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Tidal Level Response to Sea-Level Rise in the Yangtze Estuary*

GONG Zheng (龚 政)[a], ZHANG Chang-kuan (张长宽)[a, 1],

WAN Li-ming (万里明)[b] and ZUO Jun-cheng (左军成)[a]

[a] *State Key Laboratory of Hydrology-Water Resources and Hydraulic Engineering, Hohai University, Nanjing 210098, China*

[b] *Yangtze River Estuary Survey Bureau of Hydrology and Water Resource, Ministry of Water Resources, Shanghai 200136, China*

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ABSTRACT

The rise of tidal level in tidal reaches induced by sea-level rise has a large impact on flood control and water supply for the regions around the estuary. This paper focuses on the variations of tidal level response along the tidal reaches in the Yangtze Estuary, as well as the impacts of upstream discharge on tidal level response, due to the sea-level rise of the East China Sea. Based on the Topex/Poseidon altimeter data obtained during the period 1993~2005, a stochastic dynamic analysis was performed and a forecast model was run to predict the sea-level rise of the East China Sea. Two-dimensional hydrodynamic numerical models downscaling from the East China Sea to estuarine areas were implemented to analyze the rise of tidal level along the tidal reaches. In response to the sea-level rise, the tidal wave characteristics change slightly in nearshore areas outside the estuaries, involving the tidal range and the duration of flood and ebb tide. The results show that the rise of tidal level in the tidal reaches due to the sea-level rise has upstream decreasing trends. The step between the stations of Zhangjiagang and Shiyiwei divides the tidal reaches into two parts, in which the tidal level response declines slightly. The rise of tidal level is 1~2.5 mm/a in the upper part, and 4~6 mm/a in the lower part. The stations of Jiangyin and Yanglin, as an example of the upper part and the lower part respectively, are extracted to analyze the impacts of upstream discharge on tidal level response to the sea-level rise. The relation between the rise of tidal level and the upstream discharge can be fitted well with a quadratic function in the upper part. However, the relation is too complicated to be fitted in the lower part because of the tide dominance. For comparison purposes, hourly tidal level observations at the stations of Xuliujing and Yanglin during the period 1993~2009 are adopted. In order to uniform the influence of upstream discharge on tidal level for a certain day each year, the hourly tidal level observations are corrected by the correlation between the increment of tidal level and the increment of daily mean upstream discharge. The rise of annual mean tidal level is evaluated. The resulting rise of tidal level at the stations of Xuliujing and Yanglin is 3.0 mm/a and 6.6 mm/a respectively, close to the rise of 5 mm/a according to the proposed relation between the rise of tidal level and the upstream discharge.

Key words: *Yangtze Estuary*; *sea-level rise*; *stochastic dynamic analysis and forecast model*; *tidal reaches; discharge increment*

1. Introduction

Global warming is causing sea level to rise irrefutably. The global mean sea level increased with

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1 Corresponding author. E-mail: ckzhang@hhu.edu.cn

about 20 cm when the global air temperature increased with about 0.5°C~0.6°C during the 20th century. The regional mean sea level rose as well (Yu *et al.*, 2003). Over the next decade, the sea level along the coast of China will likely rise with 32 mm (3.2 mm/a) as predicted by the State Oceanic Administration of China. Accelerated sea-level rise will have intensive impacts on low-lying coastal regions around the world, causing flooding of coastal lowlands, erosion of sandy beaches and destruction of coastal wetlands (Snoussi *et al.*, 2009; Poulos *et al.*, 2009; Tian *et al.*, 2010). During the past decades, the sea-level changes in open sea have been studied including the causes, the rising rate and the impacts etc (Liu *et al.*, 2010; Tian *et al.*, 2010). The area around the Yangtze Estuary is one of the most developed regions in China with the cities of Jiangsu and Shanghai with a high population, urbanization, and economic development. For the sake of flood drainage and water supply, there are many rivers connected to the Yangtze Estuary by means of flood gates except for the Huangpu River. The sea-level rise in the East China Sea results in an additional impact on flood control, salinity intrusion, agricultural production and wetland reserves (Chen and Zong, 1999; Tian *et al.*, 2010). In different locations of the estuarine areas, there is a different response of tidal level to sea-level rise because of the interaction of river discharge and tide. Nevertheless, for many scenarios that are used to estimate the influence of sea-level rise, the local rates of sea-level rise are adopted directly from the sea-level rise in open sea (Chen and Zong, 1999; Ericson *et al.*, 2006; Tian *et al.*, 2010). In absence of long-term tidal level measurements, some sea-level rise analyses are mainly focused on the tidal gauges near the river mouth, e.g., at Wusong, where the impact of discharge on tidal level is negligible (Chen *et al.*, 1991; Xu *et al.*, 1998).

The objective of the present study is to estimate the variations of tidal level response along the tidal reaches in the Yangtze Estuary, as well as the impacts of upstream discharge on tidal level response, due to the sea-level rise of the East China Sea. For comparison purposes, long-term hourly tidal level observations at two tidal gauges are used to evaluate the rise of annual mean tidal level.

