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## RESEARCH ARTICLE

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## The variations of sediment transport patterns in the outer Changjiang Estuary and Hangzhou Bay over the last 30 years

Dongfeng Xie<sup>1</sup> , Cunhong Pan<sup>1</sup>, Xiuguang Wu<sup>1</sup>, Shu Gao<sup>2</sup> , and Zhengbing Wang<sup>3,4</sup> 

## Key Points:

- Long-term and short-term variations of suspended sediment transport were delineated
- The underlying physics for the observed variations were investigated
- A sediment flux model is proposed to explain and predict the morphological evolution trends

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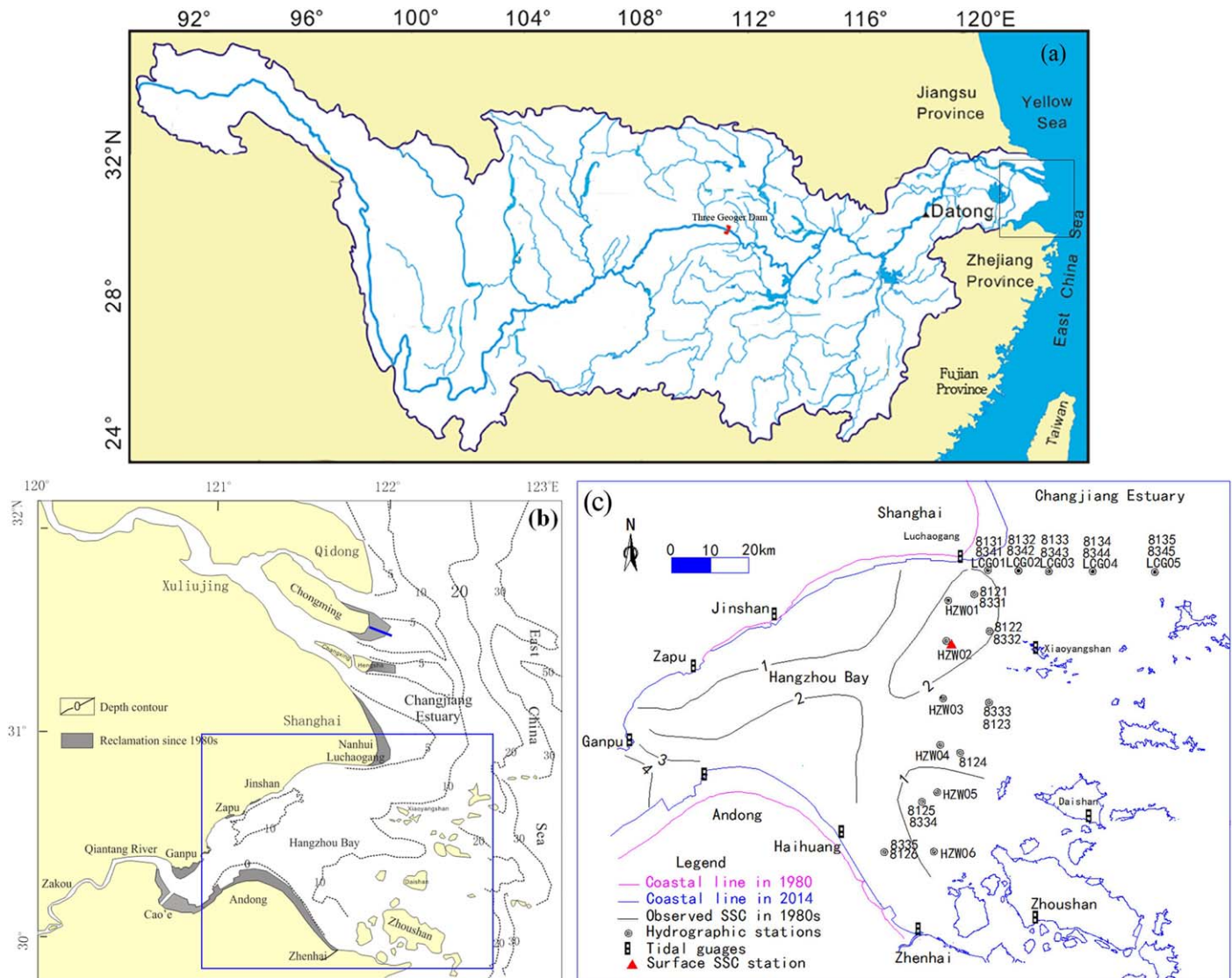
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**Abstract** The research objective is to investigate the variations of sediment transport in outer Changjiang Estuary and adjacent Hangzhou Bay, induced by the decline of Changjiang River sediment discharge and massive land reclamation in the last three decades. A synchronous hydrographic survey was conducted along two transects (at the bay-mouth and outer Changjiang Estuary, respectively) during the spring-neap tides of January and July 2014. The results show that the suspended sediment grain size, current velocity, suspended sediment concentration (SSC), and the water and sediment fluxes varied with the tidal cycles. Quantitative correlations with the tidal range were found for SSC and fluxes. These data have been compared with those at the same hydrographic stations in the summer and winter of the early 1980s. Along the outer Changjiang Estuary transect, the SSCs and sediment fluxes decreased in the winter, but no apparent changes occurred in the summer. The SSCs in the northern Hangzhou Bay decreased in both summer and winter, while the southern bay mouth has evolved from a low SSC region to a high SSC region. The findings clarify that the SSC and sediment flux changes in this area have only an indirect connection to the dramatic riverine sediment decline, because the sediment resuspension by the strong tidal currents provided a major source. At the present stage, the impact of the riverine sediment decline is insignificant for the SSC variation off the Changjiang River mouth. Finally, a sediment flux model is proposed to explain and predict the morphological evolution trends.

## 1. Introduction

Suspended sediment transport plays an important role in determining the geomorphology, ecology, and water quality characteristics [Kennedy, 1984; Dyer, 1986; Van Rijn, 1993; Trenhaile, 1997]. With the intensified human activity in the catchment basin, dam building in particular, it becomes a common phenomenon that the estuarine sediments entering the sea have been reduced in recent decades. As a result, rapid changes in estuarine environments have taken place including sediment transport adjustment, coastal retreat, changing benthic environments of estuaries, and vanishing coral reefs [e.g., Wiegand, 1996; Milliman, 1997; Syvitski et al., 2005; Yang et al., 2005; Gao and Wang, 2008].

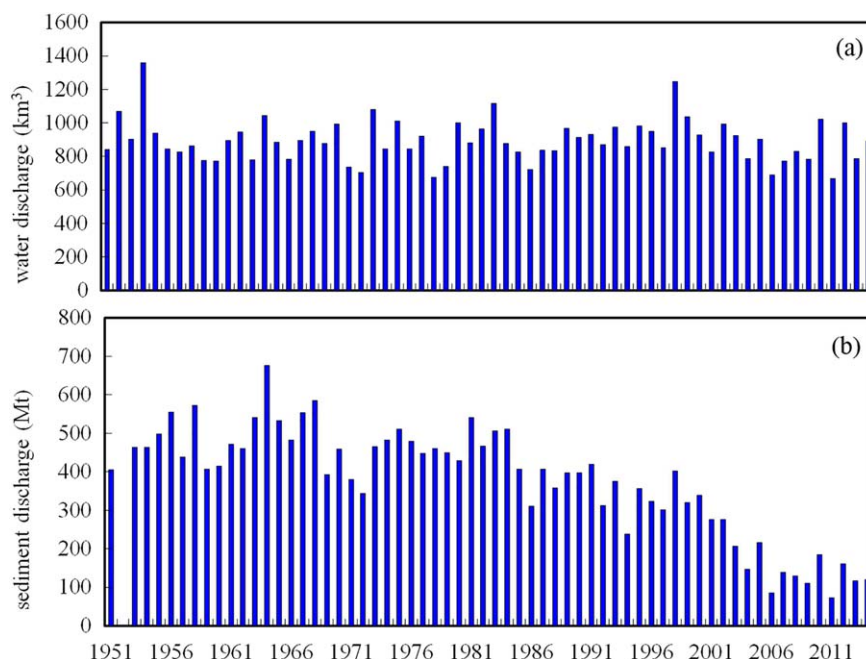
Changjiang River used to be one of the largest rivers in the world, with the third length (6400 km), the fifth runoff (925 km<sup>3</sup> per year), fourth sediment load (486 Mt per year), and a drainage area of  $1.81 \times 10^6$  km<sup>2</sup> [Eisma, 1998] (Figure 1). For the last 30 years, the sediment load from Changjiang River has evidently decreased due to water and soil conservation in the drainage area, together with reservoir and dam constructions, especially the Three Gorges Dam (TGD) closure and operation in August 2003 [e.g., Gao and Wang, 2008; Yang et al., 2014]. The annual sediment discharge has decreased from more than 400 Mt per year before the 1980s to below 150 Mt per year after 2003, with the discharge in some dry years (e.g., 2006 and 2011) falling below 100 Mt (Figure 2). In recent years, progradation rates of the tidal wetlands in Changjiang Estuary have slowed down and even turned to degradation and the subaqueous delta has been eroding [e.g., Yang et al., 2011]. Several studies have focused on the long-term trends and spatial patterns of suspended sediment concentration in Changjiang Estuary, based on multiyear time series of SSCs at various stations from twice-daily surface water sampling in the estuary [e.g., Li et al., 2012; Dai et al., 2013; Yang et al., 2015]. It is clear that the suspended sediment concentration (SSC) in the inner Changjiang Estuary, mainly controlled by river discharge, has evidently decreased by as much as 56%. The SSCs in the outer Changjiang Estuary are controlled by the interaction of discharges and tides. There are apparent cyclic



**Figure 1.** Sketch map of the study area. (a) Changjiang catchment basin, (b) Map of the Changjiang Estuary and Hangzhou Bay; (c) layouts of hydrographic stations. The blue line east of Chongming Island in Figure 1b depicts the approximate location of the cross-shore profiles in Figure 14. The observed iso-SSC lines in 1980s in Figure 1c are based on Han et al. [2003].

variations such as tides, spring-neap cycle and dry-flood seasons, for sediment transport. Subsequently, the vertical profiles of SSC can be complex temporally and spatially varying [Milliman et al., 1985; Chen et al., 1990, 2006; Gao and Wang, 2008]. Furthermore, it has been found that individual differences constrained by regional conditions may be vital [Milliman et al., 1985; Su and Wang, 1989; Song et al., 2013; Liu et al., 2014]. Hence, SSC changes in surface water or SSC profile comparisons from different hydrographic stations are inadequate to fully understand the sediment transport trends in the estuary [Liu et al., 2014].

Immediately to the south of the mouth of the Changjiang River, the funnel-shaped Hangzhou Bay is located, which is the outer extremity of the Qiantang River. Hangzhou Bay is one of the largest estuaries along the East China Sea coastlines, covering an area of approximately 4800 km<sup>2</sup>. The sediment deposited in Hangzhou Bay mainly comes from Changjiang River: the Changjiang sediment disperses toward the south after entering the sea [Su and Wang, 1989; Chen et al., 1990; Han et al., 2003]. With the sediment input from Changjiang River, the sedimentation rate reached about 11 mm per year [Xue, 1995]. With the decline of Changjiang sediment discharge, the suspended sediment transport and morphological evolution in Hangzhou Bay may be profoundly influenced. In addition, large-scale land reclamations have taken place in Hangzhou Bay and the Qiantang River areas. The configuration of the estuary has been changed to a certain



**Figure 2.** Temporal variations of (a) annual water and (b) sediment discharges at Datong station in 1951–2014 (data from the Changjiang River Hydraulic Engineering Committee).

extent, due to the advance of the coastlines (Figure 1). Hence the sediment transport in Hangzhou Bay has been influenced by both sediment supply variation and human activities over the last 30 years. However, little attention has been paid to the variations and underlying mechanisms of suspended sediment transport in the previous studies for this area.

In this study, synchronous hydrographic observations at 11 stations located at the Hangzhou Bay mouth and along the Luchaogang transect at the outer Changjiang Estuary, the interface between Changjiang Estuary and Hangzhou Bay, were carried out during spring tides, intermediate tides, and neap tides in the winter and summer of 2014. The synchronous hydrographic data at the same stations in the summer of 1981 and in the winter of 1983 have been collected as well. These data sets allow a detailed comparison between sediment transports before and after the apparent decrease of Changjiang River sediment discharge. The aims of the present contribution are to: (1) quantify the changes of SSCs and sediment fluxes in the outer Changjiang Estuary and the Hangzhou Bay mouth areas, (2) analyze the underlying physics for the observed variations, and (3) bridge the relationships between suspended sediment transport changes and the seabed morphological evolution trends.

