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Assessing changes in extreme sea levels along the coast of China

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Key Points:

- Changes in extreme sea levels here are strongly related to the changes of mean sea levels
- The tide and surge are also important in the changes of extreme sea level
- Tide-surge interaction plays an important role, but not directly

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Abstract Hourly tide-gauge data along the coast of China are used to evaluate changes in extreme water levels in the past several decades. Mean sea level, astronomical tide, nontidal component and the tide-surge interaction was analyzed separately to assess their roles in the changes of extreme sea levels. Mean sea level at five tide gauges, Kanmen, Keelung, Zhapo, Xiamen and Quarrybay, show significant increasing trends during the past decades (1954–2013) with a rate of about 1.4–3.5 mm/yr. At Keelung, Kaohsiung and Quarrybay the mean high waters increased during 1954–2013 with a rate from 0.6 to 1.8 mm/yr, while the annual mean tidal range rose at the same time by 0.9 to 3.8 mm/yr. In terms of storm surge intensities, there is interannual variability and decadal variability but five tide gauges show significant decreasing trends, and three gauges, at Keelung, Xiamen and Quarrybay, exhibited significant increases of extreme sea levels with trends of 1.5–6.0 mm/yr during 1954–2013. Significant tide-surge interactions were found at all 12 tide gauges, but no obvious change was found during the past few decades. The changes in extreme sea levels in this area are strongly related to the changes of mean sea levels (MSL). At gauges, where the tide-surge interaction is large, the astronomic tides are also an important factor for the extreme sea levels, whereas tide gauges with little tide-surge interaction, the changes of wind driven storm surge component adds to the change of the extreme sea levels.

1. Introduction

China has the largest coastal population in the world, with more than 400 million people living along the coast (National Bureau of Statistics of the People's Republic of China). The rapid economic progress of China, especially in the coastal zone, attracts more attention to the negative impacts of sea level extremes. The China Marine Disaster Bulletin (http://www.soa.gov.cn/zwgk/hygb/) shows that between 1989 and 2014, on average, extreme sea level disasters caused economic losses of 11.7 billion (RMB), 156 deaths, and affected 13.4 million people annually. As many of the Chinese coastal communities are in low-lying regions, big storm surges due to typhoons, tropical storms and winter storms frequently causes severe losses. *Hallegatte et al*. [2013] classify the China coast as one of the most vulnerable areas under climate change scenarios. It is essential to improve the understanding of sea level extremes along China coasts for coastal protection, future planning, and conservation of coastal ecosystems.

Many studies have been done in the past years about the change of mean sea level and of extreme sea levels both regionally and globally using the data from tide gauges [*Tsimplis and Woodworth*, 1994; von *Storch and Reichardt*, 1997; *Woodworth and Blackman*, 2003, 2004; *Méndez et al*., 2007; *Woodworth et al*., 2007; *Marcos et al*., 2009; *Menéndez and Woodworth*, 2010; *Mudersbach et al*., 2013; *Weisse et al*., 2014]. There is indeed evidence for a general worldwide increase in extreme high-water levels and mean sea levels in the past few decades. An interesting question is, whether the increase in the tails of the distributions is mostly because of a shift or a broadening of the distribution [*von Storch and Reichardt*, 1997; *Zhang et al*., 2000; *Bromirski et al*., 2003; *Bernier and Thompson*, 2006; *Church and White*, 2006; *Marcos et al*., 2009]. Results show that there is no uniform rule worldwide: changes of extreme sea levels are sometimes mostly due to increases in mean sea level, whereas in other cases, changes in extreme and mean sea levels seem to be decoupled. It means that changes in mean sea levels may change the shape of the distribution and there are also other reasons that can change the scale of the distribution of the extreme sea levels.

Changes in the astronomical tide may also be important. Changes in the amplitudes of some diurnal and semidiurnal tidal constituents have been identified and hypothesized as changes in the propagation of the tidal due to the changes in bathymetry associated with mean sea level changing [*Austin*, 1991; *Egbert et al*., 2004, *Uehara et al*., 2006; *Von Storch and Woth*, 2008; *Jay*, 2009; *Bolle et al*., 2010; *Green*, 2010; *Shaw et al*., 2010; *Woodworth*, 2010; *Pickering et al*., 2012]. It should be noted that the nodal and perigean modulations on high tidal levels are important as these modulations contribute to the vulnerability of coastal areas when coupled with inter-annual sea level variation or extreme storm surges.

Another important element is the wind driven (surge) component. If the frequency, strength and tracks of weather systems alter, the storm surges may change. For the change of storm surge statistics under climate change, many works have been done in the past few years to study the past statistics of storm surges or the envisaged changes of storm surges in the future [*Pirazzoli et al*., 2004; *Woth*, 2005; *Woth et al*., 2006; *Butler et al*., 2007; *Karim and Mimura*, 2008; *Pascual et al*., 2008; *Ratsimandresey et al*., 2008; *Marcos et al*., 2011; *Weisse et al*., 2014]. Results show that the changes of storm surges differ for different regions.

At certain locations, in particular, in shallow seas and estuaries, significant interaction occurs between tides and surges. This interaction produces changes in amplitude and phase of the surges [*Johns and Ali*, 1980; *Bernier and Thomspon*, 2007; *Zhang et al*., 2010]. For the East China Sea, *Zhang et al*. [2010] indicated that the difference in tidal residuals due to the interaction could reach up to 20 cm. For the Chinese coastal areas, few studies have been done to determine its role in changing statistics of extreme sea levels. And whether the characteristics of the changes of extreme sea levels in this area show same spatial pattern or not are still unclear.

In this work, hourly sea level data from 12 tide gauges and annual mean sea level data from 5 gauges at the China coast are used. The observed sea level are separated into their components (mean sea level (MSL), astronomical tide and surge parts), using means of a separate tidal analysis for each calendar year [*Pugh*, 1987]. Records from 4 gauges, at least 30 years long, are used to investigate how extreme sea levels, astronomical tide and mean sea level have changed over the period 1950–2012. Changes in the surge parts and tide-surge interaction are studied at all 12 gauges. Most of the available time series are relatively short and thus of limited use for studying long term changes in sea level statistics. The reason is that most of the tide gauge data are kept confidential, so that scholars have to rely on the available data to analyze long-term changes. In our case, data from four tide gauges are available for up to 1950–2012, while for the other eight stations only limited records (1975–1997) can be used.

The outline of this paper is as follows: A brief description and validation of the tide gauges data sets and the methodologies used in this paper are described in section 2. Changes in extreme sea level and every component are analyzed in section 3. Also the contribution of each part to the extreme sea level is discussed in this part. Finally, main conclusions are drawn in section 4.