2. Study Area

As the largest (1800000 km^2) and longest (6300 km) river in South Asia, the Yangtze River extends from the Qinghai-Tibet Plateau eastwards to the East China Sea (Fig. 1). Datong gauge station, located at approximately 600 km upstream of the river mouth and just free from tidal influences during dry season, is chosen as the hydrological control station. The Yangtze River upstream of Datong drains 94.3% of the total watershed and delivers more than 95% of water and sediment loads of the whole river. Except for several extremely wet or dry years, the water discharge has remained relatively constant since the 1950s, averaging about 900 km^3/a (28400 m^3/s). In contrast, the sediment discharge fell down from ~490 Mt/a in the 1950s and 1960s to ~150 Mt/a after the closure of the Three Gorges Dam in 2003 (Duan *et al.*, 2008; Yang *et al.,* 2011). Most of the catchment is affected by the southeast monsoon in summer, so the precipitation occurs mostly from May to October. The water discharge shows a large yearly and seasonal fluctuation. The annual mean discharge during the period 1950~ 2007 is 28400 m^3/s, and the monthly mean discharge reaches its maximum of 49700 m^3/s in July and its minimum of 11100 m^3/s in January (Zhang *et al.*, 2011). The recorded maximum monthly mean discharge is 84000 m^3/s in August 1954, and the minimum is 6730 m^3/s in September 1963. The daily minimum observed is 4620 m^3/s on 31 January 1979 (Chen and Zong, 1998; Chen and Zong, 1999; Chen *et al.*, 2001).

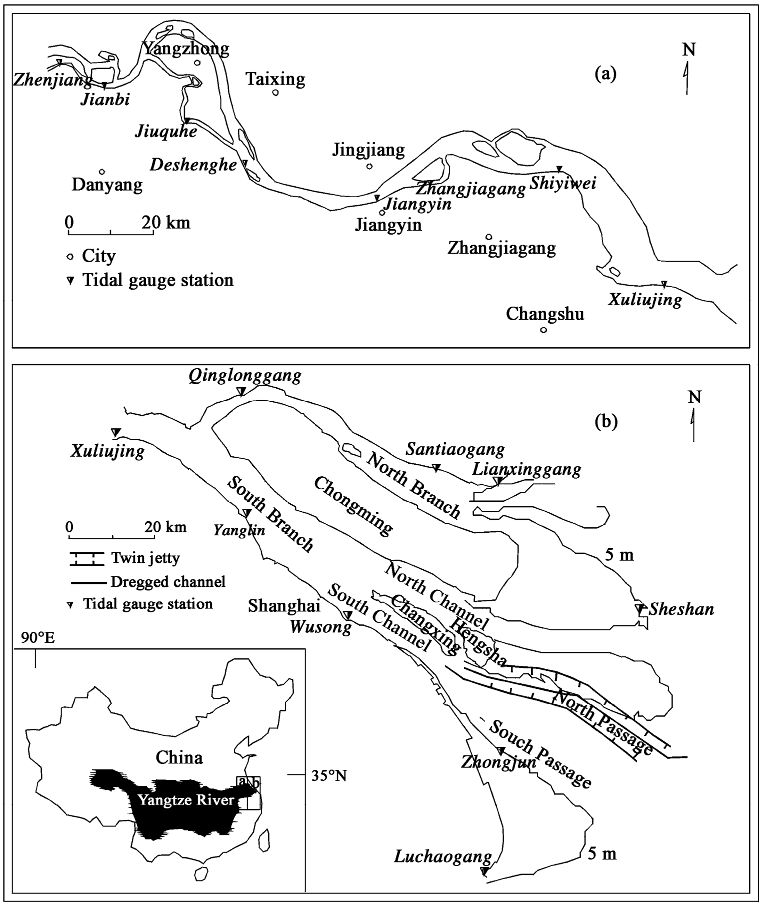

Fig. 1. Locations of study area and tidal gauge stations.

The study area is located in the Yangtze Estuary, which can be characterized as a system of tidal channels of three-ordered bifurcation with four outlets into the sea (Fig. 1). The North and South Branches are the first order bifurcation. These branches are separated by the Chongming Island. The South Branch is further divided into the North Channel and the South Channel by the islands of Changxing and Hengsha. The South Channel is once more divided into the North Passage and the South Passage by the Jiuduansha shoal. At present, the South Branch, the South Channel, the North Passage and the South Passage are the main channels carrying water and sediment. The Yangtze Estuary experiences a meso-scale tide, with a mean and a maximal tidal range of 2.67 m and 4.62 m respectively at Zhongjun station. It has an irregular semidiurnal character, with an average flood duration and ebb duration of 5 h and 7.4 h respectively at Zhongjun station (Zhang *et al.*, 2011).

3. Method

3.1 Prediction of the Rate of Sea-Level Rise of the East China Sea

Based on the Topex/Poseidon altimeter data obtained during the period 1993~2005, the rate of sea-level rise of the East China Sea is calculated by a stochastic dynamic analysis and forecast model (Zuo *et al.*, 1997; Zuo *et al.*, 2001; Xu *et al.*, 2010). The mean sea level $L(t)$ is decomposed into four parts,

$$L(t)=T(t)+P(t)+R(t)+a(t)\,, \tag{1}$$

where $T(t)$ is the trend part, $P(t)$ is the periodic part, $R(t)$ is the residual stochastic time series, and $a(t)$ is the white noise series.