## 2. Study Area

Hangzhou Bay, the outer reach of the Qiantang Estuary, is a typical funnel-shaped bay, whose width is about 100 km at the mouth and narrows to about 20 km some 100 km to the west. The bay is situated along a mesotidal coast. Qiantang is by far the most important river in discharging water and sediment directly into Qiantang Estuary, with an average runoff of 30 km<sup>3</sup> per year and an average sediment load of 8 Mt per year, consisting mainly of coarse silt to fine sand [Han *et al.*, 2003; Pan and Huang, 2010]. The semi-diurnal tide is the main driving force behind the horizontal water flow in the Hangzhou Bay, with the M<sub>2</sub> constituent being the dominant tidal component [Editorial Committee for Chinese Harbors and Embayments (ECHE), 1992]. The tidal range is 2~4 m at the northern mouth and 4~6 m further upstream. In the southern mouth, the tidal range is 1~2 m, smaller than the north, due to the hindering of the Zhoushan archipelago. Tidal currents are strong and the maximal flood velocity exceeds 3.0 m/s. Hangzhou Bay has an average depth of about 10 m. Its bottom topography is relatively flat except the 25 km stretch of deep channel along the north shore. Sediment in Hangzhou Bay is predominantly fine and medium silt which can be easily resuspended. Upstream from Jinshan, there is the largest river-mouth shoal in China, and it is

the best spot at which to watch the world famous Qiantang Bore (a tidal bore over 3 m high having semidiurnal tidal period).

Changjiang Estuary is situated immediately north of Hangzhou Bay. The part of the Changjiang Estuary downstream of Xuliujing has a pattern of three-order bifurcation and has four outlets into the sea (Figure 1b). Around half of the river's sediment is deposited in the river mouth area, and the rest is carried into the open sea and to the northern and southern coasts by littoral currents [Chen *et al.*, 1985]. Because of its overwhelming water and sediment discharges, Changjiang has important influences on both the hydrograph and the sedimentation in Hangzhou Bay. The sediment in Hangzhou Bay consists mainly of south-dispersing Changjiang River sediment after it enters the sea. With the sediment input from Changjiang River, Hangzhou Bay has been accreting with a rate of around 11 mm/yr [Xue, 1995]. There are direct exchanges of material between the northern Hangzhou Bay and Changjiang Estuary through the front of Nanhui shoal [Su and Wang, 1989; Chen *et al.*, 1990].

The wind speed in this area is highly variable with multiyear averages of 3.5–4.5 m/s. A maximum of 36 m/s recorded at the gauging stations [Group of Shanghai Coastal Investigation (GSCI), 1988; ECCHE, 1992]. Controlled by the monsoon climate, southeasterly winds prevail in summer, and northwesterly winds prevail in winter. The mean and maximum wave heights are 1.0 and 6.2 m, respectively, at the Changjiang delta front [GSCI, 1988], and 0.5 and 6.1 m, respectively at the Hangzhou Bay mouth [ECCHE, 1992; Han *et al.*, 2003].

### 3. Field Work, Data Collection, and Analytical Methods

#### 3.1. Field Work and Data Collection

A synchronous hydrographic survey was conducted at the bay-mouth transect and Luchaogang transect in January and July 2014, representing the dry and flood seasons, respectively (Table 1 and Figure 1c). The bay-mouth transect is located at the Hangzhou Bay mouth in the north-south direction, including six hydrographic stations. The length of the bay transect is about 100 km and the spaces between neighboring stations are around 10–15 km. The mean water depths at the six stations were around 10–13.5 m with the deepest at HZW04, as shown in Tables 2 and 3. The Luchaogang transect is located at the front of Luchaogang tidal gauge in the east-west direction, including five hydrographic stations. The length of this transect is 47.5 km and the distance between neighboring stations is around 10 km. The mean water depth at LCG05 was 14.5 m and those at the other four stations were 10–12 m. During both cruises, eleven ships were employed to ensure the synchronization of observed data. At all stations, tidal level, water depth, flow velocity, suspended sediment concentration, and suspended sediment grain size were measured.

To compare the variations of suspended transport, the stations in 2014 were set at the same locations as the observed stations in the summer 1981 and winter 1983 during the Zhejiang Coastal Zone Survey. The data from that survey were collected as well for this study. Since the suspended sediment concentration in the region, where the water depths exceed 15 m, is usually low, typically less than 0.5 kg/m<sup>3</sup> [e.g., Chen *et al.*, 1990; Wan *et al.*, 2009], the Luchaogang transect can represent the vast majority of the sediment flux exchanging between Changjiang Estuary and outer Hangzhou Bay. The changes of sediment load from Changjiang river in 1950~1980s were minor. After 2003, when the Three Geoges Dam was constructed, the

**Table 1.** The Measured Dates, and the River Discharge at Datong Station, the Tidal Ranges at the Luchaogang Station, and the Wind Conditions During Various Cruises

Cruises	Measured Dates	Daily Average Discharge (m <sup>3</sup> /s)	Sediment Discharges (×10 <sup>4</sup> t/d)	Tidal Range at Luchaogang (m)	Wind Conditions			
					Average Velocity(m/s)	Maximal Velocity(m/s)	dominant Direction	
Winter, 2014	Spring tide	2–4 Jan	11,533	7.97	3.88–5.10	3.6	5.8	W-N
	Intermediate tide	6–7 Jan	11,550	7.14	2.97–3.7	3.1	5.5	SE-E
	Neap tide	10–11 Jan	12,050	6.87	1.97–2.98	5.1	6.5	E
Summer, 2014	Spring tide	13–14 Jul	46,000	45.54	4.17–5.31	2.4	4.1	SE-S
	Intermediate tide	17–18 Jul	50,600	40.35	3.72–4.22	4.3	5.7	SSE
	Neap tide	20–21 Jul	53,550	33.57	2.21–3.20	2.7	3.8	ESE-SSE
Winter, 1983	Luchaogang transect	26–27 Dec	10,850	8.33	2.26–3.46	5.1	7.2	NW
	Bay-mouth	19–20 Dec	12,000	9.47	3.40–4.29	4.3	7	NE
Summer, 1981	Luchaogang transect	15–18 Jul	43,900	283.24	2.90–4.21	4.7	6.0	S-SE
	Bay-mouth	5–7 Jul	44,100	308.06	2.91–4.15	3.3	5.7	S-SE

**Table 2.** Tidal Average Values at Stations Across the Luchaogang Transect During Various Tides in 2014 and 1981/1983

2014 Cruises	Stations	LCG01		LCG02		LCG03		LCG04		LCG05	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Mean water depth (m)	12.1	11.86	10.7	10.56	10.6	10.36	11.3	11.06	14.4	14.26
	Mean SSC (kg/m <sup>3</sup> )										
	Spring tide	1.18	1.58	1.10	1.62	0.99	1.66	0.78	1.24	0.36	0.80
	Intermediate tide	1.05	1.53	0.73	1.15	0.69	1.08	0.78	0.75	0.30	0.78
	Neap tide	0.52	0.79	0.31	0.65	0.34	0.50	0.32	0.17	0.16	0.27
	Mean SSC at mean TR <sup>a</sup> (kg/m <sup>3</sup> )	0.7	1.2	0.5	1.1	0.5	1.0	0.5	0.7	0.22	0.6
1981/1983 Cruises	Stations	8131	8341	8132	8342	8133	8343	8134	8344	8135	8345
	Mean water depth (m)	9.81	10.63	8.88	9.80	8.85	9.06	9.35	9.77	12.74	13.10
	Mean SSC (kg/m <sup>3</sup> )	0.89	2.28	0.65	1.63	0.63	1.86	0.52	1.26	0.22	1.02
	Mean SSC at mean TR <sup>a</sup> (kg/m <sup>3</sup> )	0.7	2.0	0.55	1.7	0.6	1.6	0.55	1.2	0.22	1.3
	SSC variations	Insignificant	-40%	Insignificant	-41%	Insignificant	-38%	Insignificant	-41%	Insignificant	-53%

<sup>a</sup>TR denotes the tidal range at Luchaogang gauge station.

sediment load has declined dramatically. The observed data during 1981–1983 and 2014 can thus represent the characteristics before and after the dramatic decline of sediment load.

Both the summer and winter cruises in 2014 included spring, intermediate, and neap tide observations (Table 1). The measurements at all stations took place for at least a full tidal cycle (25 h). During the spring tide in the winter, the measurement period was 36 h. The flow velocity was measured by an Acoustic Doppler Current Profiler (ADCP), and SSC was measured hourly using an Optical BackScatter Sensor (OBS) instruments at the surface, 0.2 H, 0.4 H, 0.6 H, 0.8 H, and the bottom, respectively, where H is the water depth. The OBS instruments were calibrated against discrete water samples. The suspended sediment and water was sampled at the 0.6 H of various stations at the maximal flood and ebb, and high and low tides during various tides. The grain sizes were determined after sample drying. Meanwhile, the synchronous tidal level data were collected from more than 10 tidal gauges around the study area, including Luchaogang, Jinshan, Daishan, Zhenhai, Xiaoyangshan, and Xuliujing.

The measurement in the 1980s were carried out on 6–7 and 19–20 July 1981, 26–27 and 21–27 December 1983 for the bay-mouth transect and Luchaogang transect, respectively, when the tidal ranges at Luchaogang gauge were between 2.26 and 4.29 m, representing neap to intermediate tides, as shown in Table 1. The flow velocities were recorded by Ekman current meters, and the SSC was determined by taking water samples and through a process which involved filtering with preweighted paper filters and oven-drying. All water samples, as well as current measurements, were taken at 1 and 5 m below the water surface and at 1 m above the bottom. When water depth was less than 7.5 m, the 5 m sample was omitted, and when the water depth was more than 13 m, an additional sample at 10 m below the sea surface was taken.

The averaged Changjiang river discharges in January and July 2014 were 11,660 and 49,622 m<sup>3</sup>/s, respectively, while those in December 1983 and July 1981 of 11,380 and 44,642 m<sup>3</sup>/s, respectively. Although the top river discharges decreased by about 10% in the flood season and increased by about 20% in the dry season after the TGD construction [e.g., Xu and Milliman, 2009; Dai et al., 2016], and hence could influence the river plume slightly [Bai et al., 2014], the discharges during the cruises in the summer and winter in

**Table 3.** Tidal Average Values at Stations Across the Bay-Mouth Transect During Various Tides in 2014 and 1981/1983

2014 cruises	Stations	HZW01		HZW02		HZW03		HZW04		HZW05		HZW06	
		Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter	Summer	Winter
	Mean water depth(m)	11.6	11.36	11.6	11.46	10.6	10.39	13.4	13.21	13.1	12.92	11.8	11.64
	Mean SSC (kg/m <sup>3</sup> )												
	Spring tide	1.36	1.64	1.76	1.87	1.40	2.67	0.95	2.26	1.36	2.17	1.47	2.82
	Intermediate tide	1.40	1.36	1.63	1.84	1.45	2.26	1.01	1.96	1.34	1.89	1.97	2.86
	Neap tide	0.53	0.9	0.72	0.96	0.51	1.12	0.28	0.81	0.37	0.82	1.15	1.34
	Mean SSC at mean TR <sup>a</sup> (kg/m <sup>3</sup> )	0.9	1.3	1.2	1.5	0.9	2.0	0.6	2.1	0.7	1.6	1.25	2.3
1981/1983 cruises	Stations	8121	8331	8122	8332	8123	8333	8124	/	8125	8334	8126	8335
	Mean water depth (m)	9.7	10.13	11.09	11.27	9.98	10.36	11.21	/	12.26	13.78	7.01	9.31
	Mean SSC (kg/m <sup>3</sup> )	1.79	2.67	1.75	2.46	1.73	1.45	1.05	/	0.99	0.92	2.32	1.13
	Mean SSC at mean TR <sup>a</sup> (kg/m <sup>3</sup> )	1.3	2.6	1.6	2.4	1.2	1.5	0.8	/	0.85	0.9	1.9	1.3
	SSC variation	-31%	-50%	-25%	-38%	-25%	33%	-25%	/	-18%	78%	-34%	77%

<sup>a</sup>TR denotes the tidal range at Luchaogang gauge station.

2014 were comparable with those in the same seasons of 1981 or 1983. Regarding the distance of 640 km from Datong to the mouth, the transmit time from Datong to the mouth is around 10 days. Such time lag could not have led to differences in the condition in the two time periods.

