "Climate Change" 1995 (1996). The State Oceanic Administration of China summarized tide-gauge data from 44 stations along the China coast over the last 30 years (1959-1989); the mean rate of sea-level rise was 1.4 mm/year. According to the geodetic survey data from nine stations along China coast by the Station Survey Bureau of China in 1992, the sea-level rise during last hundred years has totalled 19 cm in the East China Sea, and 20 cm in the South China Sea; the rate of sea-level rise has

been 2-3 mm/year, which is predicted to continue in the future. The result of calculating data from 102 tide-gauge stations in the world are as following: the average sea-level rise has been 15 cm during last hundred years: 29 cm in the Atlantic Ocean, 10 cm in the Pacific Ocean and 39.6 cm in the Indian Ocean.

Neotectonic movements are variable along the coastal zone of China. Generally uplift has occurred along the bedrock-embayed coasts and the hilly coasts such as those around the Liaodong and the Shandong peninsulas, the hilly coasts of eastern Hebei province, eastern Taiwan Island, most parts of the coasts of Zhejiang, Fujian, Guangdong, Guangxi and Hainan provinces. Subsidence has occurred in the area of several large river deltas, and the area of sedimentary basins since the Pliocene (Figure 1). Based on the different sedimentary evidence, it is clear that there is considerable variability in the rates of tectonic change, even within the same coastal zone. The summary table (Table 1) is adopted from the authoritative study by LU and DING (1994) and can be used as a reference to the geologic background of the regional sea-level variation of China's coasts.

After correcting for vertical movements, the annual average rate of mean sea-level rise along the coast zone of China is 2.0 mm/year (CHEN *et al.*, 1994).

RELATIVE SEA-LEVEL RISE OVER THE NEXT CENTURY

The best estimate of global sea-level rise over the next century is from the Intergovernmental Panel on Climate Change (IPCC,

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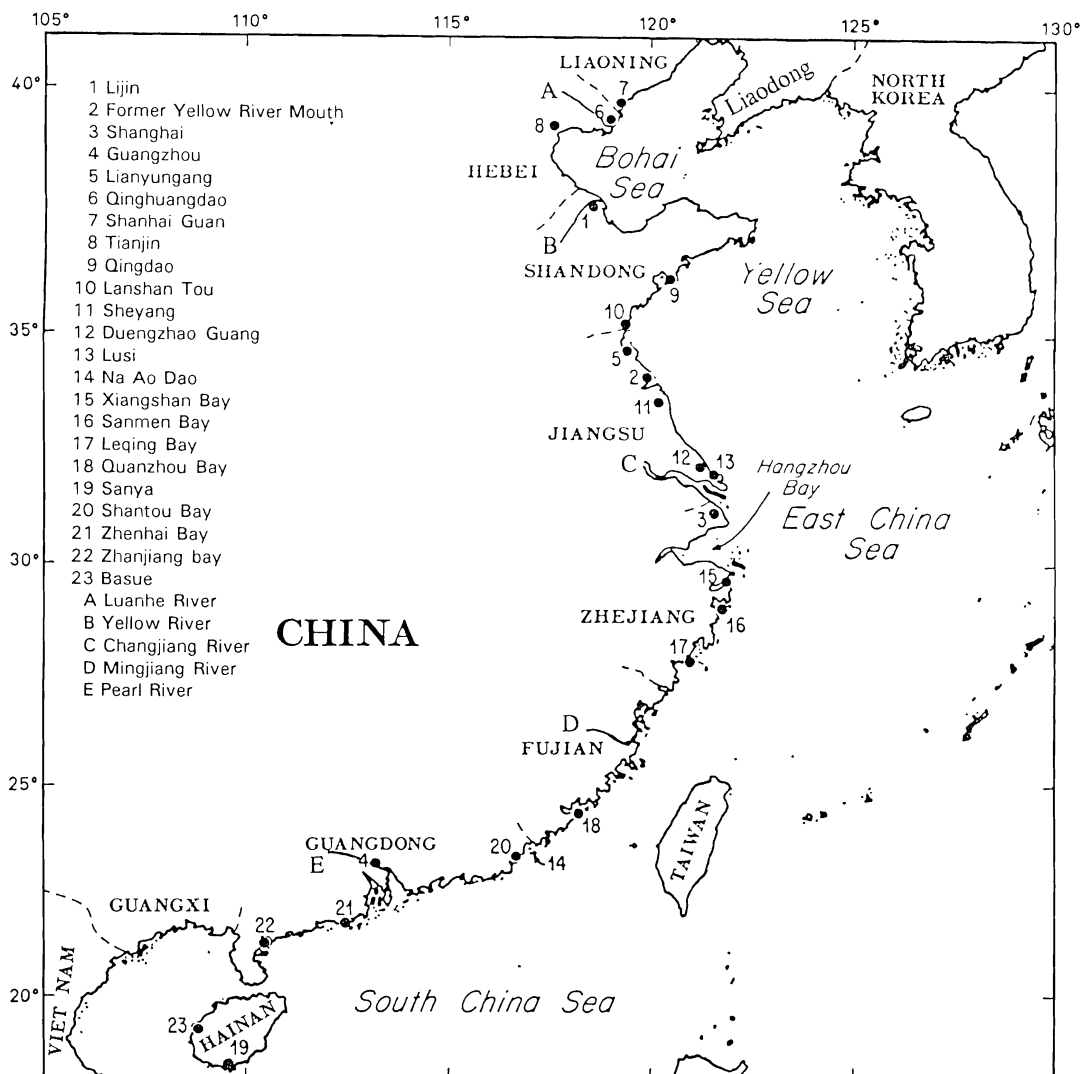