The trend part is fitted by a linear regression. The cryptic period in the time series is obtained with the maximum entropy spectrum. After substituting the two parts to Eq. (1), a linear model is built with the coefficients obtained from the least square method. The residual deviation series are obtained after subtracting certain parts from the original data. The AR(p) series model is established based on the residual deviation series. Moment number p is obtained from the least information criterion (AIC). Combining the trend part, the periodic part and the AR model, the final nonlinear superposition model is obtained. The previous parameters are used as initial values, and the iterative nonlinear least square method is adopted to obtain the parameters in the superposition model based on the original data. With more original data, these parameters can be updated dynamically, which are then substituted to superposition model for sea level prediction.

3.2 Numerical Modeling of the Tidal Waves in the East China Sea

Since the long-term sea-level variation affects notably the tidal waves in the East China Sea (Yu *et al.*, 2003), the tidal waves in the East China Sea are simulated with the Princeton Ocean Model. This is a 3-D barotropic hydrodynamic numerical model, with a *k-kl* turbulence closure sub-model developed by Princeton University (Mellor and Yamada, 1982). The model is applied for a scenario with normal sea level and a scenario with sea-level rise. The constant mean sea level is assumed in the scenario with normal sea level. The sea-level rise of the East China Sea over the next 30 years is calculated based on the existing rate of sea-level rise.

The modeling domain as shown in Fig. 2 is discretized by a grid with a size of 6’ (9.648 km) in longitudinal direction and 6’ (11.08 km) in latitudinal direction. The open boundaries at the east and south side of the domain are imposed with harmonic constants of the four major tidal components (M_2, S_2, K_1 and O_1) obtained from 25 tidal gauges. For the scenario with sea-level rise, the sea level at open boundaries follows the rising sea-level over the next 30 years. The model is calibrated by using the tidal levels of 12 tidal gauges along the coast (Fig. 2) and by assuming a roughness of 0.01 in the Bohai Sea and 0.025 in the Yellow Sea and the East China Sea.

The model is validated by comparing the simulation results for the major harmonic constants with the measured data from 13 tidal gauge stations near the Yangtze Estuary and the Hangzhou Bay. The mean error of the tidal amplitude and phase-lag of M_2 is 1.45 cm and 5.64º respectively, and that of K_1 is 1.04 cm and 6.48º respectively. For M_2 and K_1 components, the mean square deviation of the tidal amplitude is smaller than 4 cm, and that of the phase-lag is smaller than 8.5º. It shows that the simulations fit well with the observations.

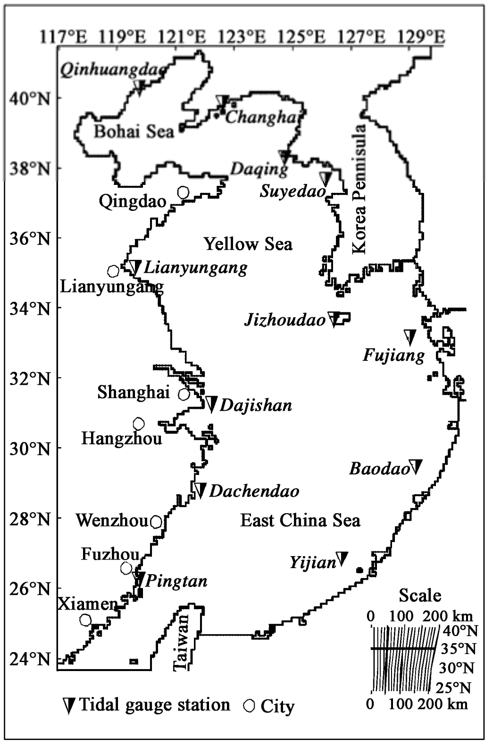

Fig. 2. Tidal wave modeling domain and tidal gauges in the East China Sea.

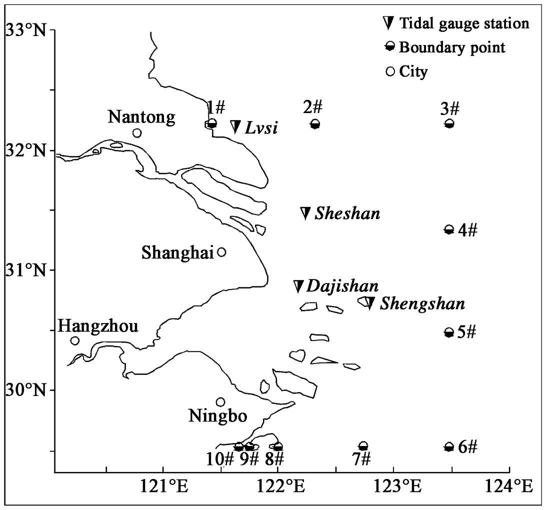

Fig. 3. Locations of open sea boundary points and long-term tidal gauges for model validation.

The harmonic constants of 12 tidal components at 10 points outside the Yangtze Estuary and the Hangzhou Bay (Fig. 3) are used as the open boundary conditions for the detailed hydrodynamic model of the estuarine areas. In addition, the tidal wave characteristics at these boundary points, such as the tidal range, the duration of flood tide and ebb tide, obtained from the scenario with sea-level rise are compared with the characteristics obtained from the scenario with normal sea level.