2. Data Sets and Methodology

2.1. Sea Level Data

Two kinds of sea level data sets are used in this paper. The locations of the gauges are given in Figure 1.

1. Hourly sea level data from 12 tidal gauges (Figure 1) along the Chinese coast were obtained from the University of Hawaii Sea Level Center. The time series' lengths of these tide gauges are shown in Figure 1.
2. Also annual mean sea level data of 5 gauges (2 are overlapped with the above 12), which are Yantai (1954–1994), Qinhuangdao (1950–1994), Kanmen (1959–2013), Zhapo (1959–2013) and Macau (1925–1982), from the Permanent Service for Mean Sea Level (PSMSL) were also used to study the change of MSL. Although the annual mean sea level data can also be obtained from the hourly sea level data at Kanmen and Zhapo, the data from PSMSL are used because of its longer time series.

The data have been rigorously checked for common errors such as data spikes and spurious records. Values with spurious jumps, datum shifts and time shifts were removed. In addition, 2 years (2001 and 2002) at Keelung when the data are less than 60% complete were excluded from the temporal analysis. At Hongkong sea level was recorded at North Point between 1962 and 1986 and then moved to Quarrybay. The offset between the two records is 1.02 cm. We combined these two data after shifting the earlier data by 1.02 cm.

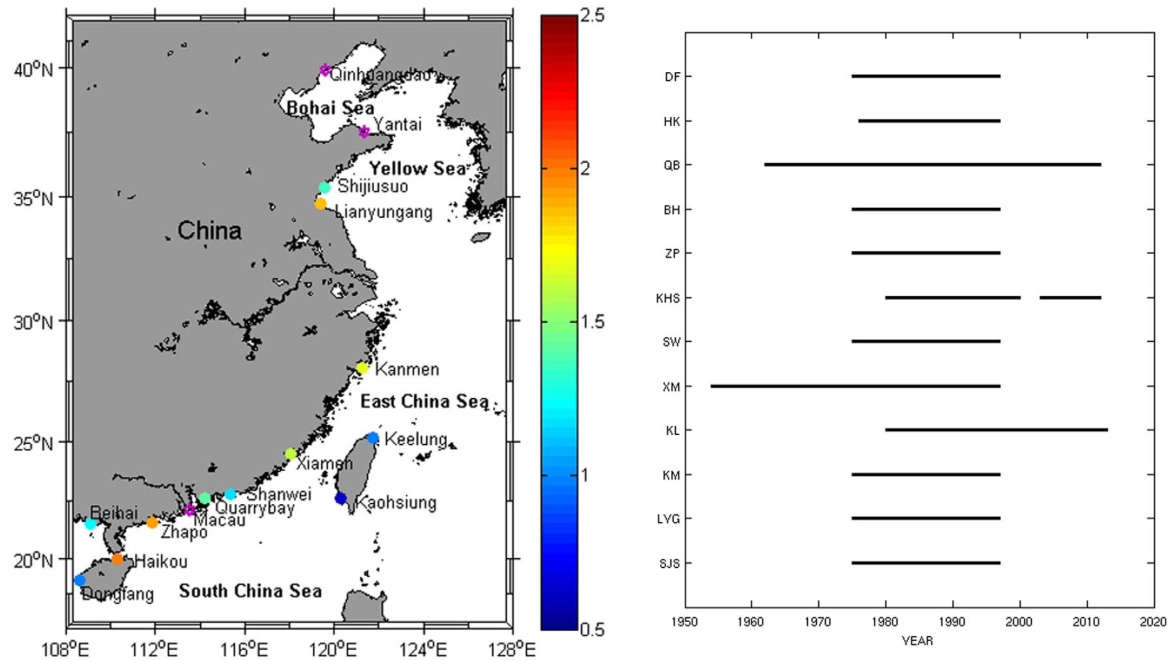

Figure 1. (left) Location of tide gauges used in this work, the color values (m) indicate the 99.9% of nontide residual levels of each gauges. (right) When only annual mean sea levels are available, the gauges are marked in purple; the time lengths of hourly data at 12 tide gauges, Shijiusuo (SJS), Lianyungang (LYG), Kanmen (KM), Keelung (KL), Xiamen (XM), Shanwei (SW), Kaohsiung (KHS), Zhapo (ZP), Beihai (BH), Quarrybay (QB), Haikou (HK) and Dongfang (DF) are shown on the right.

2.2. Methodology

2.2.1. Sea Level and Extreme Sea Level Characteristics

Changes in extreme sea levels have been assessed using a percentile analysis. The hourly data are ordered in terms of height and then used to compute percentile levels [*Woodworth and Blackman*, 2004]. Percentile values for the observed sea level have been calculated at 3 levels (99.9%, 99%, 90%), one for the total, and one after subtracting the annual medians. The trend in median supposedly represents the mean sea level rise (as we used the annual mean sea level which just equal to 50% level).

The observed sea level variation can be considered as the sum of a mean level, an astronomical tidal component and a nontidal residual [*Pugh*, 1987]. The mean level is the average height of sea level defined over an extended period of time, usually a year. The tidal and nontidal residual components have been estimated using a harmonic analysis [*Pawlowicz et al*., 2002].

For the tidal component, annual mean high water (MHW) and annual mean low water (MLW) tidal elevations relative to MSL have been calculated along with annual mean tidal range (MTR) [*Haigh et al*., 2010].

Following *Zhang et al*. [2000], three indices have been used as proxies for the intensity of the storm surge climate. There are

1. Storm surge count: the annual number of storm surges (the nontide residuals) above a given threshold;
2. Storm surge duration: the annual number of hours for which the storm surge levels were above a given threshold;
3. Storm surge intensity: the annual total integral of the sea level curve above a given threshold.

As thresholds we use the hourly 99 percentile non tidal sea level variations at each of 12 tide gauges.

Several statistical methods are available to estimate tide-surge interaction. Here we follow *Haigh et al*. [2010], which determine the dependency of the nontidal sea surge peaks beyond the threshold on the different phases of tide. The timing of the surge peaks relative to the nearest high tide is noted. The tide is then divided into hour bands with respect to timing of high tide. If the surge and tide are independent processes, each surge above the threshold will have equal chance of falling in any of these bands. On the contrary, if interaction is present, then the number of surges per band would be expected to differ from one to another. A chi-square test [*Haigh et al*., 2010] is used to quantify the level of interaction taking place at each site. The test statistic is

$$X^2 = \sum_{i=1}^{n} \frac{(N_i - e)^2}{e}$$

where N_i is the observed number of surges per tidal phase i, e is the expected number of surges per tidal phase, which is equal to peaks above the 99% threshold, divided by total number of phases (n).

When the distribution is uniform, then the expected distribution of X is χ^2(n)-distributed.