Wind conditions were recorded using aerovanes at HZW05, LCG03 during the winter and summer cruises in 2014 and at all stations during 1980s cruises. No strong winds during various cruises in 2014 and 1980s, except a maximum wind velocity of 7.2 m/s occurred for only 2 h during the observation of Luchaogang transect in the winter 1983. All the field data were thus obtained under normal weather conditions.

Furthermore, an OBS was set at the water surface near HZW02 to record the surficial SSC variations continuously for one month in each season in 2014, in order to compare the seasonal changes of SSC in the study area. The observation was conducted in April, July, October, and December 2014. A longer-time continuous observation was difficult due to the instrument maintenance caused by the high SSC, seaweed, and busy navigations, etc.

### 3.2. Analytical Methods

To examine the tidal influences, the relationship between flood/ebb-averaged SSC, i.e., the averaged SSC over flood or ebb period, and tidal ranges were analyzed. Regression analysis shows that the tidal ranges at Luchaogang gauge exhibit a good linear relationship with those at other gauges in the outer Changjiang Estuary and Hangzhou Bay, with all correlation coefficient ( $R$ ) larger than 0.97 and probability-value ( $p$ ) less than 0.001. Therefore the tidal range of Luchaogang gauge was chosen to set up the relationships between SSC and tidal ranges. The mean SSCs were calculated by the time averaging over a complete number of tidal cycles of spring, intermediate, and neap tides. The mean SSCs at the mean tidal range of Luchaogang station (around 3.50 m) during various cruises were obtained by interpolation of the scatters of SSCs versus TR.

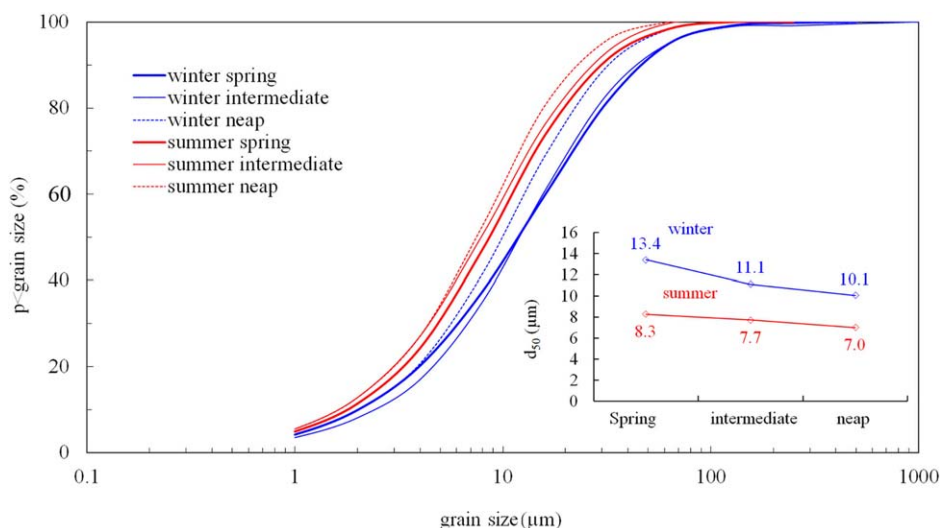
The water and sediment fluxes were calculated for various tides of each cruise, with water flux being the product of the cross-sectional area and mean velocity, and sediment flux being the product of water flux and SSC. The fluxes were calculated per layer and then integrated over the vertical profiles. We calculated the fluxes based on intratidal variations, hence the horizontal gradient is not important and the diffusive flux is much smaller than the advection-flux. The water and sediment fluxes over each tidal cycle were obtained by summing the hourly data. For the cross-section area calculation, the representing distance of each station was defined as the sum of half distances between the station and its two neighboring stations. If the station was located at the most seaward, like LCG05, then the seaward distance was assumed to be half distance of the station and its neighboring station. If the station was near the coastline, like HZW01 and HZW06, then the shoreward distance was the distance between the station and the coastline. In this way, the fluxes at the Luchaogang transect represents a length of 57 km, and the length represented by the bay-mouth transect is around 97 km in 2014 and 1980/1983, despite it was linear in 2014 while arc-shaped in 1981 and 1983. Despite the discrepancy of the transects in 2014 and the 1980s, both of them enclose the whole mouth and thus the whole fluxes entering or leaving Hangzhou Bay. As mentioned above, the water depth at the east end of the Luchaogang transect was about 15 m, and the SSC eastward was very low. The transect can thus represent the sediment exchanging flux between the Changjiang Estuary and Hangzhou Bay.

## 4. Results

### 4.1. Suspended Sediment Grain Size

The nature of the suspended sediments plays a significant role in sediment transport and estuarine biogeochemistry. The grain-size distribution of the sediment affects the sorption of elements, and organic matter, and water content of deposits, subsequently exerts a major influence on marine chemical cycles [e.g., Dyer, 1986; Uncles *et al.*, 1998; Jahnke, 2005; Yang *et al.*, 2008]. Suspended sediment in the area were mainly composed of well-sorted fine-grained silt or clay, with the medium grain size ( $d_{50}$ ) ranged between 6.7 and 15.7  $\mu\text{m}$ , and the sorting coefficient ranged between 1.32 and 1.86 in the winter cruise, and between 6.3 and 10.2  $\mu\text{m}$ , and 1.33 and 1.73, in the summer cruise.

There were no fining or coarsening trends along the two transects. However, the sizes of the suspended matter varied with tidal stage and seasons. Normally, the grain sizes were finer during neap tides than during spring tides, and in summer than in winter. Taking the sediment matter at HZW01 as an example, the



**Figure 3.** Grain-size distribution of suspended sediments during various tides in 2014 at station HZW01. The figure at the lower right corner shows the averaged  $d_{50}$  during the spring, intermediate and neap tides in the winter and summer.

averaged  $d_{50}$  were 8.3, 7.7, and 7.0  $\mu\text{m}$ , during spring, intermediate, and neap tides in the summer 2014, respectively; whereas they were 13.4, 11.1, and 10.1  $\mu\text{m}$  in the winter. Figure 3 illustrates the cumulative frequency curves at various tides and seasons at HZW01. As a whole, the averaged grain size at the 11 stations was 7.9 and 9.6  $\mu\text{m}$  during the summer and the winter cruises, respectively. A difference of 20% between the two seasons is observed. Similar variation patterns of the suspended sediment grain sizes were found at the offshore of Changjiang Estuary based on the field data in 1982 [Milliman *et al.* 1985].

With respect to the spring-neap cycle, the tidal currents were stronger during spring tides than during neap tides. As a consequence, more coarse sediments could be suspended. In winter, the wind waves could resuspend more coarse sediment from the seabed, while in summer the Changjiang River transports a large amount of fine sediment into the sea.

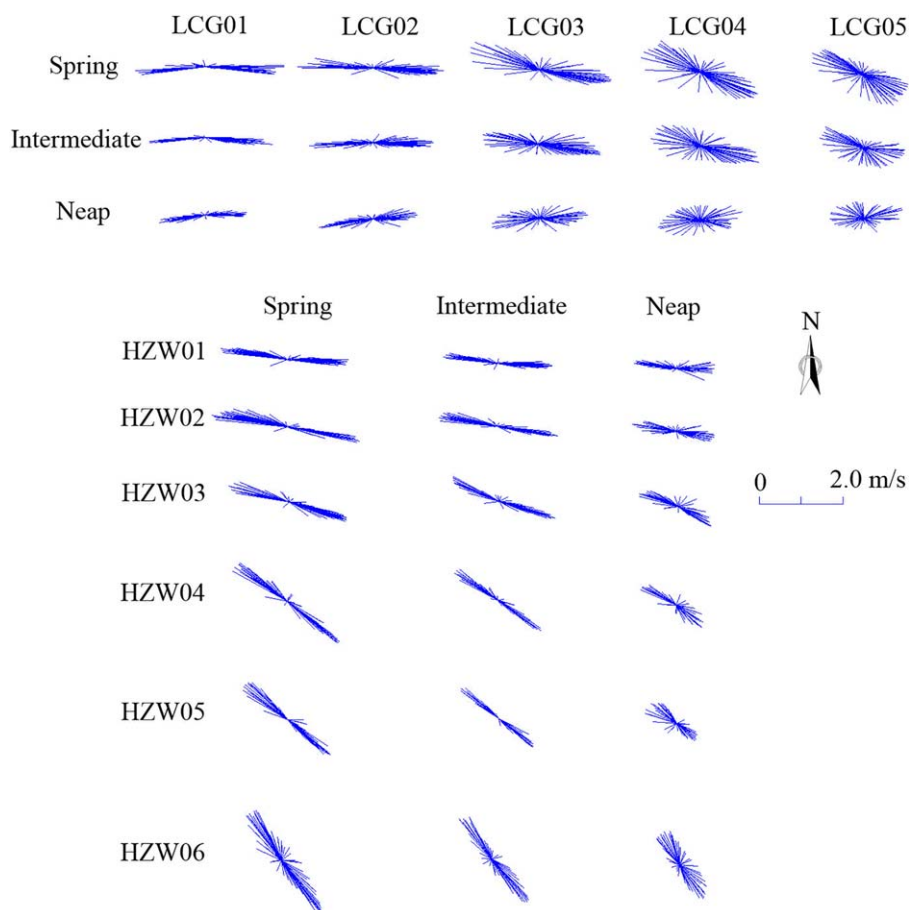
After the TGD construction, the sediment has a fining trend downstream, because both coarse and fine-grained sediments are trapped in Three Gorges Reservoir, and only fine-grained portions escape downstream [Yang *et al.*, 2014]. Regrettably, the data of sediment grain size in the 1980s were not available. This hindered a comparison of sediment grain sizes in this area during the cruises of 2014 and the 1980s.

#### 4.2. Flow Velocity

The flow field was largely controlled by the plan configurations of the estuaries, especially hindered by the archipelago in the southeast of the Hangzhou Bay [e.g., Cao *et al.*, 1985; Su and Wang, 1989; Xie *et al.*, 2009, 2013a]. In Hangzhou Bay mouth, the rectilinear current dominated, while along the Luchaogang transect rectilinear currents in the shoreward part (LCG01, LCG02) gradually translated to be rotary current seaward (LCG03, LCG04, LCG05), as shown in Figure 4. Generally, from spring tides to neap tides, the current velocities gradually slowed down, and they were larger in the summer than in the winter. Similar current patterns were also found in the data of 1980s. Because the measured data in 2014 covered larger tidal ranges, and is of a longer duration, only the flow velocity in 2014 is presented.

In the bay mouth, the flood currents were dominating at HZW01 to HZW05. During the spring tides of the summer, the maximal depth-averaged velocities of the flood and ebb tides being 1.71–2.15 m/s and 1.38–1.85 m/s, respectively, while during the spring tides of the winter, they were 1.34–1.82 m/s and 1.33–1.77 m/s, respectively. At the south end (HZW06), the ebb currents were dominating, with the maximal depth-averaged velocities of the flood and ebb tides being 1.58 and 1.68 m/s, during the spring tides of the summer, and 1.37 and 1.62 m/s during the spring tides of the winter. This is consistent with the known pattern that the currents enter the northern part while leave from the southern part of the Hangzhou Bay mouth [ECCH, 1992; Han *et al.*, 2003; Xie *et al.*, 2009, 2013a]. During neap tides, the tidal currents were





**Figure 4.** The depth-averaged current vectors at various stations of Luchaogang and bay-mouth transects during spring, intermediate, and neap tides in the winter 2014.