3.3 Hydrodynamic Numerical Modeling of the Yangtze Estuary and the Hangzhou Bay

A 2-D hydrodynamic numerical model covering the Yangtze Estuary and the Hangzhou Bay has been built, in order to analyze the variations of tidal level response along the tidal reaches in the Yangtze Estuary, as well as the impacts of upstream discharge on tidal level response, due to the sea-level rise of the East China Sea. The model has a length of approximately 400 km from west to east and a width of approximately 300 km from south to north (Fig. 3). The upstream open boundary is located at the Zhenjiang cross-section of the Yangtze River (Fig. 1). The upper part of the Hangzhou Bay is closed neglecting the upstream discharge. The open sea boundaries consist of 10 points outside the estuaries (Fig. 3). The modeling area is discretized by non-structural triangle cells, according to the finite volume method.

Because of the lack of simultaneous measurements in the large-scale modeling domain, the area is divided into several parts. Each part is calibrated by use of the data available in that part, involving water levels, flow velocities, discharges and the diversion ratio of bifurcated reaches. The lower part of the Yangtze Estuary is calibrated by use of the measurements performed during the period 21~30 September 2002, including the water levels at the stations of Xuliujing, Changxing and Lianxinggang, as well as the flow velocities in the cross-sections of Xuliujing, the North Channel and the South Channel etc. The upper part of the Yangtze Estuary is calibrated by the discharges in the cross-section of Paotaiwei near Jiangyin measured during 26~27 March 2005, as well as the water levels, flow velocities and the diversion ratio measured on the 4th of May 2005 in the bifurcated cross-sections of Lu'anzhou near Deshenghe. The roughness of the main channel is 0.011~0.016 and that of the tidal flats is 0.020~0.030. Finally, the validation of the model is carried out by use of the tidal levels measured in August 2006 at the main tidal gauges in the Yangtze Estuary and in the Hangzhou Bay, such as Jiangyin, Wusong, Luchaogang and Ganpu etc (Fig. 1). The validation shows satisfying model results.

In consideration of the notable influence of upstream discharge on the tidal level in tidal reaches, the tidal conditions at Zhenjiang in 1971 are adopted as a typical scenario with an annual mean discharge of 23100 m^3/s at Datong. From January to May, the monthly mean discharge increases from 11600 m^3/s to 24400 m^3/s. During the flood season from June to September, the monthly mean discharge decreases from 49600 m^3/s to 28600 m^3/s, and finally to 9180 m^3/s in December. For higher monthly mean discharge, the tidal conditions at Zhenjiang during the July and August 1999 are supplemented as a scenario with a monthly mean discharge of 73900 m^3/s and 60100 m^3/s respectively. Contrary to the scenario with normal sea level, the distinctive magnitude and spatial variations of monthly mean tidal level along tidal reaches due to sea-level rise over the next 30 years are associated with different upstream discharges.

3.4 Analysis of Linear Rate of Sea-Level Rise Based on Long-Term Measurements

The tidal level response to sea-level rise has been studied by predicting the rate of sea-level rise in open sea and subsequently by modeling the variations of tidal level along tidal reaches. For comparison purposes, tidal level measurements of two tidal gauges, Xuliujing and Yanglin (Fig. 1), are used to determine the linear rate of sea-level rise in tidal reaches.

In the estuarine areas, the seasonal changes of the mean sea level are influenced mainly by upstream discharge, but also by air pressure and air temperature (Shen and Wang, 1990). At certain tidal gauges in tidal reaches, upstream discharge may have a significant influence on tidal level (Li *et al.*, 2006). In order to analyze the variation of the annual mean sea level due to sea-level rise, the tidal level measurements must be corrected for the effect of upstream discharge (Chen, 1990).

In the present study, the hourly water levels measured at stations of Xuliujing and Yanglin during the period 1993~2009 were collected by Yangtze River Estuary Survey Bureau of Hydrology and Water Resource, Ministry of Water Resources, as well as the daily mean discharges measured at Datong. It is clear that the predicted tidal levels are very close to observations when the period of prediction is within that of harmonic analysis. However, it is not the case when the period of prediction is beyond that of harmonic analysis. By averaging the harmonic constants and mean sea levels of each year over the period 1993~2009, the mean harmonic constants and the annual mean sea level are used to predict the tidal levels within the period. It is assumed that the predicted tidal levels are associated with the uniform discharge during the period of 1993~2009. However, it should be noted that the tidal level response to sea-level rise is excluded in the predicted tidal levels, because the annual mean sea level is adopted for prediction. As an example, the observed, predicted and corrected tidal level, at the stations of Xuliujing and Yanglin in 1998 and 2001 respectively, are shown in Fig. 4, with the discharge increment representing the difference between the discharge of a certain prediction date and that averaged over the period 1993~2009. It is found that there is some discrepancy between the predictions and observations, especially when the discharge increment is significant.

