



Changes of Extreme Sea Level in 1.5 and 2.0°C Warmer Climate Along the Coast of China

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Using hourly sea level data from 15 tide gauges along the Chinese coast and sea level data of three simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5), we assessed the changes and benefits of the extreme sea level of limiting warming to 1.5°C instead of 2.0°C. Observations show that the extreme sea level has risen with high confidence during the past decades along the coast of China, while the mean sea level change, especially the long-term change plays important roles in the changing process of extreme sea levels. Under the 1.5 and 2.0°C warming scenarios, the sea level will rise with fluctuations in the future, so will the return levels of the extreme sea levels. Compared with the 1.5°C warming condition, the return levels under the 2.0°C warming condition will rise significantly at all tide gauges along the Chinese coast. The results indicate that a 0.5°C warming will bring much difference to the extreme sea levels along the coast of China. It is of great necessity to limit anthropogenic warming to 1.5°C rather than 2.0°C, as proposed by the Paris Climate Agreement, which will greatly reduce the potential risks of future flood disasters along the coast of China and is beneficial for risk response management.

Keywords: extreme sea level, return sea level, sea level rise, projection, storm surge

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INTRODUCTION

China has the largest coastal population in the world, with more than 40% people living in the coastal area, where the extreme sea level disasters occur frequently and have caused serious negative impacts. According to the China Marine Disaster Bulletin¹, the extreme sea level incidents have caused economic losses of 11.1 billion (RMB) and 49 deaths annually between 2000 and 2017.

Increases in the mean and extreme sea levels are regarded as one of the consequences of climate change (Church et al., 2013). In recent years, many studies have been done about the changes of extreme sea levels both regionally and globally (von Storch and Reichardt, 1997; Woodworth and Blackman, 2004; Méndez et al., 2007; Menéndez and Woodworth, 2010; Feng et al., 2015; Marcos and Woodworth, 2017). Substantial evidences have revealed the general increase in extreme sea level in the past decades worldwide. Many researches indicated that the changes of the extreme sea level, especially the long-term change, are highly correlated with the changes of mean sea level (Zhang et al., 2000; Woodworth and Blackman, 2004; Marcos et al., 2009; Menéndez and Woodworth, 2010; Tsimplis and Shaw, 2010). Meanwhile, statistical method and dynamical method

¹<http://www.soa.gov.cn/zwgk/hygb/>

are utilized to study the future changes in extreme sea level. The extreme sea levels will increase as mean sea levels rise in the future according to the future projection (Langenberg et al., 1999; Busuicoc et al., 2006; Woth et al., 2006; Grossmann et al., 2007).

Compared with the mean sea level (Ding et al., 2001; Yu et al., 2003; Zuo et al., 2007; Wang et al., 2018), fewer studies have been conducted to analyze the extreme sea levels along the China coast in the past. Chen and Wang (1993) found that the extreme sea level at Wusong and Huangpu Park increased between 1915 and 1985. Feng and Tsimplis (2014) and Feng et al. (2015) analyzed the changes of extreme sea levels using tide gauge data and indicated that the extreme sea level increased in the past decades, while the long-term change of extreme sea level was mainly affected by the change of mean sea level. Ma et al. (2016) discovered that the return levels of extreme sea level during 1980–2012 were higher than those during 1950–1979 at Tianjin. Due to the uneven distribution of tide gauges and data limitation, most studies above concentrated on the Yellow Sea, East China Sea, and the South China Sea. Besides, few work focuses on analyzing the future changes of extreme sea levels along the China coast.

The Paris Climate Agreement aims to hold global warming well below 2.0°C and to pursue efforts to limit it to 1.5°C above preindustrial temperature. Recently, increasing studies have been performed to investigate the extreme climate events at the 1.5 and 2.0°C warming levels and the superiority of limiting warming to 1.5°C rather than 2.0°C (Schleussner et al., 2016; Donnelly et al., 2017; Karmalkar and Bradley, 2017; King and Karoly, 2017; King et al., 2017; Lehner et al., 2017; Xu et al., 2017; Li et al., 2018). It is necessary to quantify the extreme sea levels changes under the 1.5 and 2.0°C warming scenarios and evaluate the differences between them.

In this paper, hourly sea level data from 15 tide gauges along the China coast and sea level data from three simulations of the Coupled Model Intercomparison Project Phase 5 (CMIP5) were used to answer the following questions: (1) How did the extreme sea level change during the past decades? (2) How will the extreme sea level change in future 1.5 and 2.0°C warming scenarios? (3) What will the extreme sea level differences be between 1.5 and 2.0°C warming climate?

DATA AND METHODS

Data

Observed and numerical sea level data are applied in this study, including hourly sea level data from 15 tide gauges (Huludao, Qinhuangdao, Longkou, Yantai, Rizhao, Lusi, Dajishan, Zhenhai, Kanmen, Shansha, Xiamen, Shanwei, Zhapo, Haikou, and Beihai) along the China coast, and three CMIP5 simulations results downloaded from the online CMIP5 datasets (CNRM-CM5, BCC-CSMI-1, MIROC-ESM-CHEM).