Here we do not use the X-test statistic directly as other works [*Horsburgh and Wilson*, 2007; *Haigh et al*., 2010; *Antony and Unnikrishnan*, 2013], as the X^2 increases with the length of the time series. For being able to compare the statistics, we normalized the test statistic by the number of years, so that we consider X^2/T, with T = number of years.

2.2.2. Significance of Trends and Correlations

Trends and correlations (between the extreme sea level and tide, surge and mean sea level) have been fitted to the time-series. Testing for the "significance" of correlations between two time series and of nonzero trends in a time series incorporates the determination of how large sample correlations and sample trends could be, when the stochastic processes, which generate the series, are not correlated or are stationary (exhibit no trends). "Significance" indicates that the actual sample correlation contradicts the assumption that there are "no correlations" between the underlying processes, or, similarly, that the detected sample trend would be unlikely to appear in limited segments of a stationary time series.

For testing these null hypotheses, that the processes X and Y share no correlation, or that segments of length L has a zero trend, standard procedures are available in the literature, namely p-value for correlations and Mann-Kendall for trends [e.g., *Kulkarni and von Storch*, 1995; *von Storch and Zwiers*, 1999].

The use of correlation depends on a normality assumption. These tests make some assumptions about the underlying processes. In the case of correlations the assumption is that the underlying processes are stationary (free of systematic trends) and serially independent, i.e., X_t and Y_t for any t are independent. In geophysical cases, not all of these assumptions are satisfied—the result is that the null hypotheses is too often falsely rejected (i.e., in cases where there are no correlations or no trends [cf. *Kulkarni and von Storch*, 1995]) than stipulated by the significance level (normally 5%).

Following *Kulkarni and von Storch* [1995], a practical remedy for avoiding such errors is to deal with normalized series (mean=0, standard deviation=1) X'_t (and Y'_t), and

1. "detrend" the time series before testing for correlations, i.e., determining the linear fit f_t^X and f_t^Y, and do the hypothesis testing with $X'_t = X_t - f_t^X$ and $Y'_t = Y_t - f_t^Y$;
2. "prewhiten" the time series, by first determining the sample autocorrelation $\alpha = 1/L\ \Sigma_t X_t X_{t+1}$ of the time series X_t of length L, and forming a series $X'_t = X_t - \alpha X_t$, and then testing for the null hypothesis of no trend.

To both cases, the standard routines are applied. If the null hypothesis is rejected at the stipulated significance level of 5%, then the sample trend f_t^X, or the sample correlation $1/L\ \Sigma_t X_t Y_t$, is considered "significant."

2.2.3. Time Series Length for Meaningful Trends for Total Sea Level Variations (Including Tides)

An important problem, before analyzing the extreme sea levels, is how many years are needed to estimate the trend of the extremes accurately. When trend is fitted to records that are not long enough, we cannot get the correct trend. As the magnitude of the trend can vary significantly depending on where the 18.6 year nodal cycle the sea level record begins and ends. Also if the sample size is too low, it may not have the power to detect an effect, or because the trend due to the climate is nonlinear. In some work [*Haigh et al*., 2010] 36 years was used. But along the China coast, only two gauges have records longer than 36 years. Here we first checked the stability of the trend when different lengths of segments L were used. Results for the two gauges with long series (Quarrybay and Xiamen) are shown in Figure 2. When only half a period (L=18) of the nodal cycle is available, the trends vary considerably from segment to segment (Figure 2). These variations flatten out, when L=30 year segments are used, the estimate of the segment trends become similar. The standard deviations of the trends at Quarrybay of different lengths L are 6.5 (L=18), 4.5 (L=24), 1.6 (L=30) and 1.7 (L=36) (mm/yr). At Xiamen there are 3.2 (L=18), 1.7 (L=24), 1.4 (L=30) and 1.3 (L=36) (mm/yr). Therefore in this work the length L=30 years is used for analyzing the trends of extremes. This added another 2 gauges long enough for determining trends, namely, Keelung and Kaohsiung.

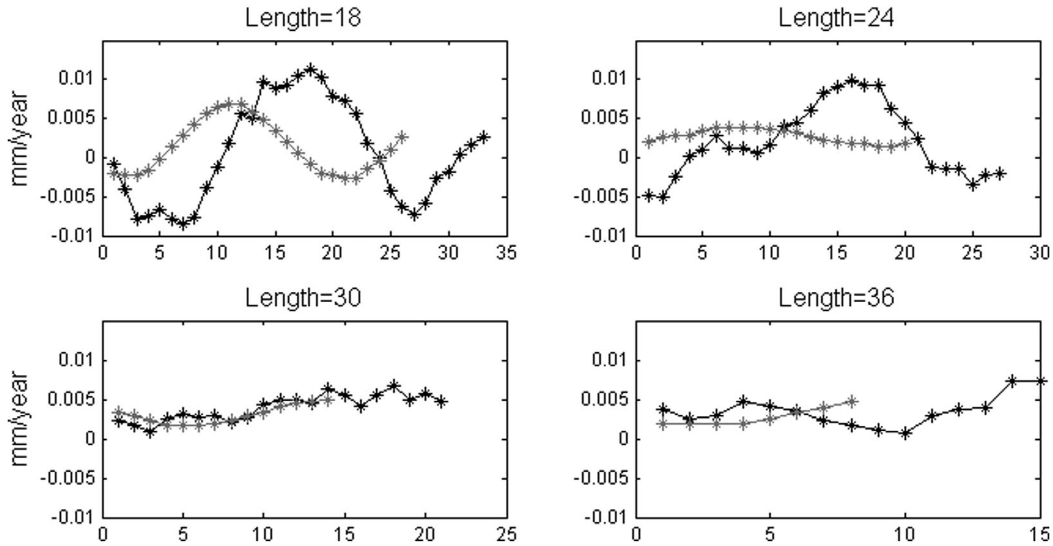

Figure 2. The linear trend of the extreme sea levels using different data length (18, 24, 30, and 36 years) at (black line) Quarrybay and (gray line) Xiamen, *x* axis stand for the time of the calculation for each length.

3. Results and Discussion

In this section, sea level has been spilt into three component parts (MSL, tide and surge). Trends in the tide and surge component, and the interaction between surge and tide, have been separately analyzed before total extreme sea levels are analyzed.

3.1. Change of the MSL

Annual MSL of the four gauges with at least 30 years of annual mean data (Keelung, Xiamen, Kaohsiung and Quarrybay) together with another five gauges (only with annual MSL data) Yantai, Qinhuangdao, Kanmen, Zhapo and Macau, were analyzed in this part. Results are shown in Figure 3, and the linear trends are listed in Table 1.