Figure 1. The coastline of China.

1992) under scenario A (Business as usual) which involves a projected sea level of 18 cm (4.5 mm/year) in 2030, and 66 cm (6.0 mm/year in 2100 with a high estimate at 110 cm and a low estimate at 31 cm). There are considerable uncertainties in these estimates. First, future sea-level rise is strongly dependent on the future rise of global mean air temperature which, in turn, is affected by future increases in concentrations of greenhouse gases, particularly CO_2 , from the energy sector which span a broad range of futures. As CO_2 emissions are chiefly of anthropogenic origin, their magnitude depends strongly on socio-economic factors, such as population and economic growth, changes in economic structures, energy prices, and government policies which change greatly through time, and are difficult to predict with precision. A second uncertainty is the stability of the West Antarctic Ice Sheet, the world's only marine based ice sheet to survive the last glaciation. Owing to its large volume it would, if disintegrated and melted, raise global sea level about

6 m. However, the relative stability/instability of the West Antarctic Ice Sheet in the last interglacial and in the future under conditions of continued global warming is still poorly known, and there is no answer yet on this issue. Third, recent improved knowledge of the emission and behaviour of greenhouse gases may modify previous estimates of the rate of global warming. For example, global emissions of methane from rice paddies may prove less than previously estimated. The cooling effect of airborne particles from sulphur emissions may have offset a significant part of the greenhouse warming in the northern hemisphere during the past several decades. It is possible therefore, that the previous global warming rate may be reduced, as may the rate of global sea-level rise.

HUMAN IMPACTS AND COASTAL RESPONSES

Sea-level rise will increase the water depth of the submarine coastal slope, and gradually decrease the winnowing ac-

Table 1. Neotectonic movements along coast zone of China (from LU and DING, 1994).

Coast location	Type and value	Total Sum of Neotectonic Movement since Pliocene			Vertical Variation during Holocene		
		Uplift (m)	Subsidence (m)	Annual Rate (mm/a)	Uplift (m)	Subsidence (m)	Annual Rate (mm/a)
Liaodong peninsula	50-100			0.02-0.03	4-6		0.5-1.0
Lower Liao River delta			500-3000	0.12-0.25		5-10, 25	0.3-1.0
Eastern Hebei & western Liaoning	100-200			0.03-0.06	4,5-10		0.3-0.5
West Bohai Bay & Laizhou Bay			500-700	0.18-0.25		10-20 (Bohai Bay)	1.5-2.5
Yellow River delta						0-10 (Laizou Bay)	0.5
Shandong peninsula	50-200			0.02-0.06		Stable	±0.1
					+		<0.5 (Qingdao, Penglai)
North Jiangsu			100-300	0.03-0.1		0-5	±0.5
Changjiang River delta			20-500	0-0.2		<10	0.5
Zhejiang & northern Fujian	300-500			0.1-0.2			0.3-1.0
Eastern Guangdong	150-250			0.05-0.1			
(1) Lingjiang & Oujiang River		+		(1) 0.5-1.5			
(2) Mingjiang River				(2) 0.1-0.2			(1)(3) 0.5-1.0
(3) Jiulongjiang River		+		(3) 0.1-0.3		+	(5) 0.5
(4) Hanjiang River				(4) 1.0-2.0			
(5) Pearl River		+		(5) 0.5-1.5			
Guangxi Beihai & Hepu		+		0.2-0.3			
Hainan Island, North			400-600	0.15-0.2		-2--10	0.2-0.5
Hainan Island, South		+		0.05-0.2			
Taiwan Island (East)	1,500			3-5, 5-7	40-50		6.2