The gauge data were obtained from the marine monitoring stations in China (Figure 1), dating from January, 1980 to December, 2016. All these data last for more than 30 years, which is essential to get the trends accurately (Feng et al., 2015). Careful quality control had been done to delete the data spikes and

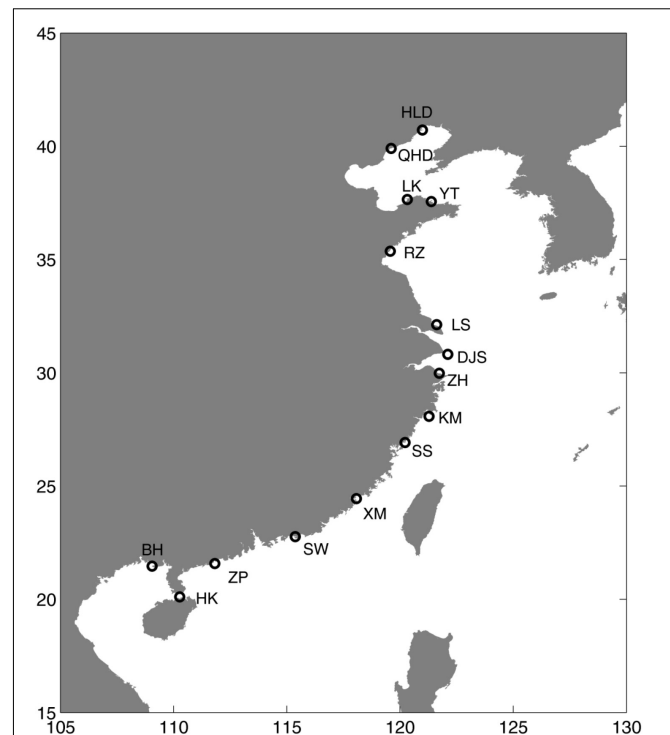


FIGURE 1 | Locations of 15 tide gauges along the coast of China used in this work: HLD, Huludao; QHD, Qinhuangdao; LK, Longkou; YT, Yantai; RZ, Rizhao; LS, Lusi; DJS, Dajishan; ZH, Zhenhai; KM, Kanmen; SS, Shansha; XM, Xiamen; SW, Shanwei; ZP, Zhapo; HK, Haikou; and BH, Beihai.

spurious records (Wang et al., 2013). In addition, data availability less than 60% were excluded in the analysis.

The sea-level projection in this study is based on CMIP5 numerical simulations. Three models were selected in this work (Table 1). The sea level data reached the warming limits of 1.5 and 2.0°C were used. Two oceanic data categories, i.e., “zostoga” (the global average sea-level change due to thermal expansion) and “zos” (the local steric and dynamic adjustment of sea-level change) are used to project the regional sea level change. The data were modified in each model through the following procedures: (I) perform a quadratic-fit as a function of time at each grid point of the piControl experiment; (II) remove the quadratic-fitted control drift from the corresponding grid point of the historical and RCPs (Representative Concentration Pathways) experiments; (III) subtract the global mean of the “zostoga” and “zos” field at each time step from each grid point (Slangen et al., 2014). The projected contributions from land ice and land water storage to local sea-level change are obtained by multiplying the

TABLE 1 | The selected CMIP5 simulations.

	Resolution	Period	Selected period
CNRM-CM5	0.6° × 1.0°	2006–2100	2006–2060
BCC-CSMI-1	0.8° × 1.0°	2006–2100	2006–2050
MIROC-ESM-CHEM	0.7° × 1.2°	2006–2100	2006–2042

global mean estimates from IPCC AR5 by the regional scaling factors given by Slangen et al. (2014). All glaciers, ice caps and the ice sheets on Greenland and Antarctica are comprised in the land ice contribution. In addition, the glacier isostatic adjustment (GIA) is also included here (Slangen et al., 2014).

Sea level data from tide gauge and satellite located in the Xisha (111.51°N, 16.44°E) were used to validate the sea level data from three models (Figure 2). Results show that although there are some differences between the observations and the model results at the interannual and decadal time scales, all three models are in good agreement with the observations at the long-term time scale. These results enhance the confidence in the quality of the projected data got from the three climate models.

Methodology

The extreme sea levels defined as the maximum level during a selected period, usually a year, were mainly caused by the storm surges. It was usually the maximum water level during a storm surge event. To calculate the precise extreme sea level rise rates and to identify potential rate changes are of vital importance for this study. In general, the sea level change trend is estimated by analyzing its oscillatory behavior, which means extracting periodic components from original observations successively until there is no periodic component left (Jevrejeva et al., 2006; Ezer and Corlett, 2012; Breaker and Ruzmaikin, 2013). Due to the empirical, intuitive, direct and adaptive characteristics, the empirical mode decomposition (EMD) method is suitable for estimating the accurate long-term trend of the sea level data (Huang et al., 1998, 1999) and has been widely used to get the long-term change of the mean sea levels recently (Ezer and Corlett, 2012; Breaker and Ruzmaikin, 2013; Ezer et al., 2013; Uranchimeg et al., 2013).

The EMD method decomposes an arbitrary time series $X(t)$ into a finite and often small number of intrinsic mode functions (IMFs), which are defined as any function with an equal number of extreme and zero-crossing. Then $X(t)$ can be described as:

$$X(t) = \sum_{j=1}^n IMF_j + r_n$$

where n is the number of IMFs, and r_n is the residual. For more descriptions of the EMD method, refer to Huang et al. (1998).