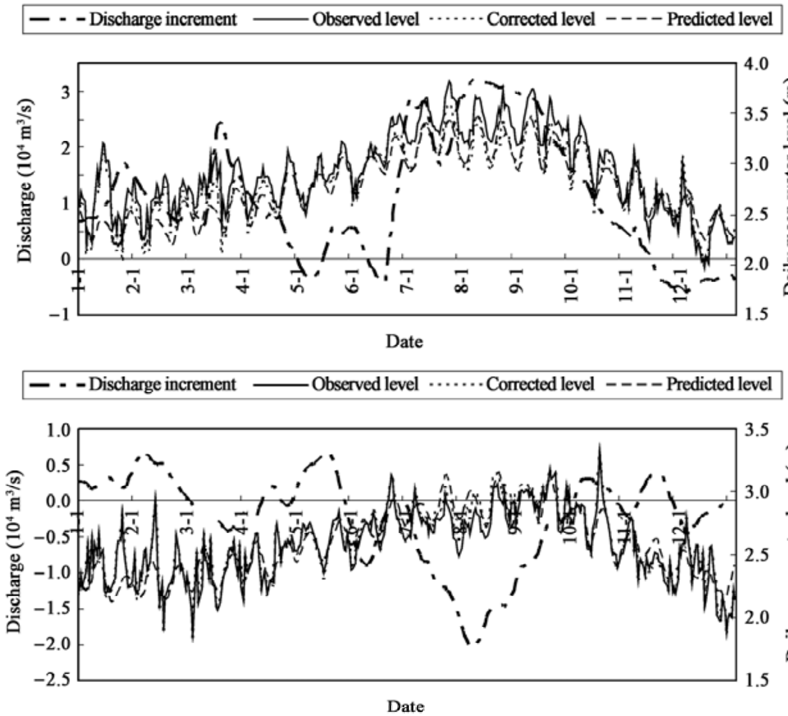

Fig. 4. Time series of discharge increment, observed, corrected and predicted water level (upper: at Xuliujing in 1998, lower: at Yanglin in 2001).

This study proposes correlations between the increment of the daily mean discharge at Datong and that of the daily mean water level during the period 1993~2009, which are applicable for hourly level correction (Fig. 5). For the stations of Xuliujing and Yanglin (Fig. 1), these correlations are:

$$\Delta Z_{\mathrm{xlj}} = -0.0116\Delta Q^2 + 0.1215\Delta Q + 0.0186\,; \tag{2}$$

$$\Delta Z_{\mathrm{yl}} = -0.0047\Delta Q^2 + 0.0671\Delta Q + 0.0177\,, \tag{3}$$

where ΔZ_{xlj} and ΔZ_{yl} are the increments of the daily mean water levels at Xuliujing and Yanglin respectively, and ΔQ is the increments of the daily mean discharges at Datong. It is estimated that the water wave propagates in about 2~5 days from Datong to the mouth of the Yangtze River. Therefore, the discharge at Datong measured three days in advance is used to correct the water levels of the reference date. The proposed correlations agree well with those of Li *et al.* (2006) based on the observations during the period 1997~2003, except that there is some discrepancy in dry season (Fig. 5). The observed water levels are corrected by use of the proposed correlations and shown in Fig. 4. Errors of daily mean water level with and without correction are shown in Table 1. It shows that the corrected levels are much closer to the predicted levels than the observations especially when the discharge increment is significant. It means that the correction eliminates the influence of different upstream discharge on tidal level during the period 1993~2009.

On the basis of the corrected hourly water levels, the linear rate of sea-level rise at the tidal reaches is determined from a trend analysis of the annual mean sea levels over the period 1993~2009.

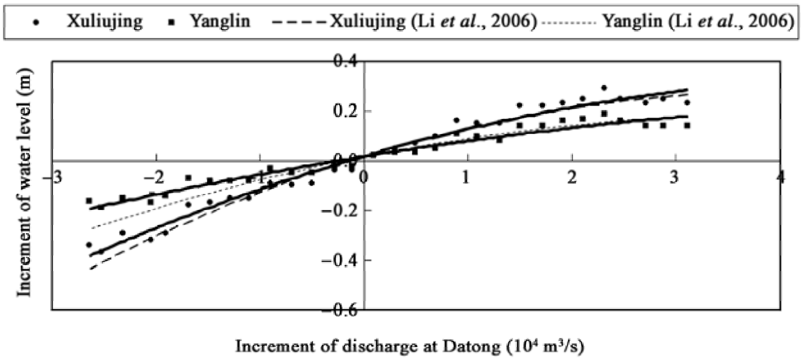

Fig. 5. Correlations between the increment of the daily mean discharge at Datong and that of the daily mean water level during the period 1993~2009.

Table 1 Errors of daily mean water level with and without correction

Station	Errors of absolute value (cm)		Percentage for error≦10 cm (%)		Percentage for error≦20 cm (%)		Percentage for error≦30 cm (%)	
	Without	With	Without	With	Without	With	Without	With
Xuliujing	13	10	47.8	61.9	78.3	88.9	93.3	96.7
Yanglin	11	10	56.5	62.5	85.6	88.1	95.8	96.4

Note: (1) 'Without' means the comparison between the observed level and the predicted level.
(2) 'With' means the comparison between the corrected level and the predicted level.

4. Results and Discussions

4.1 Mean Rate of Sea-Level Rise of the East China Sea

The outcome of the stochastic dynamic analysis and forecast model, using the Topex/Poseidon altimeter data during the period 1993~2005, is a mean rate of sea-level rise of 4.87 mm/a for the East China Sea and of 5.61 mm/a for the area near the Yangtze Estuary.