tion of waves on submerged coastal sediments, but erosion on upper beaches by breaking waves is likely to be enhanced. At the same time, the slopes of river beds will be reduced decreasing fluvial sediment discharges. On the other hand, human impacts involving diversion of river discharge for urban water supply, and the construction of dams for irrigation, have decreased sediment discharges enormously. In the Luanhe River for example, the original water discharge was $4.19 \times 10^9 \text{ m}^3$ with a total sediment supply of 2.22×10^7 tonne. After diversion, the water discharge of $3.55 \times 10^8 \text{ m}^3$ for water supply to Tianjin city reduced discharge and sediment supply, which fell to only 1.03×10^6 tonne. As a consequence, the delta coastline of the Luanhe River has been retreating at a rate of 17.4 m/year since 1988 (QIAN, 1994). The same situation has happened in the Yellow River; the annual sediment discharge of the Yellow River has decreased from 11×10^8 tonne to be 9.5×10^8 tonne as the annual water discharge now is only $3.79 \times 10^8 \text{ m}^3$, a reduction associated with water diversion for irrigation along its middle and lower reaches. It is estimated that more than $1.5 \times 10^{10} \text{ m}^3$ of water per year has been taken from the Yellow River for irrigation over the last decade, and with the volume of water about 1.74×10^8 tonnes of sediment per year. The increasing diversion of water for irrigation and other purposes over the next decade will withdraw considerable amounts of sediment from the Yellow River. As a result of both natural and human influences, a reduction in sediment supply to the coastal zone is a world-wide phenomenon, particularly when combined with the increasing frequency of storm surges and El Niño events accompanying the sea-level rise. Beach erosion and sand-barrier retreat are the result of stronger hydrodynamic processes and a smaller volume than previously of sediment supply to the coast. Directly-monitored data in-

dicate that sandy-coast retreat is occurring at a rate of 1.5-2 m/year on average along the Shandong and Liaodong peninsula coasts even with sediment supply from many small rivers along the Bohai Sea and the Yellow Sea; the 2-5 m/year average value in the Zhejiang and Fujian coasts along the East China Sea is exacerbated by the mining of sands along this coast. Along the red-sand terrace coast in Fujian and Guangxi in the East and South China Seas, the net rate of coastline erosion is 0.7-1.5 m/year. Even though most bedrock (granite and gneiss) coasts experience limited erosion, several parts exhibit as much as 0.07-0.1 m/year retreat.

By using the Bruun role, the response of major tourist beaches in Dalian, Qinghuangdao along the Bohai sea, Qingdao along the Yellow Sea, Behai and Sanya along the South China Sea, has been estimated. It is predicted that they will lose 13-66% of their present area while sea level is continually rising to 50 cm higher by the year 2100 (Table 2). Beach protection and beach nourishment provide the principal management solutions to these problems.

The response in the muddy tidal flat coasts is more complex and potentially more serious, as the major types of muddy flat coasts are distributed along the lower reaches or delta plains of larger rivers in the areas of tectonic subsidence. Even within tectonically uplifted regions, such as the Zhejiang, Fujian and Guangdong coast zone, there are embayed tidal flats which experience significant subsidence (WANG, 1983, 1994).

Background subsidence of muddy coasts has been occurring since the Tertiary and the total subsidence is quite high. Additional factors of overpumping groundwater for freshwater supply and irrigation, and overloading by constructions (the larger cities in China are located mostly in river mouth areas along the coastal zone) exacerbate modern subsidence of

Table 2. The predicted net results of beach erosion in China by 0.5 m of sea-level rise during the next century (from WANG and WU, 1995).