Ensemble empirical mode decomposition (EEMD) is the improved method to obtain IMFs with more direct physical meaning and greater uniqueness (Wu and Huang, 2009). EEMD was estimated by averaging numerous EMD runs with the addition of some white noise. By averaging the different decompositions, the noise was averaged out and the true decomposition was calculated with a confidence estimate. The EEMD method was used to analyze the extreme sea levels in the study.

The risks associated with extreme sea levels can be assessed from the estimates of return levels and return periods. The return period of extreme sea level is defined as the sea level statistically expected to be equaled or exceeded every specific year. The Federal Emergency Management Agency [FEMA] (2004) recommended the frequency analysis method to obtain the return levels. The traditional probability distribution methods, including the Gumbel, Weibull, Generalized Pareto Distribution (GPD), and Generalized Extreme Value (GEV) distributions, are typically used to analyze annual extreme sea levels. According to previous studies (Vogel et al., 1993; Huang et al., 2008; Feng and Jiang, 2015) the GEV distribution was used in this work to get the return levels of the extreme sea levels. As

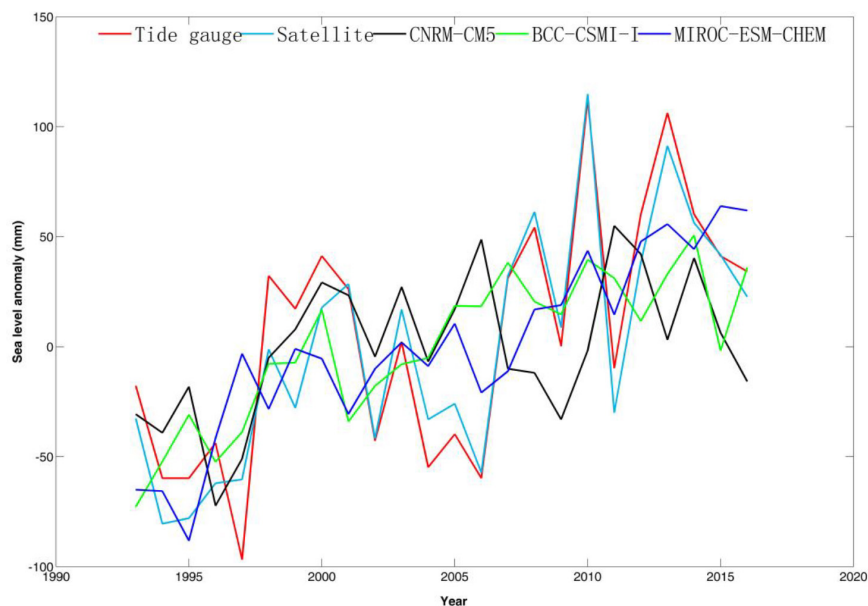


FIGURE 2 | The sea level anomaly calculated using the data from the tide gauge, the satellite, CNRM-CM5, BCC-CSMI-I, and MIROC-ESM-CHEM during 1993 and 2016.