The tidal level measurements of the four tidal gauges (Fig. 3) outside the Yangtze Estuary are used to calculate the mean rate of sea-level rise (Table 2). It is found that the rate of sea-level rise near the Yangtze Estuary is 4~6 mm/a since the 1970s, and that the rate obviously increased during the last decade. The IPCC (Intergovernmental Panel on Climate Change) reported that the rate of sea-level rise along the coast of the East China Sea is 4.5 mm/a. It shows that the present predictions are reasonable.

Table 2 Rate of sea-level rise outside the Yangtze Estuary

Station	Tidal level measurements	Rate of sea-level rise (mm/a)
Dajishan	January 1978~ December 2006	4.0
Lvsi	January 1969~December 2006	6.2
Shengshan	January 1996~December 2006	6.3
Sheshan	January 2003~ December 2006	9.7

4.2 Changes of Tidal Wave Characteristics Due to Sea-Level Rise

Based on a mean rate of sea-level rise of 4.87 mm/a, the sea level in the East China Sea will rise with about 14.61 cm during the next 30 years. This is equivalent to a lowering of the topography of the East China Sea with the same rate in the scenario with sea-level rise. It will generate some influences on tidal wave characteristics, including the tidal range, the duration of flood and ebb tide, etc.

The changes of the tidal wave characteristics at 10 boundary points (Fig. 3) due to sea-level rise over the next 30 years are presented in Table 3. Compared with the scenario with normal sea level, a trend can be observed that the duration of flood tide gets slightly longer while that of ebb tide becomes shorter accordingly. The maximum change is 4.2 minutes. The tidal range decreases slightly with a maximum change of 2.7 cm.

Yu *et al.* (2003) concluded that in general tidal amplitude increases with rising mean sea level in most of nearshore areas rather than in deep ocean. In the northeast of the Yangtze Estuary, the tidal amplitude decreases most remarkably with the rising mean sea level (such variation is called variation out of the phase). Meanwhile, the corresponding locations are different for semidiurnal tide and diurnal tide. The amplitude of semidiurnal tide is maximally out of the phase in the region between the Yangtze Estuary (and the Hangzhou Bay) and the west coast of South Korea. The amplitude of diurnal tide is maximally out of the phase in the region between the Yangtze Estuary and the amphidromic point of semidiurnal tide near Lianyungang (Fig. 2).

In present study area, the semidiurnal tide is dominant. The north-west corner of the open boundaries (points 1 and 2) is located in the transitional area. The tidal amplitude variation is in the phase in the north of the Yangtze Estuary, and out of the phase in the south of the Yangtze Estuary. Therefore, the changes of the tidal wave characteristics at points 1 and 2 differ from those at somewhere else.

Table 3 Changes of tidal wave characteristics due to sea-level rise over the next 30 years

Points	1	2	3	4	5	6	7	8	9	10
Duration of flood tide (min)	–1.8	0	3.0	3.6	3.0	1.8	0.6	2.4	4.2	3.0
Duration of ebb tide (min)	1.8	–0.6	–3.0	–4.2	–3.0	–1.2	–0.6	–1.8	–4.2	–3.0
Tidal range (cm)	6.5	0.2	–1.5	–2.3	–1.5	–0.4	–0.5	–2.1	–2.7	–2.6

Note: The minus value represents the shortened duration of flood/ebb tide, or the decreased tidal range for the scenario with sea-level rise.

4.3 Tidal Level Response Along the Yangtze Estuary Due to Sea-Level Rise

The 2-D hydrodynamic numerical model covering the Yangtze Estuary and the Hangzhou Bay is used for the scenarios with normal sea level and sea-level rise respectively, applying the appropriate boundary conditions obtained from the East China Sea model. The tidal conditions at Zhenjiang during the period 1971 and July~August 1999 are used for the upstream open boundary conditions. The monthly mean discharge varies from 9180 m^3/s to 73900 m^3/s.

For certain stations in the tidal reaches, the monthly mean tidal level is simulated for the combination of upstream discharge and open sea boundary conditions for both scenarios with normal sea level and sea-level rise. The variation of the monthly mean tidal level associated with the same upstream discharge reflects the contribution of sea-level rise. However, the variation of the tidal level in the scenario with sea-level rise reflects the influence of upstream discharge on monthly mean tidal level. Along the Yangtze Estuary, data of typical stations are extracted for analyzing the rate of sea-level rise. The relative distances from Zhenjiang downwards are listed in Table 4.