Results clearly show decadal variability at all gauges. The MSL rise rates along the China coast have a highly nonuniform distribution in space. At Macau and Quarrybay the changes are quite different even if their locations are close. Linear increasing trends are significant at 5 tide gauges: Kanmen, Keelung, Zhapo, Xiamen and Quarrybay. Rates are between about 1.4 and 3.5 mm/yr. At the other four gauges, both positive and negative trends exist, but they are all nonsignificant.

Uncertainties exist for the above results, the uncertainties may come from the land movements and the quality of tidal data. Such as in Yantai and Qinhuangdao, the annual MSL have obvious inhomogeneities in some years. Also the vertical land movements in China vary highly geographically [*Hu et al*., 1992, 1993]. *Huang et al*. [1991] summarized the rates of land movement of some tide gauges along the China coast using data from 1966 to 1988. Their results concern 5 tide gauges which we studied here: Yantai (2.1 mm/yr), Qinhuangdao (3.9 mm/yr), Kanmen (−2.2 mm/yr), Zhapo (2.5 mm/yr) and Xiamen (1.5 mm/yr).

3.2. Changes of the Tide

In this part, the annual mean high water (MHW), annual mean low water (MLW) and annual mean tidal range (MTR) were used to analyze the changes of tides at four gauges, where time series were long enough. The annual results and trends are shown in Figure 4. There is considerable variability from year to year in the time series in which a significant part is related to the 18.6 year nodal cycle. This variability distorts the fitted trends, particularly over short records.

Annual values show that the tidal ranges at Xiamen are largest among the four gauges, ranging from 3.80 to 4.10 m. The tidal ranges at Kaohsiung and Keelung are very close, ranging from 0.65 to 0.85 m. At Quarrybay, the ranges are smaller than those at Xiamen while much larger than at the other two gauges, which is from 1.50 to 1.65 m.

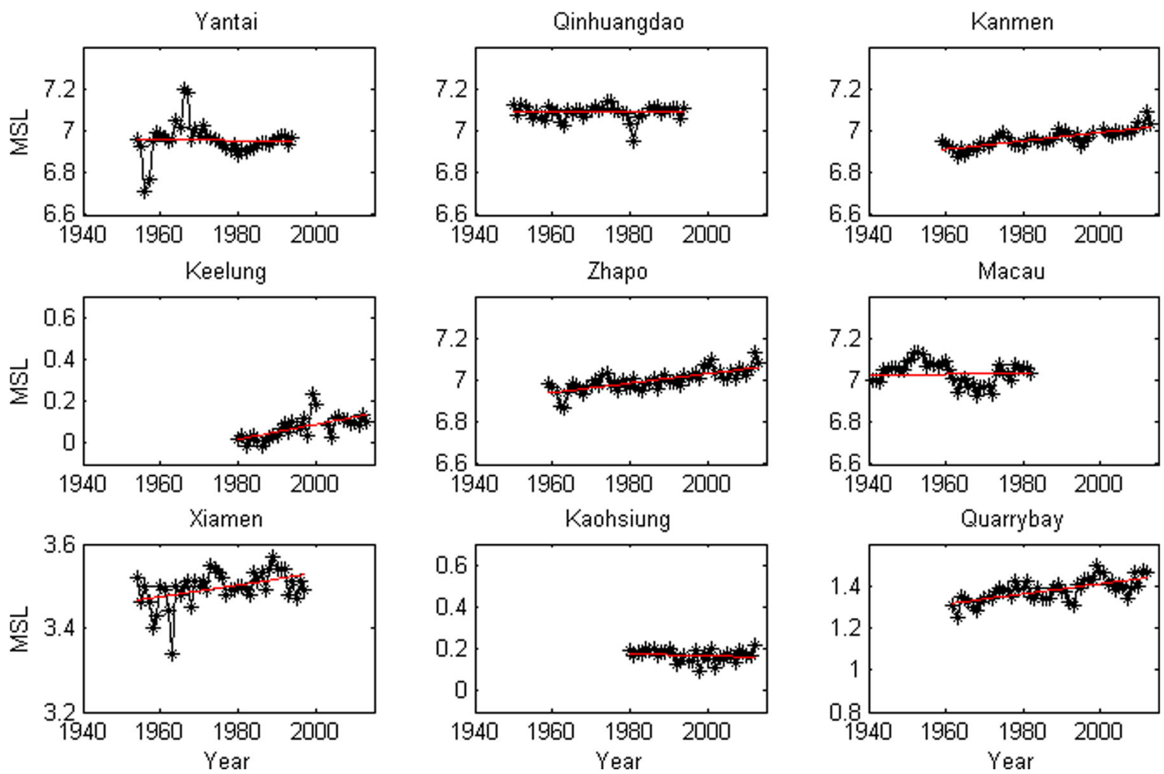

Figure 3. Time series of annual mean sea level (stars) with fitted linear trends at nine gauges along the Chinese coast (red straight line). Unit: m.

The long time trend rates are listed in Table 2.

They are all statistically significant. At Xiamen, Kaohsiung and Keelung there are increases in MHW and decreases in MLW resulting in increases in MTR. Especially at Xiamen, the rate of the MHW-trend is 3 times of that at Kaohsiung and Keelung. At Quarrybay, there is a small decrease in MHW and an increase in MLW resulting in an overall decrease in MTR.

The increase of −0.2 to 1.8 mm/yr in MHW is small when compared with the MSL (mean sea level) trends experienced in these four gauges (−0.5 to 3.5 mm/yr; see Table 1). In relation to extreme sea levels, the increase in MHW is also important.

3.3. Changes of the Surge

As mentioned before, the surge is determined by subtracting the tidal harmonics from the time series of hourly sea level variations at the tide gauges. The three indices described above (frequency, duration and intensity) of storm surges at all tide gauges have been calculated and they showed quite similar characteristics. Here we only show the results of the intensity (the annual total integral (hour) of the nontidal components above the 99% (hour•m)) as it reflects more directly in the changes of the extreme sea levels.

Table 1. List of MSL Trends at Nine Tide Gauges[a]

Tide gauges	Period	Length (year)	Trend (mm/yr)
Yantai	1954–1994	41	−0.2
Qinhuangdao	1950–1994	45	0.1
Kanmen	1959–2013	54	*2.0*
Keelung	1980–2013	34	*3.5*
Zhapo	1959–2013	54	*2.3*
Macau	1925–1982	58	0.3
Xiamen	1954–1997	44	*1.4*
Kaohsiung	1980–2012	33	−0.5
Quarrybay	1962–2012	51	*2.4*

[a]Trends with significance at the 95% confidence level are italicized.