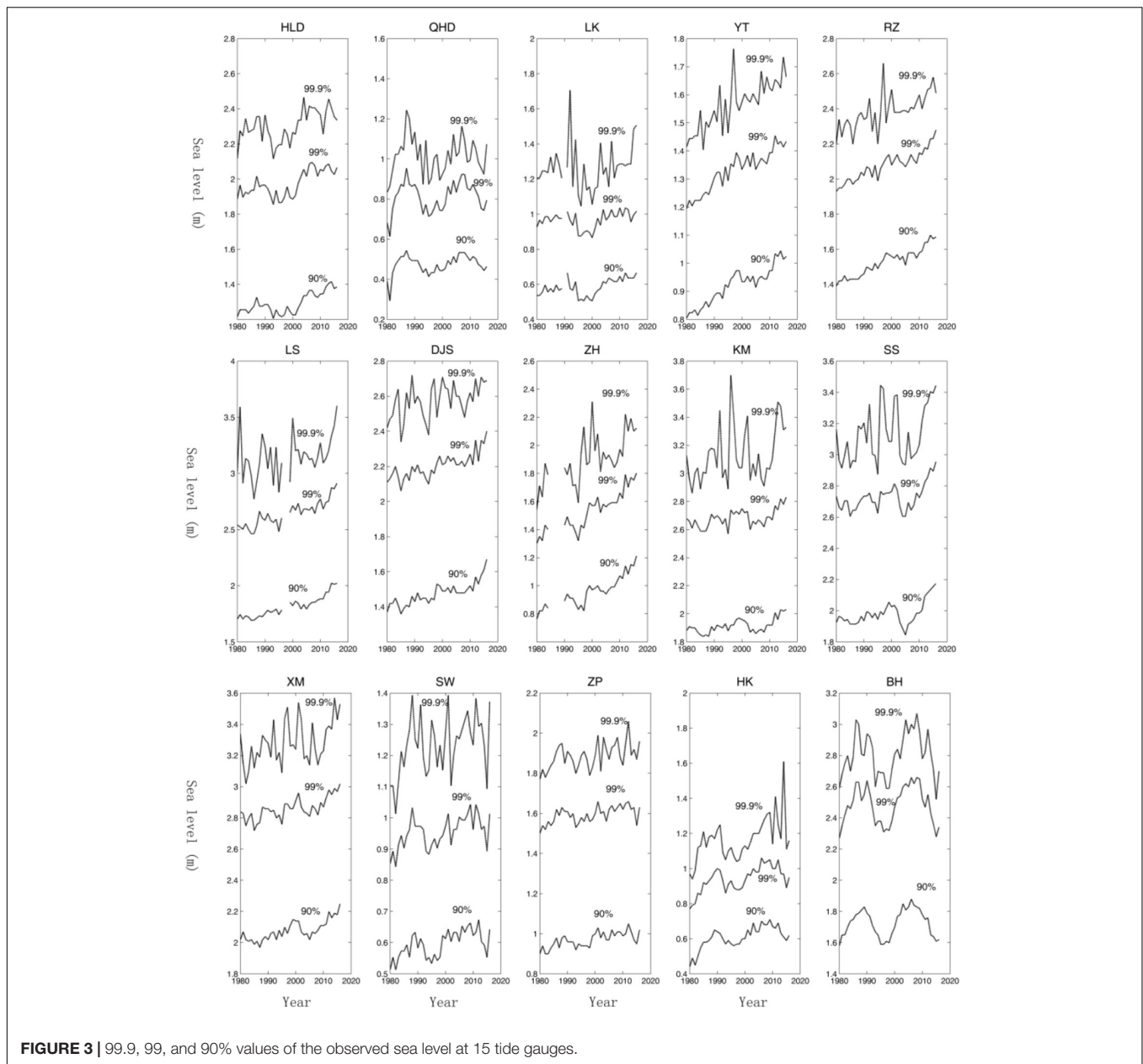


FIGURE 3 | 99.9, 99, and 90% values of the observed sea level at 15 tide gauges.

described in FEMA'S guideline (2014) the GEV distribution can be described by the probability density function (PDF) listed as follows:

$$f(x) = \frac{1}{b} \left\{ 1 + c \left(\frac{x-a}{b} \right) \right\}^{-[1/c-1]} e^{-(1+c(x-a)/b)^{-1/c}}$$

for $-\infty < x \leq a - \frac{b}{c}$ with $c < 0$
 and $a - \frac{b}{c} \leq x < \infty$ with $c > 0$

$$f(x) = \frac{1}{b} \exp \left\{ -\frac{(x-a)}{b} - \exp \left[-\frac{(x-a)}{b} \right] \right\}$$

for $-\infty \leq x < \infty$ with $c = 0$

where, a , b , and c are the location, scale and shape factors.

RESULTS AND DISCUSSION

Changes of the Extreme Sea Level

Percentile analysis method has been widely used to assess the extreme sea level changes (Menéndez and Woodworth, 2010; Feng et al., 2015; Marcos and Woodworth, 2017). 99.9, 99, and 90% levels of the observed sea level have been calculated at all 15 tide gauges (Figure 3). Results show that the three percentile levels of extreme sea level all rose with fluctuations at nearly all tide gauges except at QHD, SW, and BH. Also the long-term trend was not significant at the 95% confidence level at QHD, LK, SW, KM, and BH. Results also show that the increase rates are different at different percentile levels. Meanwhile clear decadal variations and interannual variations exist in the extreme sea

TABLE 2 | Correlation coefficient between the extreme sea level and mean sea level at 15 tide gauges (C1) and the correlations after detrending (C2), the P1/P2 are the p -value from t -test (where $p < 0.05$ means that the correlation was significant at 95% confidence level).

	C1	P1	C2	P2
HLD	0.33	0.04	-0.06	0.73
QHD	0.46	0.01	0.53	0.01
LK	0.28	0.09	0.28	0.09
YT	0.79	< 0.01	0.22	0.19
RZ	0.66	< 0.01	0.21	0.22
LS	0.43	0.01	0.28	0.10
DJS	0.61	< 0.01	0.43	0.01
ZH	0.68	< 0.01	0.39	0.02
KM	0.45	0.01	0.30	0.07
SS	0.66	< 0.01	0.56	< 0.01
XM	0.47	0.01	0.24	0.16
SW	0.41	0.01	0.12	0.47
ZP	0.49	< 0.01	0.19	0.24
HK	0.33	0.05	-0.32	0.05
BH	0.15	0.37	0.12	0.46

levels at all tide gauges. Especially the interannual variation was quite large at KM, SS, XM, and BH, where the amplitude of interannual variations were larger than 0.40 m.

Previous researches Feng and Tsimplis (2014) and Feng et al. (2015) show that the changes of extreme sea levels along the China coast were highly affected by the sea level change especially the long-term change. The correlations between the extreme sea level and mean sea level were calculated and shown in **Table 2**. Results show that the extreme sea levels were significantly correlated with the mean sea levels at most of the 15 tide gauges. The correlations were larger than 0.5 at YT, RZ, DJS, ZH, and SW. There are two tide gauges, LK and BH, where the

extreme sea level was not significantly correlated with the mean sea level. Moreover, the correlation coefficients after detrending were also calculated. Results show that the correlations decrease after detrending. The correlation became non-significant at 95% significant level after detrending at HLD, YT, RZ, LS, XM, SW, ZP, and HK. Results indicate that the changes of mean sea level play important roles in the changes of extreme sea level along the China coast, and mean sea levels mainly affected the long-term change of the extreme sea levels. This conclusion coincides with previous studies, which indicated that the long-term trend of the extreme sea levels was mainly affected by the mean sea levels (Zhang et al., 2000; Woodworth and Blackman, 2004; Marcos et al., 2009).