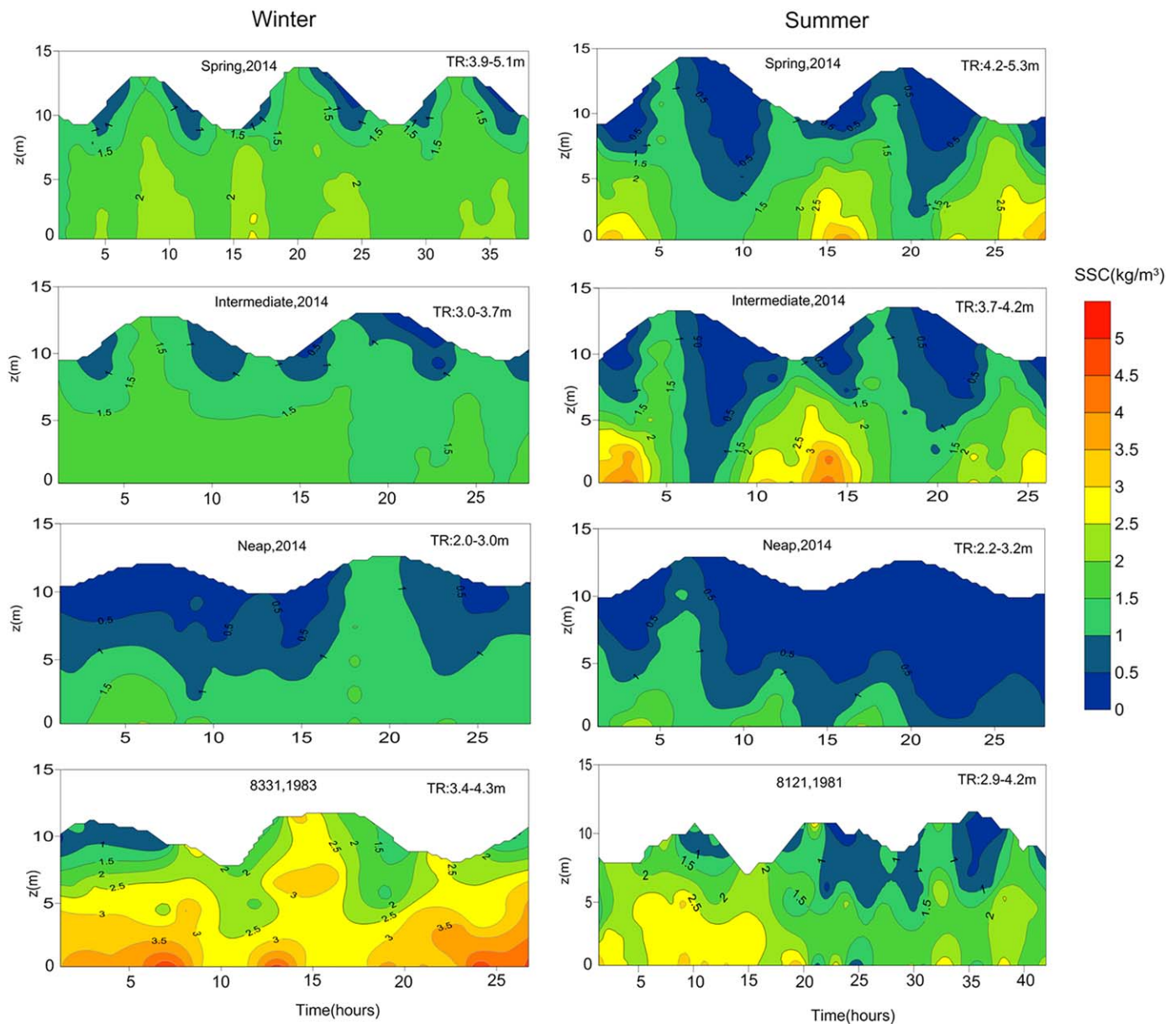
weaker than during spring tides. The ratio of the maximal velocities between neap and spring tides at various stations ranged between 59 and 76% in the summer, and 45 and 65% in the winter.

Along the Luchaogang transect, the flow was ebb-dominant at LCG01 to LCG03. During the spring tides of the summer, the maximal depth-averaged velocities of the flood and ebb tides ranged between 1.87 and 2.02 m/s and 1.98 and 2.06 m/s, respectively. During the spring tides of the winter, they were 1.69–1.81 m/s and 1.70–1.89 m/s, respectively. The flow was usually flood-dominant at LCG04 and LCG05. The maximal depth-averaged velocity of the flood and ebb tides were around 1.70 m/s and 1.45–1.68 m/s, respectively, during the spring tides of the summer. During the spring tides of the winter they were 1.31–1.47 m/s and 1.13–1.47 m/s, respectively. Like the bay-mouth transect, the tidal currents at various stations were weaker during the neap tides than during the spring tides. The ratios of the maximal velocities between neap and spring tides at various stations ranged between 67 and 73% in the summer, 67 and 84% in the winter. The average ratios of current velocities between neap and spring tides at the Luchaogang transect was 53 and 57% in summer and winter, respectively, smaller than at the bay-mouth transect, 59 and 68%, in summer and winter, respectively. This reflected the influences of the Changjiang River discharge on the current in the outer estuary. The ebb-dominant currents westward from LCG03 reflected the influences of the Changjiang secondary plume that moves across the Nanhui tidal front [Su and Wang, 1989; Chen *et al.*, 1990].

#### 4.3. Temporal and Spatial Distribution of SSC in 2014

##### 4.3.1. Intratidal, Spring-Neap, and Seasonal Variations

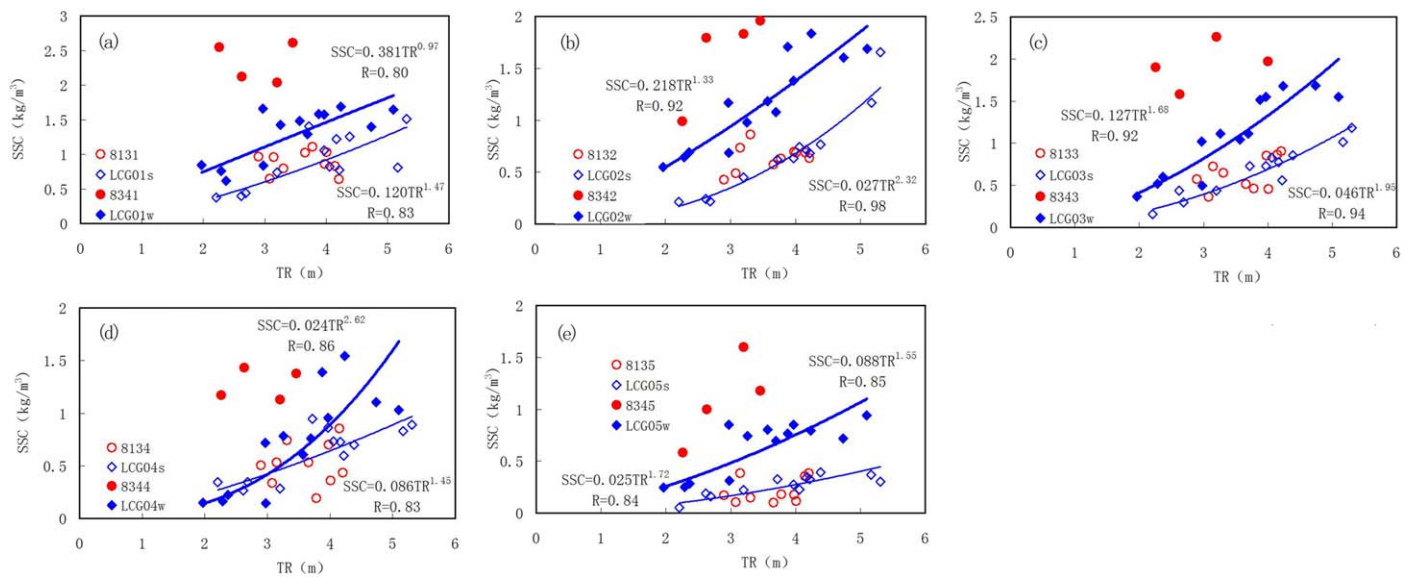
The intratidal and spring-neap cycle in tidally dominated estuaries presents the most significant effect [e.g., Dyer, 1987; Van Rijn, 1993; Wang *et al.*, 2002; Xie *et al.*, 2009; Wang *et al.*, 2013; Yu *et al.*, 2014]. As a result, the general characteristics of suspended sediment concentrations at various stations changed considerably



**Figure 5.** Time series profiles of suspended sediment concentrations at HZW01 during various tides in the winter and summer of 2014 and 1980s.

with tidal phase. Figure 5 illustrates the time series of SSC at station HZW01 during various cruises. The surface SSC decreases with the incoming tides and increased during the ebb tides. The bottom SSC was very high during both maximal floods and maximal ebbs, because the fine sediments in the area were easily resuspended by the tidal currents. This is consistent with the previous studies, despite of the individual differences constrained by regional conditions in the area [e.g., *Su and Wang, 1989; Chen et al., 2006; Liu et al., 2014; Song and Wang, 2014*].

The vertical SSC distributions were highly nonuniform, the stratification was influenced by the tidal range. It was well-mixing during spring tide and partly stratified during neap tide. Taking the Luchaogang transect as example, during spring and neap tides in the winter 2014, the SSC at the bottom was 1.9–3.6 times and 4.8–7.5 times greater than the SSC at the water surface, and the depth-averaged SSC was 1.5–2.5 times and 1.9–5.9 times greater than the surficial SSC, respectively. Whereas during spring and neap tides in the summer 2014, the bottom SSC was 7–20 times and 6–31 times greater than the surface SSC, and the depth-



**Figure 6.** The relationship between flood/ebb-averaged suspended sediment concentrations (SSC) and the corresponding tidal ranges of the Luchaogang gauge station (TR) at the five stations along the Luchaogang transect during various cruises.

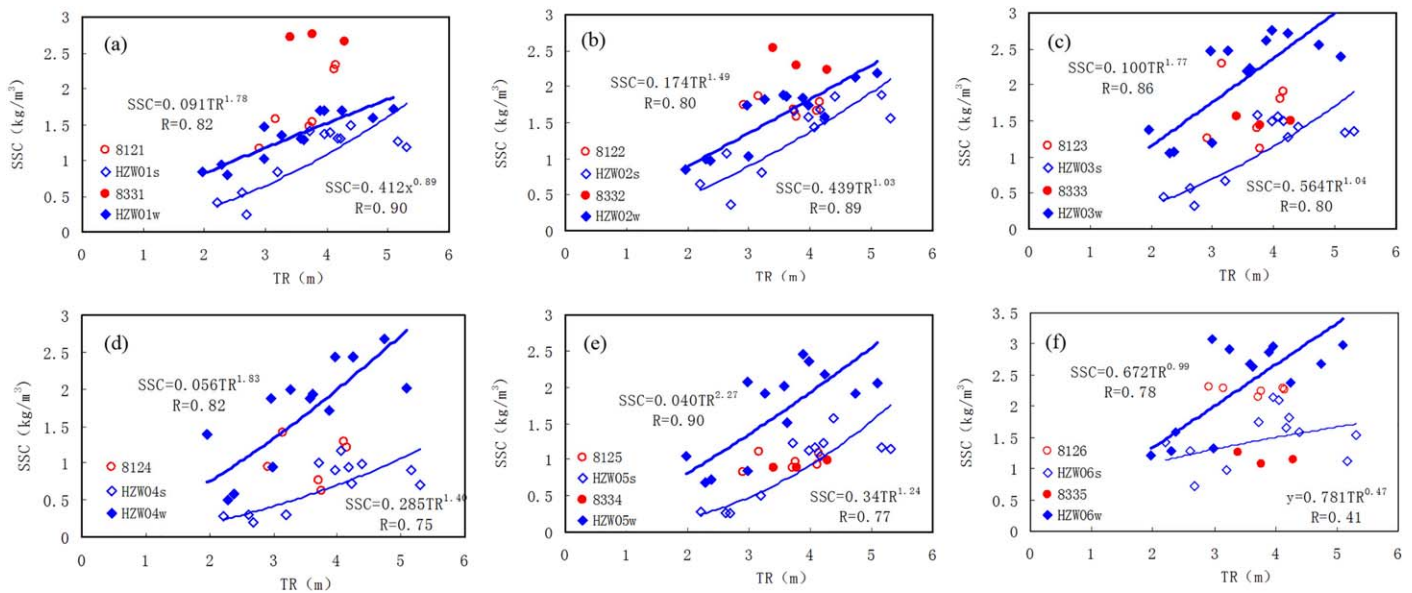
averaged SSC was 3.5–7 times and 3–6.5 times greater than the surface SSC, respectively. The vertical distributions of SSC along the bay-mouth transect showed similar spring-neap cyclic and seasonal variations despite minor difference at various stations.

In view of the seasonal changes, the stratification is more obvious in summer than in winter. Compared to that in 1980s, the SSC during intermediate tide in winter 2014 is lower than in 1983 winter, whereas in the summer, the difference is not apparent. These general trends were also observed at all the other stations, although quantitatively each station was different. At HZW01, the wintertime SSC was 2.9 times greater than that in summer. At other stations, SSC was also higher in winter than in summer, with the mean SSC being 1.5–1.9 times greater than in summer (Table 2). The increased river discharge in summer can result in enhanced stratification and reduced vertical mixing of the water column. Meanwhile, the sediment resuspension in the Changjiang Estuary and Hangzhou Bay is generally strong in winter and weak in summer. In summer, the river discharge is high, but the sediment suspension is weak. In contrast, in winter, the river discharge is low, but wind waves and currents increase. Accordingly, the sediment resuspension is quite intense.