The annual average intensities at Shijiusuo, Lianyungang, Kanmen, Xiamen and Zhapo are higher and at Keelung, Kaohsiung and Dongfang the intensities are smallest of all gauges (in Figure 5). Time series of annual intensity of surges at all 12 gauges are shown in Figure 5. The interannual variability and decadal variability are obvious at most of the tide gauges, and the interannual variability

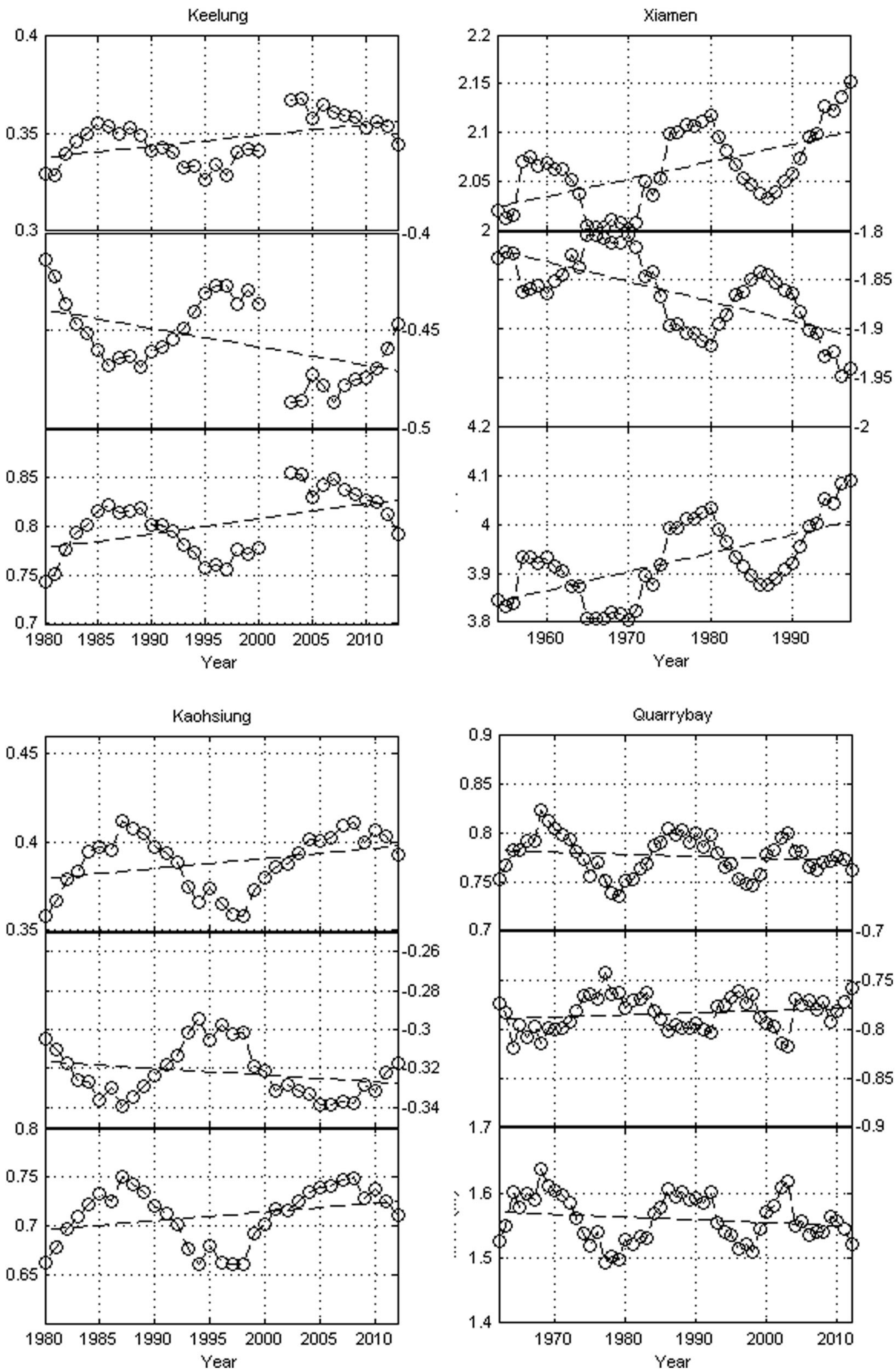

Figure 4. (top) Annual mean high water (MHW), (middle) annual mean low water (MLW), and (bottom) annual mean tidal range (MTR) at Keelung, Xiamen, Kaohsiung and Quarrybay. The dotted lines show the linear trends. Units: m.

Table 2. The Linear Trends (mm/yr) of the MHW, MLW, and MTR at Four Tide Gauges[a]

Trends at Gauge	Data Available	Number of Years	MHW-Trend (mm/yr)	MLW-Trend (mm/yr)	MTR-Trend (mm/yr)
Quarrybay	1962–2012	51	*−0.2*	*0.2*	*−0.4*
Xiamen	1954–1997	44	*1.8*	*−2.0*	*3.8*
Kaohsiung	1980–2012	33	*0.6*	*−0.3*	*0.9*
Keelung	1980–2013	34	*0.6*	*−0.9*	*1.5*

[a]They are all significant at 95% confidence level (italicized).

is larger than the decadal variability. The intensity of surges appears to be larger in the middle of 1960s and around the 1990. There are also gauges, Zhapo and Haikou, where the decadal variability is very small. The total intensity of different gauges has maxima in different years. The long-time trends at five tide gauges, Shanwei, Kaohsiung, Zhapo, Quarrybay and Haikou, are significantly decreasing (Table 3). At other gauges both positive and negative trends exist, but they are not significant at the 95% confidence level.

3.4. Changes to Tide-Surge Interaction

The frequencies of surge above 99% level with respect to the timings of high tide for each of the 12 stations, i.e., the characteristics of tide-surge interaction (see section 2.2), show four kinds of pattern (Figure 6). The distribution is significantly different from uniform distributions.

At Shijiusuo, Lianyungang, Kanmen, Xiamen and Haikou, the peak often occurs at a rising tide (about 4–5 h before the high tide). At Kaohsiung and Zhapo, the surge happens mostly at a falling tide (about 4–5 h after the high tide). At Shanwei, Beihai, Quarrybay and Dongfang the distribution has peaks at both, i.e., rising and falling tides. Finally, at Kanmen, Shanwei, Beihai and Dongfang storm surges tend to occur together with the high tide.