Using the EEMD method the long term trends of the extreme sea levels along the Chinese coast were estimated in the study. **Figure 4** shows that the extreme sea levels along the Chinese coast show increase trend in general. Meanwhile the long term trends show various patterns at different tide gauges. At HLD, LK, KM, and BH the increase rate accelerates during the past years. At YT, RZ, DJS, ZH, XM, and SS the increase trends were nearly linear. At QHD, SW, and ZP the increase trends were not significant at 95% confidence level. At LS the increase rate first slowed down but after 2000 the increase rate accelerated. At HK the increase trend slowed down during the past years.

Projections of the Extreme Sea Level Return Levels

The projected sea levels from three simulations of the CMIP5 were used in the work (section Data). The sea level data reached the 1.5 and 2.0°C scenario of three models were shown in **Figure 5**. Results show that the sea level of the three selected models rise with fluctuations. The sea levels were much higher at the 2.0°C warming conditions than the 1.5°C warming conditions at all three models. Among the three

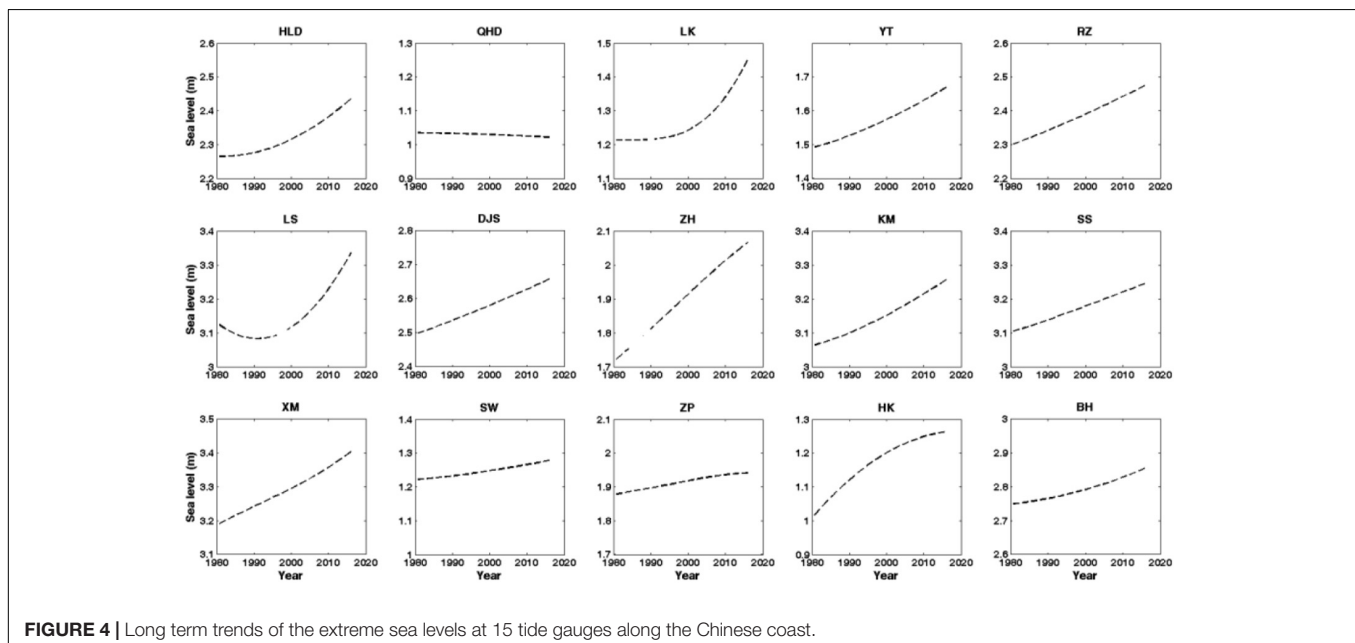


FIGURE 4 | Long term trends of the extreme sea levels at 15 tide gauges along the Chinese coast.