Besides the tidal currents, the SSC vertical stratification in this area was related to the stratification of salinity in the Changjiang plume. Salinity affects the aggregation and settling of the particles and can be important for the formation of the stratification [McManus, 2005]. The detailed salinity variations in the Changjiang Estuary and Hangzhou Bay were presented in Su and Wang [1989] and Shi and Zhou [2004].

Regression analysis showed that all hydrographic stations exhibited good power relationships between the flood/ebb-averaged SSC and the tidal range, regardless of the seasons (Figures 6 and 7). The maximal mean SSC occurred during spring tide and minimal during neap tide. The correlation coefficients varied between 0.75 and 0.98, with all  $p < 0.001$ , except the station at the south end of Hangzhou Bay mouth in the summer 2014 (HZW06). It is well-known that suspended sediment concentration within estuarine environments is proportional to a higher power of current velocity and that tidal flow velocity is proportional to tidal range. The power correlation between SSC and tidal range is, therefore, to be expected.

It should be noted that the flood/ebb-averaged SSC was not only related to the tidal range but also to the period before the measurements. For example, in the winter 2014 at HZW03 the SSC were  $2.47 \text{ kg}/\text{m}^3$  during the first flood of the intermediate tide but  $1.19 \text{ kg}/\text{m}^3$  during the second flood tide of the neap tide, despite the tidal ranges of the both floods were close, 2.97 and 2.98 m, respectively. These factors resulted in the scatter of the data points in Figures 6 and 7 and hence reduced the correlation coefficient between SSC and tidal ranges.



**Figure 7.** The relationship between flood/ebb-averaged suspended sediment concentrations (SSC) and the corresponding tidal ranges of the Luchaogang gauge station (TR) at the six stations along the bay-mouth transect during various cruises.

### 4.3.2. Surficial SSC Variations in the Four Seasons in 2014

Besides the synchronous hydrographic measurements, a medium-term OBS observation of the surficial suspended sediment concentration near HZW02 was carried out, about 0.5 m below the water surface. The surficial SSC was recorded continuously for 1 month in April, July, October, and December in 2014, representing the four seasons. The data was recorded hourly, hence 720 sampling data were obtained for each season.

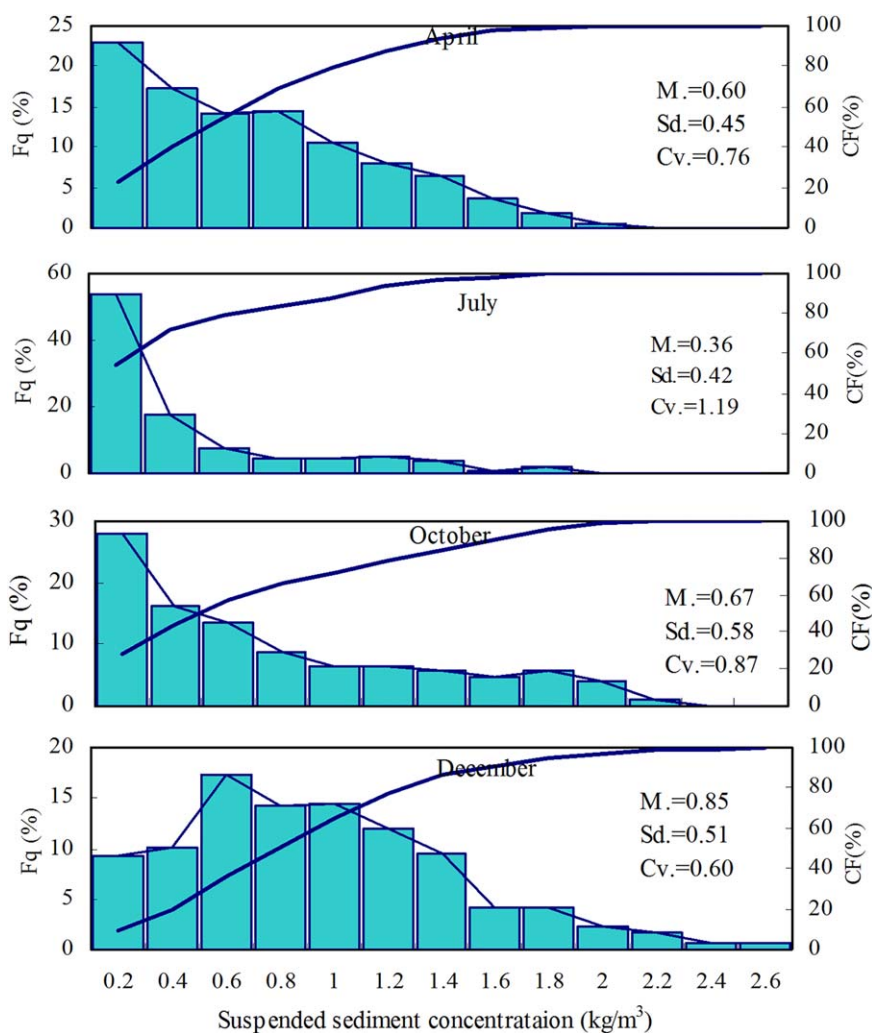
The surficial SSC was also characterized by the spring-neap cycles and seasonal variations, varied between 0.013 and 1.905 kg/m<sup>3</sup>, 0.002 and 1.82 kg/m<sup>3</sup>, 0.011 and 2.159 kg/m<sup>3</sup>, and 0.024 and 2.483 kg/m<sup>3</sup>, respectively, in the four seasons. The average surficial SSC was 0.603, 0.356, 0.666, and 0.847 kg/m<sup>3</sup>, respectively, revealing that the SSC were comparable in spring and autumn, whereas the SSC in winter was about 2 times of SSC in summer.

A frequency analysis of 13 SSC grades with an interval of 0.2 kg/m<sup>3</sup> was applied to discern the frequency of the different hourly SSC levels. Figure 8 gives the surficial SSC occurrence during the four seasons. It is seen that in July the SSCs less than 0.2 kg/m<sup>3</sup> account for over 50%, in April and October, the SSCs less than 1.0 kg/m<sup>3</sup> account for 79.6 and 72.4%, but in winter, the SSCs between 0.6 and 1.2 kg/m<sup>3</sup> were in the majority, accounting for 57.9%. In addition, the frequency of the surficial SSC levels above 2.0 kg/m<sup>3</sup> was more than about 3.0%, while SSC levels above 2.0 kg/m<sup>3</sup> hardly occurred in the other three seasons.

### 4.3.3. Longitudinal Distributions Along the Transects

The tidal current, the bathymetry, and geography also has important effects on the offshore waters of Hangzhou Bay and Changjiang Estuary. Tables 2 and 3 and Figures 9 and 10 show the distribution of the mean SSC at the bay-mouth and the Luchaogang transects during the different tides of various cruises.

At the Luchaogang transect, the mean SSC reduced gradually eastward. The mean SSC was much higher during spring tides than during neap tides, and higher in winter than in summer. During spring tides of the winter 2014, mean SSC at the five stations were 1.58, 1.62, 1.66, 1.24, and 0.80 kg/m<sup>3</sup> from west to east, while during neap tide they were 0.79, 0.65, 0.50, 0.17, and 0.27 kg/m<sup>3</sup>. The distributions in the summer 2014 were similar, but the mean SSC were lower by 30% than those in the winter. The distance between the west and east end is 47.5 km, hence the SSC gradient along the Luchaogang transect was about 0.02 kg/m<sup>3</sup> per kilometer during spring tides and 0.01 kg/m<sup>3</sup> per kilometre during neap tides, in both summer and winter. Besides the bathymetry, the salt wedge also plays an important role in this longitudinal distribution [e.g., Su and Wang, 1989; Wan et al., 2009]. Since the density of saltwater is greater than the density of freshwater, the diluted water flows above the high-density saltwater from the upper reach of the



**Figure 8.** Frequency of hourly surficial SSC binned in  $0.2 \text{ kg/m}^3$  intervals for the April, July, October, and December in 2014. Fq: frequency curve (boxes and thin blue line); CF: cumulative frequency curve (thick blue line); M: mean SSC; Sd: standard deviation; Cv: variation coefficient.

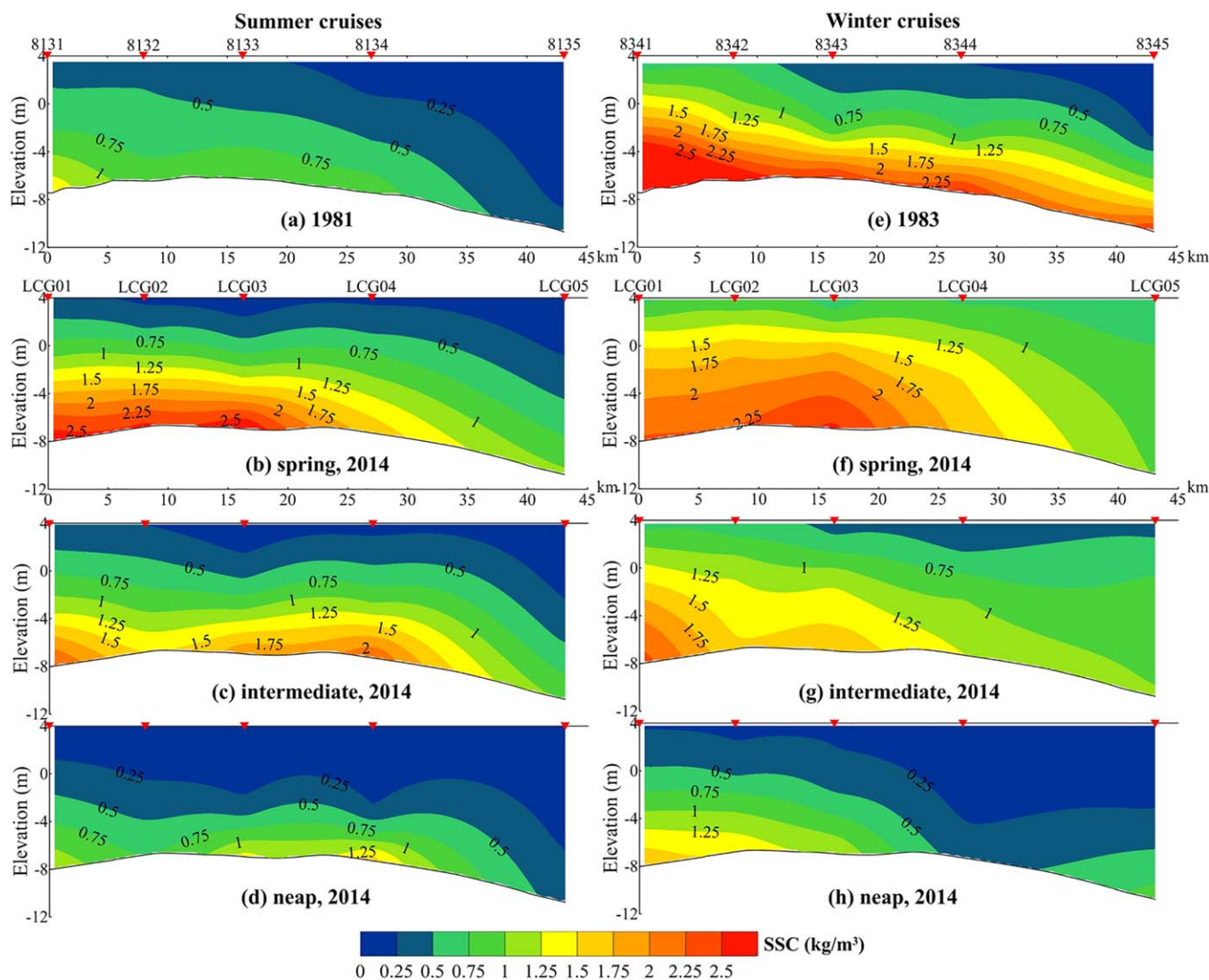
estuary. The influence of the salt wedge results in a turbidity maximum with higher concentration of fine sediments in the vicinity of the mouth than in other regions.