Location	Estimated Beach Response of 0.5 m Sea Level Rising												
	Modern Beach				Natural Flooding				Beach Erosion				Sum Value
	Length (m)	Average Width (m)	Relative Height (m)	Areas (m ²)	Beach Retreating (m)	Loss of the Area (m ²)	Rate of Loss (%)	Beach Retreating (m)	Loss of the Area (m ²)	Rate of Loss (%)	Beach Retreating (m)	Loss of the Area (m ²)	
Dalian													
Xing Hai Park	2,125	68.5	6.1	145,613	6.8	14,450	9.9	26.5	56,314	38.7	33.3	70,764	48.6
Dongshan Hotel	510	42.4	3.8	21,645	7.4	3,774	17.4	15.8	8,078	37.3	23.2	11,852	54.7
Grand Beach	756	56.3	3.8	42,560	7.9	5,972	14.0	24.7	18,674	43.9	32.6	24,646	57.9
Summary	3,391	61.9		209,818	6.8-7.9	24,196	11.5	15.8-26.5	83,066	39.6	23.2-33.3	107,262	51.1
Qinghuangdao													
Bei Dai He	7,850	87.1	5.9	683,456	8.7	68,295	10.0	48.8	383,080	56.1	57.5	451,375	66.1
West Xiang He Zhai	3,124	223.6	6.4	698,466	6.7	20,930	3.0	41.5	129,650	18.6	48.2	150,580	21.6
Shandong Bao	756	88.2	3.5	66,672	7.5	5,670	8.5	25.4	19,202	28.8	32.9	24,872	37.3
Summary	11,730	123.5		1,448,594	6.7-8.7	94,895	6.6	25.4-48.8	531,932	36.7	32.9-57.5	626,827	43.3
Qingdao													
Qingdao Bay	1,356	72.8	6.0	98,650	8.5	11,526	11.7	37.9	51,455	52.2	46.4	62,981	63.9
Hui Quan Wan	1,124	70.6	6.0	79,356	7.0	7,868	9.9	38.6	43,386	54.7	45.6	51,254	64.6
Fu Shan Sou Mouth	1,625	193.1	5.4	313,857	8.9	14,462	4.6	26.4	42,932	13.7	35.3	57,394	18.3
Summary	4,105	119.8		491,863	7.0-8.9	33,856	6.9	26.4-38.6	137,773	28.0	35.3-46.4	171,625	34.9
Beihai													
Wai Sha	2,530	60.8	6.2	153,750	5.8-9.5	17,254	11.2	27.9	70,587	45.9	33.7-37.4	87,841	57.1
Da Dun Hai	5,516	258.4	5.0-9.2	1,425,588	5.4-9.8	41,926	2.9	48.1	265,335	18.6	53.5-57.9	307,261	21.5
Bai Hu Tou	5,165	183.2	5.0-7.2	946,363	5.4-8.7	36,457	3.9	45.2	233,458	24.7	50.6-53.9	269,915	28.6
Summary	13,211	191.2		2,525,701	5.4-9.8	95,637	3.8	27.9-48.1	569,380	22.5	33.7-57.9	665,017	26.3
Sanya													
Da Dong Hai	2,650	81.5	5.9	215,905	7.9	20,935	9.7	12.2	32,330	15.0	20.1	53,265	24.7
Ya Long Bay	8,880	166.1	5.4-13.4	1,475,184	6.8-9.8	74,592	5.1	12.7	112,776	7.6	19.5-22.5	187,368	12.7
San Ya Sand Bar	16,360	296.2	3.3-11.6	4,846,024	5.6-10.2	137,654	2.8	43.6	713,296	14.7	49.2-53.8	850,950	17.5
Summary	27,890	234.4		6,537,113	5.6-10.2	233,181	3.6	12.2-43.6	858,402	13.1	20.1-53.8	1,091,583	16.7
Total	60,327	185.9	3.3-13.4	11,213,085	5.4-10.2	481,765	4.3	12.2-48.8	2,180,553	19.4	20.1-57.9	2,662,314	23.7

Table 3. Land subsidence (mm) 1985–1991 in the Tianjin area (from HAN, 1994).

	Tianjin City	Tanggu Harbour	Hangu, NE Coast	Dagong, SE Coast
1975	130	144		
1980	89	36		
1981	119	140		
1982	94	188		
1983	71	116		
1984	58	137		
1985	86	100		
1986	62	54	40	41
1987	43	46	46	41
1988	24	29	53	25
1989	18	44	68	56
1990	15	19	66	18
1991	17	24	38	45

these areas. These processes have compacted sediments and caused rapid relative sea-level rise, especially in the delta plain coasts, where the major muddy flat coasts in China are located. Four examples are given below.