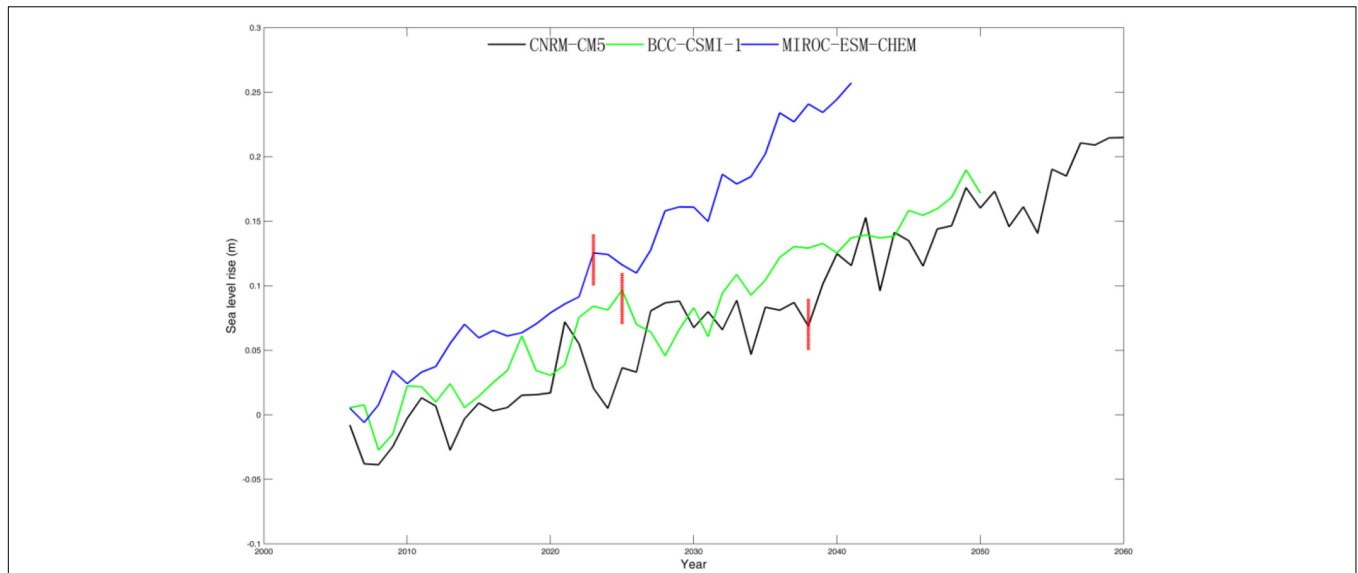


FIGURE 5 | The sea level rise (compared with the mean sea level from 1985 to 2016) of three models under RCP4.5 scenarios, the sea level rise reached the 2°C scenario (whole line), the sea level rise reached the 1.5°C scenario (2006- red line break).

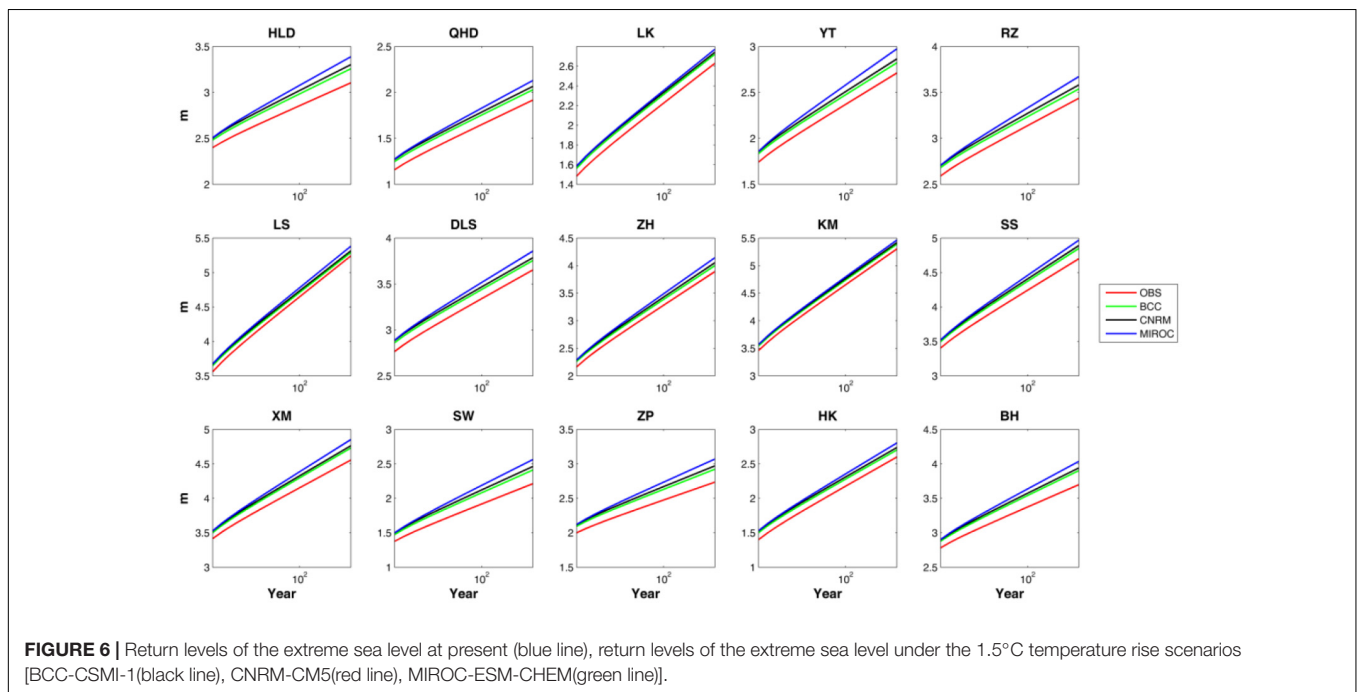


FIGURE 6 | Return levels of the extreme sea level at present (blue line), return levels of the extreme sea level under the 1.5°C temperature rise scenarios [BCC-CSMI-1 (black line), CNRM-CM5 (red line), MIROC-ESM-CHEM (green line)].

models the sea level of the MIROC-ESM-CHEM increased the fastest. The increase rate of the CNRM-CM5 and BCC-CSMI-1 is nearly the same. The CNRM-CM5 reached 1.5°C warming conditions in 2038 and reached 2.0°C warming conditions in 2060. The BCC-CSMI-1 and MIROC-ESM-CHEM reached 1.5 and 2.0°C warming conditions earlier than the CNRM-CM5.