At the bay-mouth transect, in the winter 2014, SSC was a little lower in the northern part than those in the southern part, at the northern stations (HZW01, HZW02) being  $1.64, 1.87 \text{ kg/m}^3$  during spring tide and  $0.90, 0.96 \text{ kg/m}^3$  during neap tide. At the southern stations (HZW03~ HZW06) they were  $2.67, 2.26, 2.17, 2.82 \text{ kg/m}^3$  during spring tide and  $1.12, 0.81, 0.82, 1.34 \text{ kg/m}^3$  during neap tide. In summer, the SSC was a little larger in the northern part than those in the southern part, at the northern stations (HZW01, HZW02) being  $1.36, 1.76 \text{ kg/m}^3$  during spring tide and  $0.53, 0.72 \text{ kg/m}^3$  during neap tide; while at the southern stations (HZW04, HZW05, HZW06) being  $0.95, 1.36, 1.47 \text{ kg/m}^3$  during spring tide and  $0.28, 0.37, 1.15 \text{ kg/m}^3$  during neap tide.

#### 4.4. SSC Comparison Between 2014 and the 1980s

The cruises in the summer 1981 and the winter 1983 covered continuous 5 days and 1 day for intermediate and neap tides, respectively (Table 1). It might be misleading to compare concentrations at stations which were observed randomly, but the variations of SSC at all the stations could be compared to those in 2014 by excluding the influence of tidal ranges (Figures 6 and 7; Tables 2 and 3).

At the Luhaogang transect, the SSC at the five stations were smaller in the winter of 2014 than in winter 1983. At the annually averaged tidal range of Luhaogang, i.e., about 3.5 m, the SSCs in 2014 were 30–50%



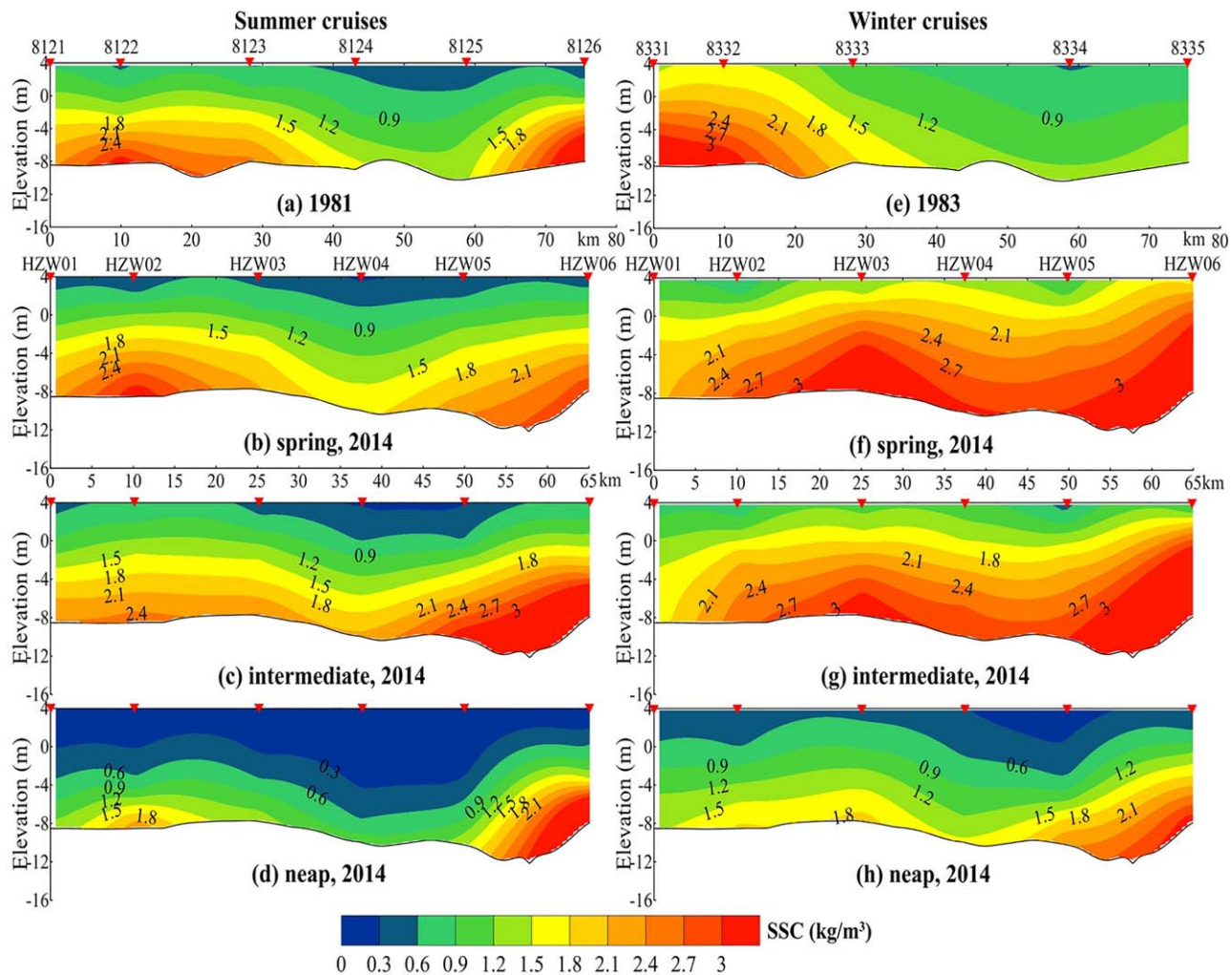
**Figure 9.** The longitudinal distribution of suspended sediment concentrations along the Luchaogang transect during various tides in the winter and summer of 2014 and 1980s.

lower than in 1983, with an averaged decline of 43%. While in the summer, the SSC was basically consistent with those in 1981, and no obvious decrease or increase could be found. As a whole, the general shape of the SSC profile is determined mainly by local hydrodynamics and sediment properties, and not by fluvial sediment supply.

At the bay-mouth transect, the SSC in winter 2014 decreased by 33–50% in the northern part (HZW01~HZW03) than those in 1983 at the same tidal range, but the SSC in the southern mouth (HZW04~HZW06) increased by over 70%. The SSC in the summer 2014, showed at all stations a slight decrease compared to those in the summer 1981, with the extent ranging from 18 to 34%, and an average of 26%. It is noteworthy that the longitudinal distribution in the winter 2014 was different than that in the winter 1981 when the SSC in the north were larger than that in the south.

#### 4.5. Water and Sediment Fluxes and Their Variation

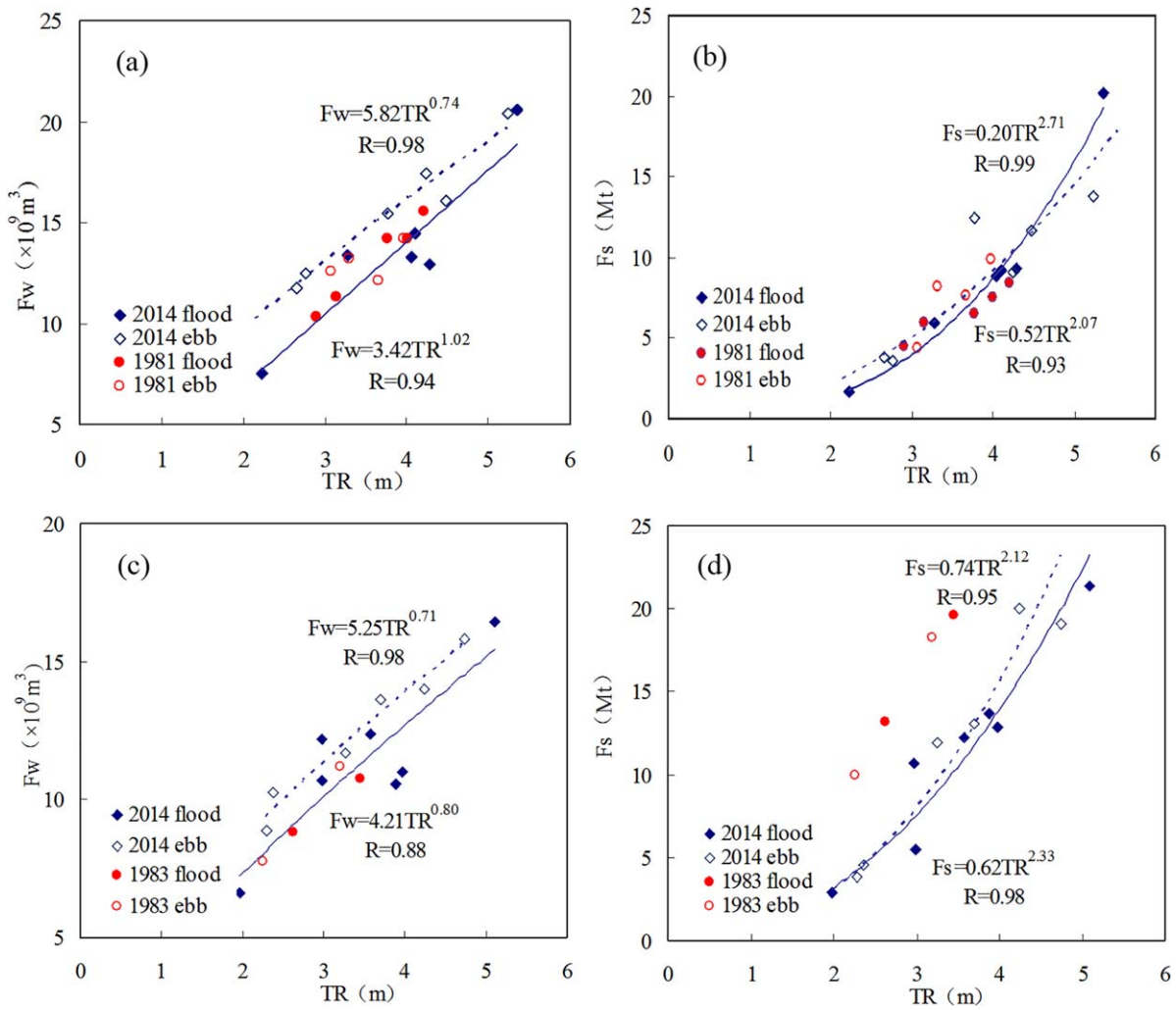
Figures 11 and 12 show the relationship of flood/ebb-averaged water and sediment fluxes versus tidal range at Luchaogang gauge station for both transects during various cruises. Like the SSC, the fluxes were also correlated with the tidal range, with  $R$  between 0.88 and 0.99, and  $p < 0.001$  being even better than the correlation coefficients between flood/ebb-averaged SSC and tidal range.



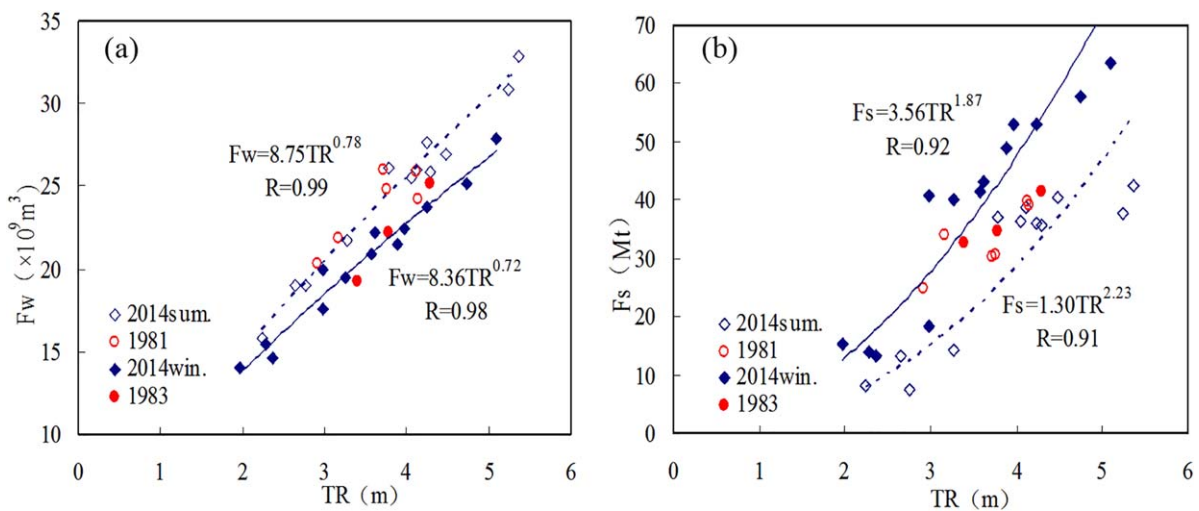
**Figure 10.** The longitudinal distribution of suspended sediment concentrations along the bay-mouth transect during various tides in the winter and summer of 2014 and 1980s.