- (1) Tianjin city and harbour are located in the northern part of the North China plain. They can be taken as an example of sites on the old Yellow River delta in west Bohai Bay. The rate of land subsidence is shown in Table 3 (from HAN 1994). Recently, expansion of the city area has been controlled in order to decrease the rate of subsidence, but in the coastal area to which much of the growth has been redirected, particularly around Tanggu and Hangu, the average rate of subsidence during 1989–1991 was 29 mm/year and 64 mm/year (HAN, 1994). Including land subsidence, the relative sea-level rise was 24.5 mm/year between 1956 and 1985 (REN, 1994), but reached 50 mm/year between 1983 and 1988 with additional land subsidence. The 1983–88 average rate is far greater than the average rate of sea-level rise either of global or for the whole coast of China. At present sea levels, the frequent high water can inundate the area below the 2 m contour and can flood the area below 3 m contour line where high tide coincides with a storm surge which may reach 1 m in height (HAN, 1994). As a comparison, the rate of land subsidence in the modern Yellow River delta was 3–4 mm/year between 1956 and 1985, a reflection of the limited economic and urban development in that area at the time; the average rate of relative sea-level rise was 4.5–5.5 mm/year during the same period (REN, 1994). The rapid increase of relative sea-level rise here has brought disaster to the rapid development of Shengli oil field and the surrounding agriculture.
- (2) The North Jiangsu coastal plain was formed by the coalescence of the ancient Yellow and Changjiang River deltas. It is the most extensive mud flat coast in China. The coast is in an early stage of economic development and may this represent the natural condition of such environments. Recent sea-level rise is 2–3 mm/year here according to tide-gauge records. This is particularly worrying because any rise of sea level here will have severe

Table 4. Land subsidence of Shanghai and its vicinity (from LIU, 1994).

Time Period	Subsidence Rate (mm)	
	Annual Average	Annual Maximum Average
1921–1948	24.0	42
1949–1956	40.0	96
1957–1961	110.0	287
1962–1965	69.0	164
1966–1992	2.5	19.3

results on account of the extensive low-lying nature of this coast. For example, the strong tropical storm from August 29 to September 1, 1992, which was superimposed on a high astronomical tide, caused the water level to rise 2–3 m above the normal maximum flood tide level. This disaster resulted in the death of 300 people and an economic loss of about 9.2 billion yuan.

- (3) Shanghai is representative of the situation at the Changjiang River mouth. This delta is the largest urban area in China with a large population and developing economy. Both overpumping of groundwater and overloading by constructions has caused serious land subsidence and rapid relative sea-level rise, even though artificial recharge of aquifers has been regarded as successful (Table 4, from LIU 1994). But the lowland suffers from storm surges and floods, phenomena which are increasing in both frequency and magnitude as a result of recent relative sea-level rise. The relative sea-level rise is 6.5–11.5 mm/year, which had caused saline water intrusion, floods which have extended 170 km upstream from river mouth, and harmed industry, agriculture and the daily life of Shanghai residents.
- (4) Pearl River (Zhujiang) delta. The ground subsidence of 0.5–1.5 mm/year in the Pearl River delta is less than for other deltas, but increased human influences, such as the reclamation project to unite embankments and the damming of distributaries, have affected river-bed and water-level characteristics. Thus, there are two types of seasonal change in tidal level: estuary type and coastal type. The amplitudes of annual sea-level change has varied by 20–30 cm over the past 30–40 years. Relative sea-level rise has occurred at a rate of 1–2 mm/year since 1955 (CHENG and YANG, 1994). Rising sea-level effects on the estuary environment have caused the submergence of a large area of lowland, waterlogging of construction foundations, saline-water intrusion harming irrigation and drainage, threatening the town, cities, airports, and harbours along the coast.

The above examples indicate the effects and spatial variations of sea-level rise in the muddy coasts, particularly those affected greatly by human activity. Coastal responses differ from sand to rocky coasts. Coastal erosion is very variable depending on the coastal sediment supply, which is mainly from larger river inputs. Under conditions of continued rise of sea level, the frequency and amplitude of storm surges has been enhanced. This has caused coastal erosion, lowland flooding over coastal marshes, flats, and fishing villages; it

has extended saltwater intrusion inland to harm coastal aquifers, agricultural irrigation and freshwater supply, and has also prevented the effective dispersal of flood waters and urban pollutants. The risk to China's coastal zone is manifest, as a total of 11 provinces and more than 60% of larger cities in China are located in the coastal zone, about one half of total annual agricultural products are from the coastal region, and the height to which most areas of the coastal plain rise is less than 2 metres above present sea level. A systematic study of the effects of sea-level rise along the whole coastal zone of China, especially the river mouth area and the lowland coasts, is required to understand properly the challenge of this situation and to solve the problems step by step.

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