Using the method described in section Methodology the return levels of the extreme sea level under the 1.5 and 2.0°C warming conditions were calculated. **Figures 6, 7** show that the

return levels of the extreme sea level changed under the 1.5 and 2.0°C warming conditions. And the differences between the 1.5 and 2.0°C scenarios were quite large. Under the 1.5°C warming condition the changes of the return levels were small. At some tide gauges there are nearly no changes in the return levels. Under 2.0°C warming condition the return levels of the extreme sea level of three models significant increased. In order to show the changes of the return levels more clearly, the 100-year return levels under three scenarios were calculated and shown in **Table 3**.

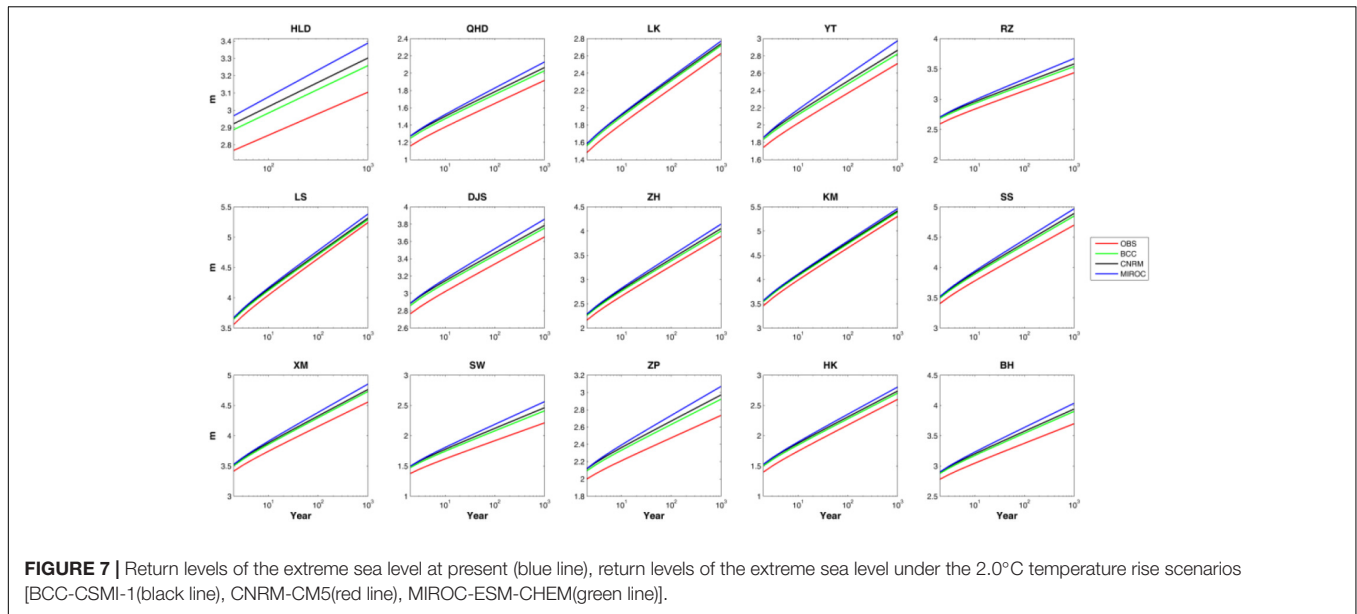


FIGURE 7 | Return levels of the extreme sea level at present (blue line), return levels of the extreme sea level under the 2.0°C temperature rise scenarios [BCC-CSMI-1(black line), CNRM-CM5(red line), MIROC-ESM-CHEM(green line)].

Compared with the present scenario, the 100-year return levels under the 1.5°C warming condition changed little at most tide gauges in BCC-CSMI-1 and CNRM-CM5. The 100-year return level changes ranged from -3 to 5 cm in BCC-CSMI-1. And in CRRM-CM5 the 100-year return level changes ranged from -4 to 4 cm. The changes of 100-year return levels in MIROC-ESM-CHEM ranged from -3 to 6 cm, and the 100-year return levels were larger than in the other two models at most tide gauges.