At the Luchaogang transect, the water discharges in the spring-neap cycle varied from  $7.5 \times 10^9 \text{ m}^3$  to  $20.6 \times 10^9 \text{ m}^3$  per flood or ebb tides in the summer 2014 and from  $6.6 \times 10^9 \text{ m}^3$  to  $16.5 \times 10^9 \text{ m}^3$  in the winter 2014. With the same tidal range, the water fluxes in winter was smaller by about 10% than those in summer, reflecting the influences of the Changjiang River discharge, which was smaller in winter than in summer, with averages of 11,711 and 50,050  $\text{m}^3/\text{s}$ , respectively, in the measured periods. Furthermore, the water fluxes during the ebb tides were 12–15% larger than those during the flood tides, revealing the impact of the river discharge on the water fluxes. The sediment flux during the spring-neap cycle varied between 1.7 and 20.1 Mt per flood or ebb tides in the summer 2014, and 2.9 and 21.4 Mt in the winter 2014. At the same tidal range, the sediment fluxes in winter were about 1.5 times higher than those in summer. This is consistent with the aforementioned seasonally variation trends of suspended sediment concentration. The differences between flood/ebb-averaged sediment fluxes were not as obvious as those between water fluxes. However, the fluxes during ebb tides were indeed slightly larger than during flood, revealing a southward net sediment transport. Comparing the sediment fluxes in 2014 and 1980s, an apparent decline up to about 38% in sediment flux in the winter can be seen, but no obvious decline in the summer of 2014 than 1981.

At the bay-mouth transect, the water discharges varied from  $15.9 \times 10^9 \text{ m}^3$  to  $32.8 \times 10^9 \text{ m}^3$  per flood or ebb tides in the summer 2014, and from  $14.0 \times 10^9 \text{ m}^3$  to  $27.9 \times 10^9 \text{ m}^3$  in the winter 2014. No obvious difference in the water fluxes between flood and ebb tides during the summer or winter cruises, but the water fluxes in summer were larger by 5~10% than in winter, probably due to the larger tidal range in the summer, about 0.2 m. The lack of obvious discrepancy in the water fluxes between flood and ebb tides reveals



**Figure 11.** The relationships between flood/ebb-averaged water fluxes (Fw) and sediment fluxes (Fs) versus the corresponding tidal ranges of the Luchaogang gauge station (TR) at the Luchaogang transect, during flood and ebb tides in the cruises of the winter and summer 2014, the winter 1983 and the summer 1981.



**Figure 12.** The relationships between flood/ebb-averaged water fluxes (Fw) and sediment fluxes (Fs) versus the corresponding tidal ranges of the Luchaogang gauge station (TR) at the bay-mouth transect, during various tides in the cruises of the winter and summer 2014, the winter 1983 and the summer 1981.



that the influences of the Changjiang River discharge on the Hangzhou Bay mouth is negligible. Overall, the water fluxes in 2014 were comparable to those in 1980 or 1983, revealing that no obvious tidal power variations in the bay mouth over the last 30 years. The sediment fluxes varied between 7.4 and 42.4 Mt per flood or ebb tides in the summer 2014, and 13.2 and 63.6 Mt in the winter 2014. At the same tidal range, the sediment fluxes in winter were 30~40% larger than those in summer. Compared to 1980s, the sediment fluxes were decreased by about 20% in summer, consistent with the decreasing trends in the suspended sediment concentration at the stations, whereas it was increased by about 10% in winter, mainly caused by the marked increased concentrations in the southern mouth.

## 5. Discussions

### 5.1. The Influences of Sediment Load Decline

*Li et al.* [2012] and *Yang et al.* [2015] studied the surficial SSC variations in Changjiang Estuary and its adjacent coastal areas using long-term SSC data by twice-daily or daily at high tide sampling at various stations before and after 2003. Their results showed that the SSC at the Changjiang Estuary and the northern Hangzhou Bay had decreasing trends. In the outer Changjiang Estuary and the northern Hangzhou Bay mouth, the SSC have decreased by 20–30% after the TGD construction in 2003. In the present study, the SSC at the Luchaogang transect decreased by 43% in 2014 winter with respect to 1983 winter, but no apparent change in 2014 summer compared to those in 1981 summer was observed. The averaged SSC ratios between the spring, summer, autumn, and winter in 2014 were about 1.5:1:1.5:2. Assuming that the averaged change in the winter and summer represents the range of annual variations, the SSC variations were about 21.5% at the Luchaogang transect and about 25% in the northern bay mouth, consistent with the studies of *Li et al.* [2012] and *Yang et al.* [2015]. However, because of the twice-daily or daily sampling at the water surface procedure, the intratidal variations and the vertical distributions during flood or ebb could not be resolved. Furthermore, when comparing the data before and after the time periods of sediment load decline, the seasonal variations should be taken into account as well.

The sediment discharge from Changjiang River is highly seasonal due to monsoon precipitation. The vast majority of sediments enter the sea during the flood season (from June to September). Most of the decline of the annual sediment load of Changjiang River has occurred during the flood season while changes in the dry season over recent decades is relatively small [*Xu and Milliman, 2009; Dai et al., 2016*], as shown in Figure 13. According to the observations in the present study, SSC at the Luchaogang transect in the summer of 2014 were comparable to those in the summer of 1983, revealing there were no obvious SSC variations in the outer Changjiang Estuary. Therefore, it can be deduced that the SSC in the outer Changjiang Estuary cannot be directly related to the decline of the sediment load of Changjiang Estuary.

In fact, the sediment fluxes across the Luchaogang and bay-mouth transects are very large. In the summer 2014, the maximal sediment fluxes could reach as much as about 20.1 and 42.4 Mt per single flood or ebb tide, respectively. This means that at present, the sediment fluxes across the Luchaogang transect in one

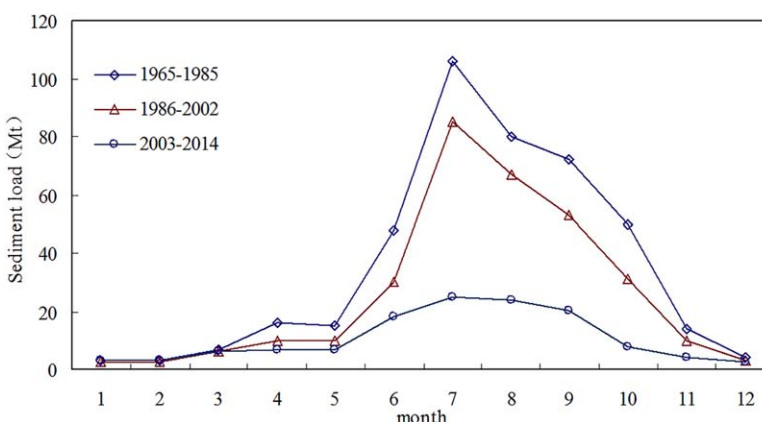


Figure 13. Monthly averages of sediment load at Datong station during the periods 1965–1985, 1986–2002, and 2003–2013.

tidal cycle is comparable with the monthly averaged sediment discharge at Datong station (averagely 21.9 Mt in 2003–2014), and the sediment fluxes entering or leaving Hangzhou Bay in one tidal cycle is about 2 times the monthly averaged sediment discharge at Datong. Apparently, the riverine sediment load plays only a minor role on the sediment transport in the outer Changjiang Estuary and Hangzhou Bay.

The variation of SSC in the estuary results from the combined influences of upstream changes of sediment load and discharge and the response of the estuary. When sediment is trapped behind upstream dams, the amount of marine sediment can be increased by strong tidal currents [Philips and Slatter, 2006]. The SSC in the outer Changjiang Estuary was an order of magnitude higher than that at Datong, probably due to strong tidal currents as the pattern of SSC was strongly related to the tidal range [Chen *et al.*, 2006; Li *et al.*, 2012; Dai *et al.*, 2013]. There exists an extensive near shore mud wedge extending to the Taiwan Strait, that deposited over the past 7000 years since the sea-level rise of the Holocene [Liu *et al.*, 2007]. In addition, the water depths along the two transects were less than 15 m. Therefore, local resuspension, driven by strong tidal currents and waves, is probably a key control on SSC variation.

### 5.2. Reasons for the SSC Decrease in the Winter

There is a large amount of tidal flats in Changjiang Estuary. Four major shoals—Chongming East flat, Hengsha shoal, Jiudian shoal, and Nanhui tidal flat—account for over ninety percent of the total tidal flat area. The widest is more than 10 km. The lower part of the intertidal flats is permanently bare whereas the higher part is covered by *Scirpus* and reeds during the growing seasons [Yang *et al.*, 2005, 2008]. Being located at the mouth of the estuary, these areas are significantly influenced by both tidal flows and waves.

Historically, tidal flat growths in Changjiang Estuary have shown to be dependent on the rate of riverine supply [Yang *et al.*, 2007; Van Maren *et al.*, 2013; Wang *et al.*, 2015]. Due to the rapid reduction of sediment discharge from Changjiang River, the sediment supply for tidal flat growths is now less than the potential for sediments to be removed by tidal currents and waves, resulting in a net loss. In addition, the losses have been compounded by extensive reclamation of the intertidal areas. Since 1950s, a total of more than 1259 km<sup>2</sup> tidal flats have been reclaimed, which accounts for 50% of the whole tidal flats of the Changjiang Estuary (Figure 1), and most reclamation were carried out in the last 30 years [Wei *et al.*, 2015]. As a result, the area above 0 m have decreased, meanwhile, the cross-shore profiles have steepened to a great extent [Yang *et al.* 2005; van Maren *et al.*, 2013] (Figure 14). For example, the tidal flat area above 0 m at the Nanhui shore decreased by 81% in the last decades [Wei *et al.*, 2015].

The wind waves in Changjiang Estuary are relatively strong in winter and weak in summer. The water depth of the measured area is less than 15 m. Therefore, local resuspension, driven by strong tidal currents and waves, is an important key control on the SSC in the winter. With the decrease of the tidal flat area in Changjiang Estuary, less sediment could be resuspended in the winter 2014 than in the 1980s. Probably this is the reason that the suspended sediment concentration at the Luchaogang in the winter 2014 decreased

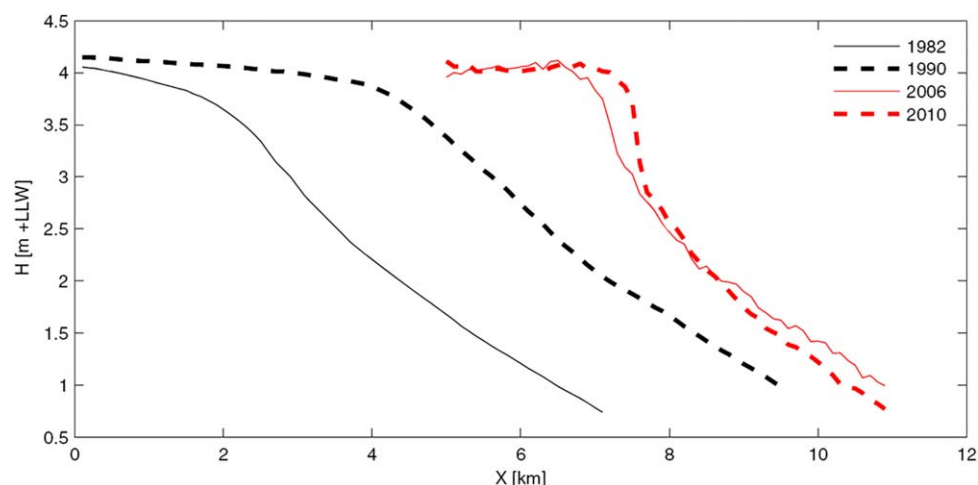


Figure 14. Cross-shore profile of the tidal flats east of Chongming Island (see Figure 1b for location). From Van Maren *et al.* [2013].

compared to that in the winter 1983. While in summer, because of the large river discharge, deeper water depth, weak wind waves, the variations of suspended sediment concentrations were not obvious.