We use the test statistic X^2/T to quantify the strength of the nonuniformity of the distribution. i.e., of the tide-surge interaction at all gauges (included in Figure 6). It shows that the tide-surge interactions differ among the gauges

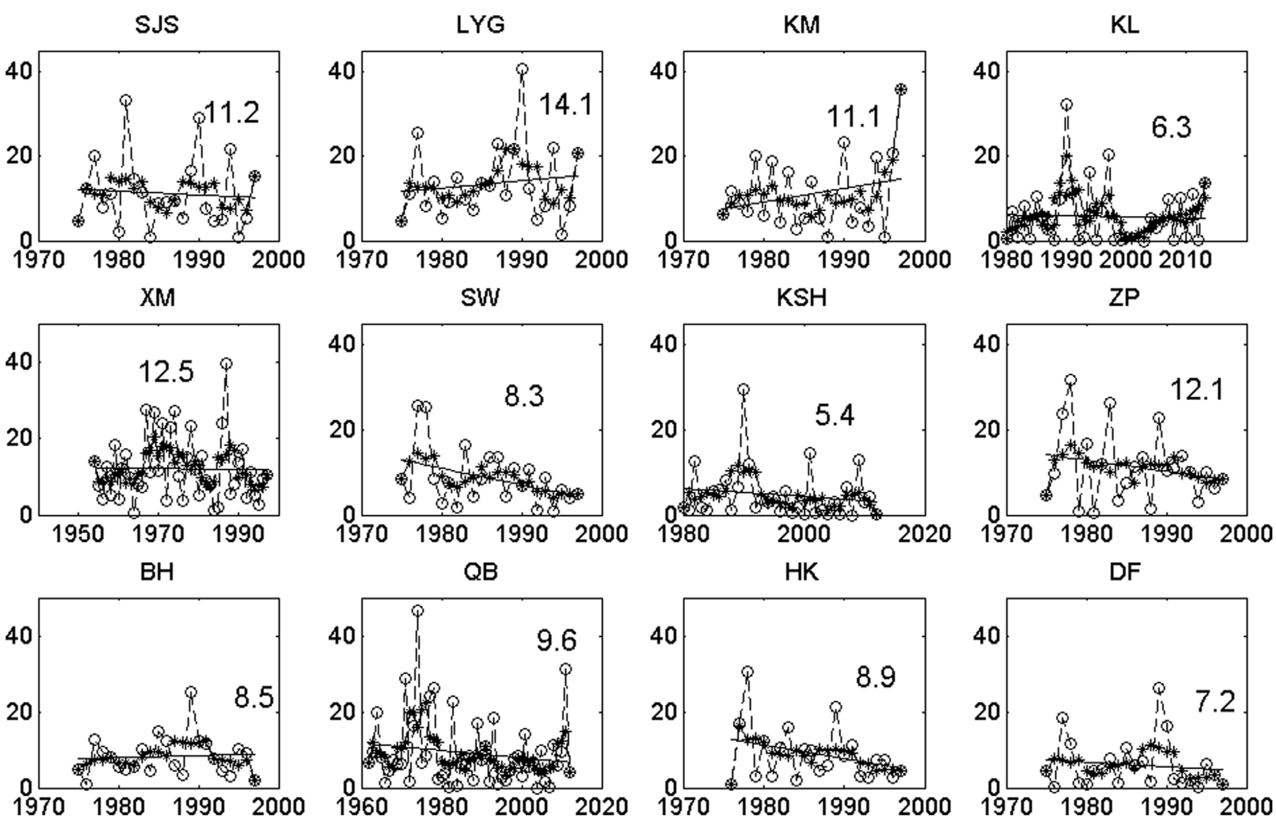

Figure 5. Annual surge total intensity (dashed line), and long-time trend (straight line) and the mean value of the intensity (number) at all 12 tide gauges. Unit: m×hour.

Table 3. Long-Time Trend of the Surge Intensity at All Gauges[a]

Tide gauge	Time	Length (years)	Trend (m×h/yr)
Shijiusuo	1975–1997	23	−0.09
Lianyungang	1975–1997	23	0.17
Kanmen	1975–1997	23	0.32
Keelung	1980–2013	34	−0.03
Xiamen	1954–1997	44	−0.02
Shanwei	1975–1997	23	*−0.39*
Kaohsiung	1980–2012	33	*−0.10*
Zhapo	1975–1997	23	*−0.26*
Beihai	1975–1997	23	0.06
Quarrybay	1962–2012	51	*−0.10*
Haikou	1976–1997	22	*−0.36*
Dongfang	1975–1997	23	−0.12

[a]Trends with significance at the 95% confidence level are italicized.

stations, also among neighbouring gauges. At Lianyungang and Xiamen the interactions are much more pronounced than at other gauges. Interaction is weakest at Keelung and Kanmen, with $X^2/T < 2$.

In order to test whether changes in tide-surge interaction have taken place over the past decades at these 4 gauges, the phases of the surge peaks have been plotted for all 10 year overlapping periods at the four gauges with time series of at least 30 years(Figure 7). At Xiamen, Kaohsiung and Quarrybay the phases of the peaks are quite stable. Especially at Xiamen station nearly no change happened during the past decades in the distribution of the tide surge interaction. At Keelung some differences exist in the past few decades, especially for the peaks which happened on the falling tide. It seems that the tide-surge interaction become more stable as the strength of interaction increases.

In summary, results show that tide-surge interaction is important along the China coast and needs to be taken into account in the extreme sea level assessment. But as the interaction at Xiamen, Kaohsiung and Quarrybay are stable and the tide-surge interaction at Keelung is quite small, the tide-surge interaction seem to play a minor direct role in the decadal and long-time changes of extreme sea levels at those stations.

3.5. Changes to Extreme Sea Levels

In this section, we study the changes of extreme sea level (including the tidal components) for separating the change due to mean sea level rise and due to changing dynamical factors (tides, storms). Results are shown in Figure 8. In terms of total sea level variations, the three percentiles have statistically significant positive trends at Keelung and Xiamen. The trends are larger than that of the mean sea levels (section 3.1) especially for the 99.9% trend. Especially at Xiamen the rate of extreme sea level is about 4 times of the mean sea level. At Kaohsiung, positive trends are also found at all percentile levels but they are not significant. At Quarrybay, the 99% and 90% have statistically significant positive trends, with magnitude greater than the mean sea levels. At the 99.9% level, the trend is also positive but not statistically significant.

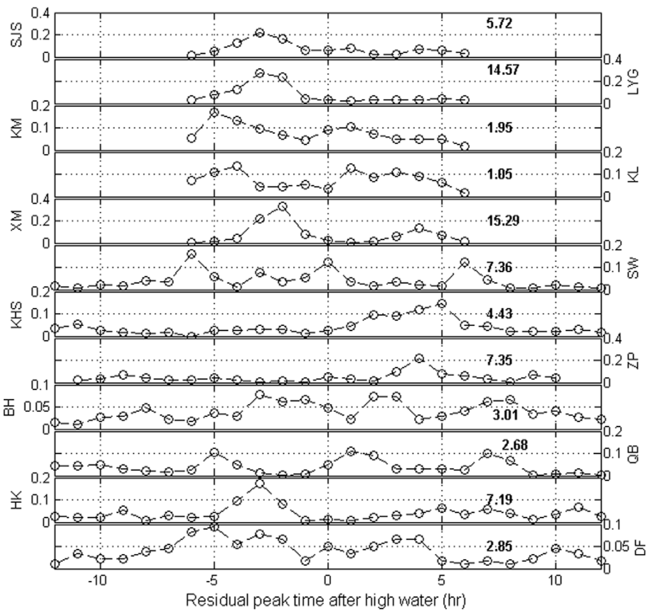

Figure 6. Number of surge peaks above the 99% plotted with respect to timing of the high tide (in hours) for all stations, *y* axes is the percentage, the tide-surge interaction at all tide gauges are significant at 95% confidence levels.