Under the 2.0°C warming condition, the changes of 100 year return levels were much larger than those under the 1.5°C warming condition in all three models. In BCC-CSMI-1 the 100-return level changes ranged from 8 to 20 cm, and the

100-year return levels correspond to the water levels of 140~562 year return period under the present condition. Comparing to the 1.5°C warming condition the 100-year return levels increased about 4~18 cm. In CNRM-CM5 the 100-return level changes ranged from 6 to 17 cm, and the 100 year return levels under the 2.0°C warming condition correspond to the water levels of 127~394 return period under the present condition. Comparing to the 1.5°C warming condition the 100 year return levels increased about 8~14 cm. In MIROC-ESM-CHEM the 100 return level changes ranged from 13 to 27 cm, and the 100 year return levels under the 2.0°C warming condition correspond to the water levels of 165~998 year return period under the present condition. Comparing to the 1.5°C warming condition

TABLE 3 | Hundred-year return levels of the extreme sea level in present (unit is meter), under the 1.5 and 2°C scenario (from climate model) at 15 tide gauges, the return period (year) of the water levels in present scenario were listed in the bracket.

(m)	OBS	BCC-CSMI-1		CNRM-CM5		MIROC-ESM-CHEM	
		1.5°C	2.0°C	1.5°C	2.0°C	1.5°C	2.0°C
HLD	2.85	2.86 (102)	3.02 (460)	2.86 (102)	2.98 (327)	2.89 (134)	3.08 (777)
QHD	1.65	1.67 (117)	1.79 (322)	1.66 (105)	1.75 (244)	1.68 (131)	1.83 (467)
LK	2.22	2.26 (121)	2.33 (184)	2.24 (109)	2.31 (163)	2.25 (116)	2.35 (207)
YT	2.37	2.34 (85)	2.51 (255)	2.33 (80)	2.47 (201)	2.37 (100)	2.58 (415)
RZ	3.14	3.14 (100)	3.27 (255)	3.11 (95)	3.24 (212)	3.14 (100)	3.33 (445)
LS	4.65	4.64 (96)	4.73 (140)	4.62 (90)	4.71 (127)	4.62 (90)	4.78 (166)
DJS	3.34	3.35 (111)	3.47 (256)	3.34 (100)	3.44 (207)	3.35 (111)	3.52 (364)
ZH	3.28	3.27 (95)	3.42 (174)	3.27 (95)	3.39 (148)	3.30 (106)	3.49 (218)
KM	4.65	4.66 (103)	4.76 (148)	4.66 (103)	4.74 (135)	4.66 (103)	4.80 (165)
SS	4.24	4.26 (112)	4.41 (228)	4.26 (112)	4.37 (191)	4.28 (117)	4.46 (296)
XM	4.15	4.16 (105)	4.33 (269)	4.16 (105)	4.30 (227)	4.18 (119)	4.39 (377)
SW	1.92	1.94 (121)	2.12 (491)	1.95 (124)	2.08 (355)	1.96 (143)	2.19 (822)
ZP	2.48	2.49 (108)	2.67 (562)	2.49 (108)	2.63 (394)	2.52 (145)	2.74 (998)
HK	2.18	2.17 (97)	2.31 (207)	2.19 (108)	2.28 (174)	2.20 (110)	2.35 (263)
BH	3.37	3.42 (136)	3.57 (411)	3.41 (132)	3.54 (325)	3.43 (153)	3.64 (643)

the 100-year return levels increased about 10~23 cm. Results indicated that a 0.5°C warming will make much difference in the extreme sea levels along the Chinese coast in all three models.

CONCLUSION

The growing concerns about climate change have motivated numerous researchers to study the effects of climate change in coastal areas. As one of the most important marine factors in coastal areas, extreme sea level has drawn more and more attentions in recent years. In this paper, we used hourly sea level data from 15 tide gauges along the China coast and numerical sea level data from three simulations of the CMIP5, to analyze the changes of extreme sea level in the past and under the 1.5 and 2°C warmer future scenarios.

The extreme sea levels rise with fluctuations at most tide gauges along the China coast, and the long term trends show various patterns. Quasi-linear trends are found at YT, RZ, DJS, ZH, XM, and SS, while no significant trends exists at QHD, SW, and ZP. The extreme sea level starts to rise since 2000 at LS, and the rise decelerates at HK during the past years. The mean sea level changes play important roles in the changes of extreme sea levels along the China coast, especially for the long-term change.

Under the 1.5 and 2.0°C warming scenarios, the sea level rise with fluctuations according to the simulation results by three selected models, and the sea levels are much higher under the 2.0°C warming scenarios. The return levels of the extreme sea level vary significantly under different warming scenarios, and there is considerable increase of the return levels at all tide gauges along the China coast under 2.0°C warming scenario compared with that under 1.5°C warming scenario. The results indicated

that a 0.5°C warming will bring about major difference for the extreme sea levels along the China coast. It is reasonable to limit the anthropogenic warming to 1.5°C rather than 2.0°C based on this study, as proposed by the Paris Climate Agreement, and it is necessary and practical for future flood risk management and response along the coast of China.

There are also some caveats in this study. In order to meet the warming condition of 1.5 and 2.0°C, the data lengths of the three model here are different. And only three models are analyzed in this study and there may be some uncertainty in the results presented in this manuscript. Besides, only the results of the RCP4.5 scenario were applied in this work.

AUTHOR CONTRIBUTIONS

JF conceptualized the research and contributed to the discussion and interpretation of the results. HL gave the sea level rise results used in this work. DL, QL, HW, and KL prepared and conducted some of the data analysis in the work. All authors contributed to the revision and approved the manuscript.

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Conflict of Interest Statement: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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