Table 4 Relative distance from Zhenjiang to the tidal gauge stations (km)

Station	Jianbi	Jiuquhe	Deshenghe	Jiangyin	Zhangjiagang
Relative distance	18	54	79	113	138
Station	Shiyiwei	Xuliujing	Yanglin	Wusong	Luchaogang
Relative distance	180	220	260	298	378

The rate of sea-level rise along the Yangtze Estuary associated with different discharge is presented in Fig. 6. For more clarity, curves are listed with a monthly mean discharge increase of approximately 10000 m^3/s from its minimum to maximum, in which the thick curves in 1999 are combined with the thin curves in 1971. When the same upstream discharge occurs, the rising rate of monthly mean tidal level decreases from the river mouth upwards and nearly gets the minimum at the station of Jianbi. This means that the contribution of sea-level rise on the tidal level in tidal reaches decreases with increasing distance from the river mouth. The step between the stations of Zhangjiagang and Shiyiwei divides the tidal reaches into two parts, in which the tidal level response declines slowly. The rate of sea-level rise is 1~2.5 mm/a between the stations of Jiuquhe and Zhangjiagang, and that is 4~6 mm/a outside the station of Shiyiwei. The step may be caused by the sharp decrease of cross sections between the stations of Zhangjiagang and Shiyiwei, where lie several islands as well.

For certain stations, it is found that the rate of sea-level rise varies in a regular way with the upstream discharge, especially in the upper part of the estuary. This is illustrated for the stations of Jiangyin (located at 113 km in the upper part of the estuary) and Yanglin (located at 260 km in the lower part of the estuary) by showing the relation between the rate of sea-level rise and the upstream discharge. The relation for Jiangyin is fitted well by a quadratic function rather than for Yanglin (Fig. 7). In the case of low discharge, the rate of sea-level rise increases with increasing upstream discharge, whereas it decreases beyond the threshold discharge of approximately 40000 m^3/s. This means that upstream discharge below the threshold has a positive contribution to the tidal level response in the tidal reaches to the sea-level rise in open sea, whereas it has a negative contribution when discharge is above the threshold.

In the lower part of the estuary, the tide is dominant relative to the upstream discharge. When the runoff and the tidal range in the Yangtze Estuary are in their annual mean level, the flood tide discharge is 266300 m^3/s, which is about nine times the annual mean upstream discharge (Chen *et al.*, 1991). Thus, here the upstream discharge has very little impact on the contribution to the tidal level response in the tidal reaches to the sea-level rise in open sea.

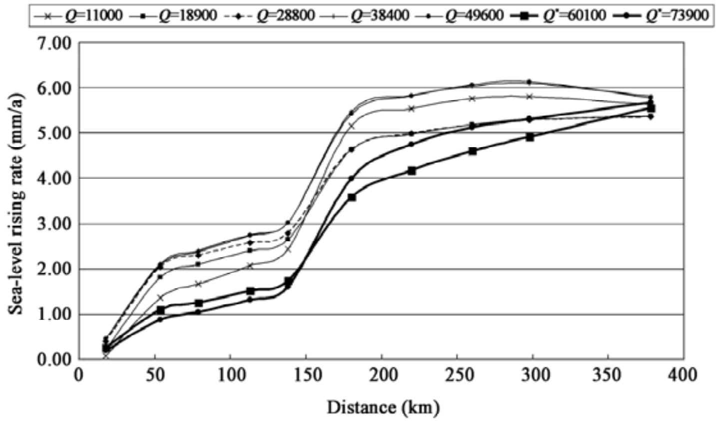

Fig. 6. Rate of sea-level rise along the Yangtze Estuary for different discharge (Q means the discharge in 1971 and Q* means the discharge in 1999).

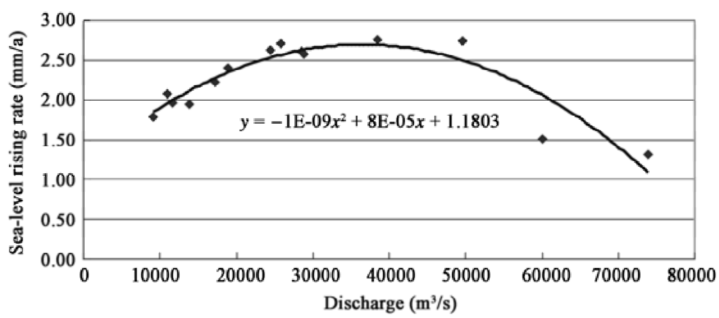

Fig. 7. Relation between discharge and rate of sea-level rise in Jiangyin.

4.4 Linear Rate of Sea-Level Rise Based on Long-Term Measurements

The variation of the annual mean sea level at Yanglin and Xuliujing is shown in Fig. 8, associated with the annual mean discharge measured during the period 1993~2009. Although the annual mean discharge shows a periodic fluctuation, it decreases gradually at a rate of 439 m^3/s/a. The annual mean sea-level at Xuliujing is higher than that at Yanglin, because the former is about 40 km more upstream than the latter. The linear rate of sea-level rise at Xuliujing and Yanglin is 3.0 mm/a and 6.6 mm/a respectively, which is qualitatively consistent with the preceding results. The mean discharge by averaging over the period 1993~2009 is 28550 m^3/s, which is very close to 28400 m^3/s, the annual mean discharge during the period 1950~2007. The rate of sea-level rise at Xuliujing and Yanglin should be about 5 mm/a according to the curves shown in Fig. 6, and the former is slightly lower than the latter. It shows that these results agree well with each other.