Once the percentile time series are reduced by subtracting the annual medians mean sea levels, none of the trends is statistically significant. Positive trends remain at Keelung, Xiamen and Kaohsiung. At Quarrybay, the 99.9% percentile level has a negative trend but the 90% and 99% percentiles have positive trends.

The time series also exhibit marked decadal variability at all four tide gauges, but their characteristics of decadal variability differ due to their locations.

3.6. Relationship Between Extreme Sea Levels and Components

We examine the relationship between the annual variations of the extreme

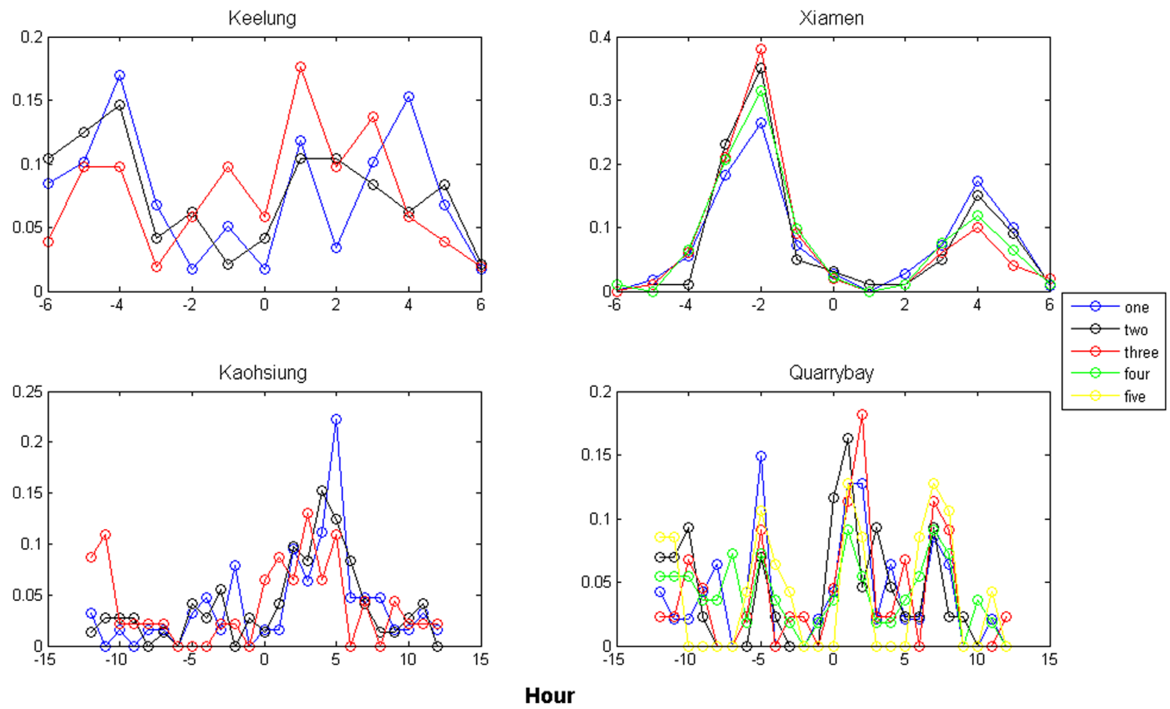

Figure 7. The frequencies of surge peaks plot for all 10 year overlapping periods at Keelung, Xiamen, Kaohsiung, and Quarrybay, *y* axes is the percentage.

sea levels (in terms of 99.9 percentiles of total sea level) and of the variations components of sea level separately. Here the annual surge intensity is considered to represent the surge part, whereas the annual mean high level can be regarded as the representative for the tide component. The correlations are shown in Table 4.

Results show that there are some characteristics in common among these four tide gauges. The extreme sea level and the MSL show significant positive correlation at all four tide gauges, especially at Keelung, Xiamen

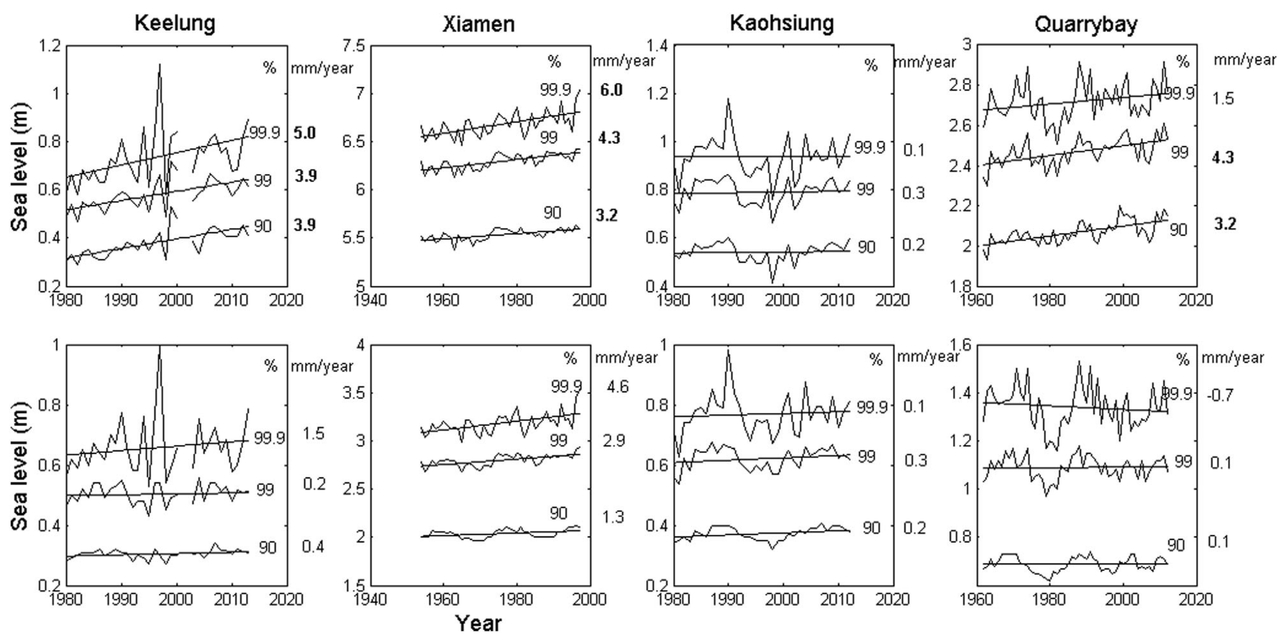

Figure 8. Time series of percentiles of (top) total and (bottom) reduced sea level for Keelung, Xiamen, Kaohsiung, and Quarrybay. The straight lines are the linear trends, their change rates (mm/yr) are listed at right of the figures, (in bold if significant at 95%).