### 5.3. Mechanisms for the SSC Variations in the Outer Hangzhou Bay

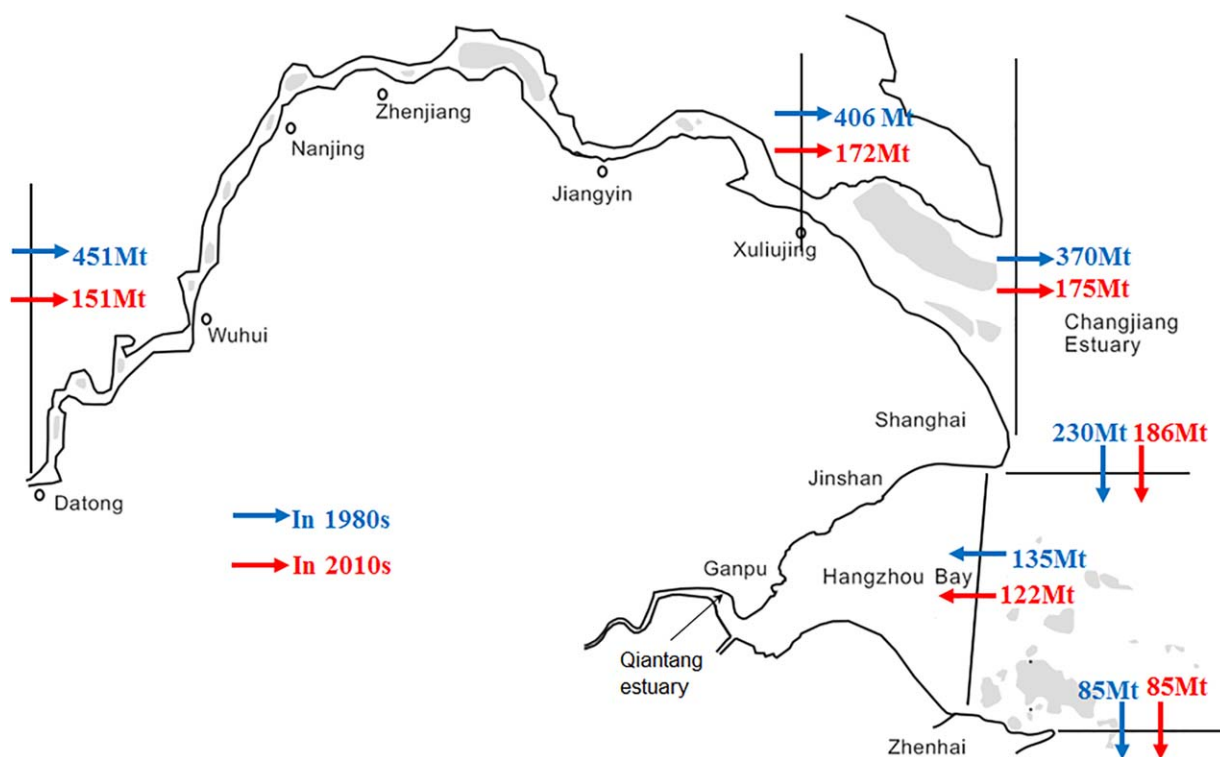
There is intensive sediment exchange between Changjiang Estuary and Hangzhou Bay. The sediment deposited in Hangzhou Bay mainly comes from the Changjiang Estuary. There are two paths for the sediment from the Changjiang Estuary entering Hangzhou Bay. One part of sediment from the Changjiang Estuary diffuses south-eastward along with the Jiangsu-Zhejiang coastal current, from where it can be resuspended and transported into Hangzhou Bay by flood currents. The other way is directly entering the northern Hangzhou Bay by the secondary Changjiang plume, i.e., a residual current pointing SW-S at the front of Nanhui flat [Su and Wang *et al.*, 1989; Chen *et al.*, 1990]. With the suspended sediment concentration at the outer Changjiang Estuary decreasing in the winter, the concentrations in northern Hangzhou Bay have decreased accordingly. A more important factor is the eastward propagation of the Nanhui flat in recent years, by a distance of around 10 km, which increased the distance and changed the route for Changjiang material directly entering Hangzhou Bay.

There was an apparent change in the plan distributions of suspended sediment concentration in the southern Hangzhou Bay from 1980s to 2014. Based on the large-scale synchronous field survey in 1980s, it was concluded that Hangzhou Bay has three regions with high concentrations: the areas of the large sandbar at upstream, off the southern tidal flat and the northeast mouth, with average SSC to be 3.4–4.4, 1.2–3.2, and 1.0–2.6 kg/m<sup>3</sup>, respectively, and two low concentration regions: the southeast and northern tidal channel with suspended sediment concentration to be around 1.0, 0.5–1.0 kg/m<sup>3</sup>, respectively, as shown in Figure 1c [Cao *et al.*, 1985; Chen *et al.*, 1990; ECCHE, 1992; Han *et al.*, 2003]. The low SSC in southern Hangzhou bay is mainly due to the large water depth of more than 10 m in average. However, in the winter 2014, flood/ebb-averaged suspended sediment concentration was more than 2 kg/m<sup>3</sup>, which indicates that the southern mouth has evolved from a low concentration region to a high concentration region. This is consistent with the studies of He *et al.* [2013], based on hourly GOCI (the Geostationary Ocean Color Imager) data over one tidal cycle. Their data show that the southern bay is a high-SSC region in 5 April, 2011, with the surficial SSC exceeding 1.5 kg/m<sup>3</sup> in most of the area of southern Hangzhou Bay, even higher than the northern Hangzhou Bay mouth. Furthermore, from the remote sensing in April 2011, the high SSC region just off the southern flats has elongated northeastward by about 30 km, with the east boundary close to the bay-mouth transect. Based on field data in the present contribution and the remote sensing, it could be deduced that the horizontal distribution of SSC in outer Hangzhou Bay has changed to a large extent. This is probably related to the land reclamation since 1970s. The coastline of Andong flat and Zhenhai has moved seawards by about 6 and 2 km, respectively, resulting in the change of the large-scale hydrodynamic patterns. According to the numerical modeling by Liu and Wu [2015], despite the cross-section width narrowing in southern Hangzhou Bay, the tidal prism has increased by about 8% and the hydrodynamics strengthened and the seabed has been eroded significantly since 2002.

### 5.4. Sediment Budget and the Trends of the Seabed Evolution

A sediment budget is a quantitative inventory of all the sediment input, output, and storage within a selected segment of coast or estuary [Townend and Whitehead, 2003]. Since the 1980s, many scholars studied the characteristic of sediment transport and deposition in the Changjiang Estuary [e.g., Milliman *et al.*, 1985; Wu *et al.*, 2006; Yang *et al.*, 2015]. Wu *et al.* [2006] calculated the sediment load allocation in Changjiang Estuary based on charts in 1953 and 1993. It was shown that most of the sediment from Changjiang River deposited in the outer Changjiang Estuary, Hangzhou Bay, and the coastal area in Zhejiang Province, 31% of the sediment deposited in the outer Changjiang Estuary, and 51% in the latter, indicating that 230 Mt sediment per year across the Luchaogang transect before 2003. Xie *et al.* [2013b] concluded that the sediment deposited in Hangzhou Bay was 135 Mt per year based on bathymetric data in 1959 and 2003.

The quantity crossing the bay-mouth and Luchaogang transects were more than 60 and 20 Mt per flood/ebb tides, respectively. However, the net flux is a very small number, based on the difference between the very large flood and ebb fluxes, and is therefore extremely difficult to measure or compute with any degree of accuracy [Townend and Whitehead, 2003].



**Figure 15.** Sediment flux model in Changjiang Estuary and Hangzhou Bay. The data across the Xuliujing and the eastern Chongming transects in 1980s and 2010s are from *Wu et al.* [2006] and *Yang et al.* [2015], respectively; Those of the Luchaogang and bay-mouth transects in 1980s are from *Wu et al.* [2006] and *Xie et al.* [2013b]; The data across the Zhoushan transect was evaluated with unpublished data.

Without obvious changes in large-scale hydrodynamics over the last 30 years, it could be roughly assumed that the net sediment flux across the Luchaogang transect and the bay-mouth transect are proportional to the cross-section fluxes, then the net sediment flux from Changjiang Estuary to the south through the Luchaogang transect has decreased by 19% (the average of flux decreases in summer and winter), i.e., 186 Mt per year at present. Likewise, the net sediment influx into Hangzhou Bay is 122 Mt per year presently. In other coastal zone of Zhejiang Province, the sediment amount was 85 Mt per year before 2000 (unpublished data from chart comparisons in the Zhejiang coastal area). The SSC in Zhoushan area have not shown a decreasing trend (unpublished data), hence there is no decrease in the annual net sediment flux across the Zhoushan transect. Thus, a total scheme of the sediment budget can be delineated, as illustrated in Figure 15.

The reduction of annual sediment input in Hangzhou Bay was 13 Mt (from 135 Mt in 1980s to 122 Mt in 2010s, Figure 15), much smaller than 44 Mt at the Luchaogang transect (from 230 Mt in 1980s to 186 Mt in 2010s). This shows that the morphodynamic adjustment in Hangzhou Bay would be later than the outer Hangzhou Bay, i.e., the erosion response to the sediment load decline in Hangzhou Bay would first happen in the outer area. One reason is the compensation by the muddy area of the outer Changjiang Estuary and Hangzhou Bay. Furthermore, the large amount of land reclamation at the upper Hangzhou Bay, e.g., the Qiantang Estuary, intensified the landward sediment transport of Hangzhou Bay. In the last 50 years, more than 1000 km<sup>2</sup> tidal flats have been reclaimed within the Qiantang River and the upper Hangzhou Bay for the aim of estuary regulation and fulfilling land requirement [*Han et al.*, 2003; *Pan et al.*, 2010] (Figure 1). As reported in many other coastal systems, the enclosure of land led to increased sedimentation in the estuaries [e.g., *Sherwood et al.*, 1990; *Nichols and Howard-Strobel*, 1991; *Van der Wal et al.*, 2002], due to the fact that a decreasing tidal flat area enhances flood dominance [*Van der Spek*, 1997], and more sediment carried by flood currents deposited in the estuaries. In recent years, more sediments in outer Hangzhou Bay are transported to supply the accelerated deposition in upstream [*Xie et al.*, 2013b]. Nevertheless, with the continued erosion of the outer Hangzhou Bay, the sediment flux across the bay-mouth transect would reduce. According to the relationship between the various temporal and spatial scales for the coastal morphological

evolutions proposed by *De Vriend* [1996], a long-term timescale of decades is needed for the response of morphology and sediment transport, considering the huge spatial scales.

## 6. Conclusions

Since the 1980s, the sediment discharge of Changjiang River has a decreasing trend, especially after the TGD closure in 2003. Based on the synchronous hydrographic data of the Luchaogang transect and the Hangzhou bay-mouth transect in the winter and summer, 2014 and during the summer 1981 and the winter 1983, the variations of suspended sediment concentration and sediment fluxes along the two transects over the past 30 years were compared. The findings are summarized below.

1. The suspended sediment concentration and sediment fluxes have apparent tidal, spring-neap cycle, and seasonal variations. Good power relationships with tidal range exist for concentrations, fluxes, larger in spring tides than in neap tides. In addition, they are 2–3 times larger in winter than in summer.
2. At the Luchaogang transect, the suspended sediment concentrations and sediment fluxes have clearly decreased in winter but no obvious changes have occurred in summer comparing 2014 with the early 1980s. This is the opposite of the seasonal changes in riverine sediment discharge over the last decades. The lack of change in the summer reveals that the sediment transport in the outer Changjiang Estuary is not related directly to the sediment discharge from Changjiang River but mainly controlled by the sediment resuspension due to the strong tidal currents and waves. The decreases of SSC and sediment flux in winter can probably be attributed to the decrease of area of the tidal wetlands in the estuary, caused by the decreasing sediment source and land reclamation. Overall, the impact of the riverine sediment decline is insignificant in term of SSC variation off the Changjiang River mouth at the current stage.
3. The SSC in the northern Hangzhou Bay decreased both in winter and summer, particularly by up to 70% in the winter. This is related to the SSC decrease along the Luchaogang transect because some of the sediment from the Changjiang Estuary enters Hangzhou Bay through the Nanhui flat front by the Changjiang secondary plume. In addition, the eastward progradation of Nanhui flat have increased the transport distance for the sediment from the Changjiang Estuary to enter the northern Hangzhou Bay and thus the sediment transport route has been changed to a certain extent.
4. The SSC in southern Hangzhou Bay has increased by 70% in winter of 2014 compared to the winter of 1983, and the southern bay mouth has evolved from a low SSC region to high SSC region. This is probably related to the large-scale hydrodynamic and sediment transport changes within Hangzhou Bay, resulting from the massive land reclamation along the south bank.
5. The annual sediment flux through the Luchaogang transect southerly has decreased by about 20%, but only minor flux changes have occurred at the Hangzhou Bay mouth. The morphological evolution in the outer Hangzhou Bay and Changjiang Estuary is related to the variations of sediment transport. As a whole, the morphological response within Hangzhou Bay should lag behind that in outer part by decades, except the northern bay mouth where sediment exchanges directly with Changjiang Estuary.

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