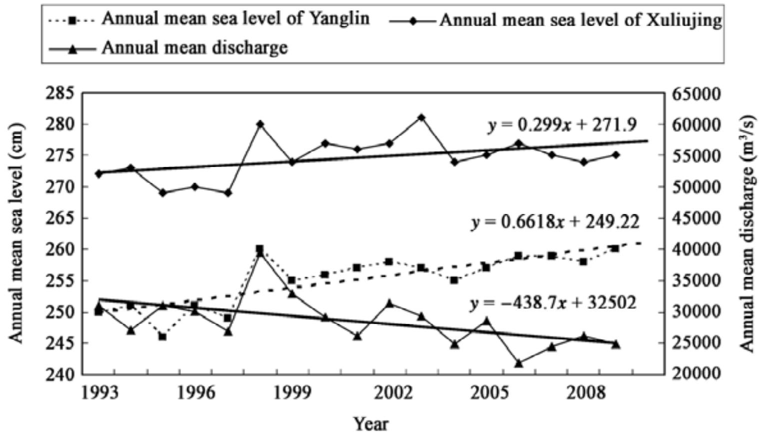

Fig. 8. Variation of annual mean sea level of Yanglin and Xuliujing, as well as annual mean discharge at Datong measured during the period 1993~2009.

5. Conclusions

Global warming is unavoidably causing the sea level to rise, which in turn causes the tidal level in tidal reaches to rise. This will induce higher flood risk, more serious salt intrusion and so on. Numerous researchers have focused a lot on estimating the rate of sea-level rise and the causes of it. However, not much attention has been given yet on the response of the tidal level in tidal reaches to sea-level rise. This study focuses on the variations of tidal level response along the tidal reaches in the Yangtze Estuary, as well as the impacts of upstream discharge on tidal level response, due to the sea-level rise of the East China Sea. For comparison purposes, long-term hourly tidal level observations at two tidal gauges are used to evaluate the rise of annual mean tidal level.

In the present study, the integrated methods are used to analyze the tidal level response to sea-level rise in the Yangtze Estuary, including the stochastic dynamic analysis and forecast model for predicting the sea-level rise of the East China Sea, 2-D hydrodynamic numerical models downscaling from the East China Sea to estuarine areas for analyzing the rise of tidal level along the tidal reaches due to sea-level rise. For comparison purposes, long-term hourly tidal level observations at two tidal gauges are used to evaluate the rise of annual mean tidal level. The results show that the above methods are reasonable and feasible for analyzing the tidal level response in tidal reaches due to sea-level rise.

The mean rate of sea-level rise of the East China Sea is 4.87 mm/a, and that of the area near the Yangtze Estuary is 5.61 mm/a. Sea-level rise has an influence on the tidal wave characteristics in nearshore areas outside the estuaries. Owing to sea-level rise over a period of 30 years, the duration of flood tide gets slightly longer while that of ebb tide becomes shorter accordingly. The tidal range decreases slightly. This type of change of the tidal wave characteristics is called out of the phase (Yu *et al.*, 2003).

The contribution of sea-level rise on the change of the tidal level in the tidal reaches decreases with the increasing distance from the river mouth. The step between the stations of Zhangjiagang and Shiyiwei divides the tidal reaches into two parts, in which the tidal level response declines slowly. The rate of sea-level rise is 1~2.5 mm/a between the stations of Jiuquhe and Zhangjiagang, and that is 4~6 mm/a outside the station of Shiyiwei. The step may be caused by the sharp decrease of cross sections between the stations of Zhangjiagang and Shiyiwei, where lies several islands as well. However, the exact reason deserves to be studied in further research.

In the upper part of the estuary, the relation between the rate of sea-level rise and the upstream discharge is fitted well by a quadratic function. The upstream discharge below the threshold discharge of approximately 40000 m^3/s has a positive contribution to the tidal level response in tidal reaches to sea-level rise in open sea, whereas it has a negative contribution when the discharge is above the threshold. In the lower part of the estuary, the tide is dominant relative to the upstream discharge. Thus, the upstream discharge has little impact on the contribution to tidal level response in tidal reaches due to sea-level rise in open sea.

This study proposes correlations between the increment of the daily mean discharge at Datong and that of the daily mean water level during the period 1993~2009. On the basis of the corrected hourly water levels during the period 1993~2009, the linear rate of sea-level rise at Xuliujing and at Yanglin is 3.0 mm/a and 6.6 mm/a respectively. The mean discharge by averaging during the period 1993~2009 is 28550 m^3/s, and the rate of sea-level rise at Xuliujing and Yanglin should be about 5 mm/a according to the proposed relation between the rate of sea-level rise and the discharge. It can be found that these results agree well with each other. In further research, long-term tidal levels at the upper part of the estuary need to be collected for analyzing the linear rate of sea-level rise.

The eustatic sea-level rise is obtained from the Topex/Poseidon altimeter data. In contrast, the relative sea-level rise, traditionally defined as the combination of the eustatic sea-level rise and subsidence, is obtained from the measurements of tidal gauges. Effective sea-level rise is the combination of relative sea-level rise and the gross rate of fluvial sediment deposition, and it has direct impacts on the coastal disasters (Ericson *et al.*, 2006). The construction of upstream reservoirs has resulted in decreased fluvial accretion (Walling and Fang, 2003) and in turn increases the effective sea-level rise. In future studies, the integrated considerations of eustatic sea-level rise, subsidence and fluvial sediment deposition are requested to assess the impacts of the effective sea-level rise on deltas.

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