Table 4. The Correlations Between the 99.9% Total Sea Level Variations and the Sea Level Components, MSL, Surge and Tide[a]

	MSL	Surge	Tide
Keelung	*0.58*	*0.52*	−0.01
Xiamen	*0.52*	−0.05	*0.54*
Kaohsiung	*0.65*	*0.65*	*0.52*
Quarrybay	*0.37*	*0.51*	0.19

[a]Correlations with significance at the 95% confidence level are italicized.

and Kaohsiung (of above 0.50). This finding is generally consistent with studies in other regional studies, e.g., English Channel [*Pirazzoli et al*., 2006; *Haigh et al*., 2010]; Liverpool, UK [*Woodworth and Blackman*, 2002]; San Francisco, USA [*Bromirski et al*., 2003], also in a global assessment [*Woodworth and Blackman*, 2004].

As for the surge and tide, results differ due to their locations. The surge shows significant positive correlation (larger than 0.50) to the extreme sea level at Keelung, Kaohsiung and Quarrybay. It means that the storm surges also play important roles in the change of extreme sea levels at these three gauges. However, in Xiamen there is no obvious correlation between the extreme sea level variations and surge variations. A possible reason is that the tide surge interaction in Xiamen station is much larger than those at the other three. Nearly all surge maxima occur on the rising tide and falling tide (section 3.4), and the tide amplitude in Xiamen is much larger than the others, which may be also an important reason (section 3.2). Thus the sea level reaches its peak not at the time when the wind effect reached its maxima. Thus the changes of the surges were less important to the change of extreme sea levels.

The tide shows significant positive correlations, of 0.50 and more, with the variations of annual extreme sea level at Kaohsiung and Xiamen. But at Keelung and Quarrybay, no significant correlations were found. This difference may also be caused by the tide surge interaction. Figures 6 and 7, demonstrate that at Keelung and Quarrybay, the timing of many surges was close to that of the high tide time, compared to Xiamen and Kaohsiung. Thus the tide plays a more important role in Xiamen and Kaohsiung than in Keelung and Quarrybay. It seems that Kaohsiung differs from the other three gauges, as both the surge and tide show significant positive correlation to the extreme sea levels. From Figures 6 and 7, the storm surges most happen during 0 to 6 (h) after the high tide. Thus, both the surge and tide play important roles in generating the extremes. Summing up, the tide surge interaction affects the extreme sea levels through the surge part and the tide part rather than itself.

4. Conclusions

Hourly sea level data from tide gauges along the Chinese coast are used for analyzing changes of the extreme sea level in this area and to assess to what extent changes in extreme sea level over the past several decades were driven by, changes in mean sea level, tide, surge, or in tide-surge interaction. The mean sea level (MSL), tide, surge and tide surge interaction have been separately examined for trends.

Unfortunately, the data are of limited quality, both in terms of time period, spatial coverage and, possibly homogeneity. It would be favorable, if more data would be made accessible for scientific analysis.

Clearly, decadal variability exists in the MSL at the selected tide gauges, while the mean sea level trends exhibit, spatially, a highly nonuniform distribution. Five of 9 tide gauges (Kanmen, Keelung, Zhapo, Xiamen and Quarrybay) show significant positive trends. The tide component was analyzed at tide gauges with data more than 30 years. Significant but spatially nonuniform trends in tide characteristics were found at all four gauges. The surge component was studied at all 12 tide gauges, obvious interannual variability and decadal variability exists at all tide gauges. As for the long term trend, annual tide intensity at 5 tide gauges shows significant decreasing trends. Significant but spatially nonuniform tide-surge interactions were found at all 12 tide gauges. No obvious change, in particular where the tide surge interactions were strong, was found in the tide surge interaction during the past few decades.

There is evidence for an increase in extreme sea levels during the past few decades at Keelung, Xiamen and Quarrybay. Also clear decadal variability is present at these tide gauges. The variations in annual extreme sea level and in the annual MSL show significant positive correlation at all four tide gauges, which means that the change in mean sea level play an important role in the change in extreme sea levels in this area. The surge shows significant positive correlation to the extreme sea level at Keelung, Kaohsiung and Quarrybay, thus the storm surges play important roles in the changes of extreme sea levels. The tide shows significant positive correlation to the extreme sea level at Kaohsiung and Xiamen, thus the tide play important roles in the changes of extreme sea levels at these two gauges. Tide surge interaction play an important role in determining which component, the surge or the tide, is more important for the change of extreme sea levels.

In conclusion, the changes in extreme sea levels along the China coast are highly affected by the changes in mean sea levels. But the changes are not totally due to the change of mean sea levels. Changes in surges and astronomic tide contribute––in a spatially nonuniform manner. The tide surge interactions are important in the changes of extreme sea levels, but not in a direct way. Thus, if we want to envisage possible changes of the extreme sea levels in one area in the future along the China coast, we need taking the characteristic of this area into consideration.

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References

Antony, C., and A. S. Unnikrishnan (2013), Observed characteristics of tide-surge interaction along the east coast of India and the head of Bay of Bengal, *Estuarine Coastal Shelf Sci.*, *131*, 6–11, doi:10.1016/j.ecss.2013.08.004.

Austin, R. M. (1991), Modelling Holocene tides on the NW European continental shelf, *Terra Nova*, *3*, 276–288, doi:10.1111/j.1365-3121.1991.tb00145.x.

Bernier, N. B., and K. R. Thompson (2006), Predicting the frequency of storm surges and extreme sea levels in the northwest Atlantic, *J. Geophys. Res.*, *111*, C10009, doi:10.1029/2005JC003168.

Bernier, N. B., and K. R. Thompson (2007), Tide-surge interaction off the east coast of Canada and northeastern Unite States, *J. Geophys. Res.*, *112*, C06008, doi:10.1029/2006JC003793.

Bolle, A., Z. B. Wang, C. Amos, and J. De Rone (2010), The influence of changes in tidal asymmetry on residual sediment transport in the Western Scheldt, *Cont. Shelf Res.*, *30*, 871–882, doi:10.1016/j.csr.2010.03.001.

Bromirski, P. D., R. E. Flick, and D. R. Canyan (2003), Storminess variability along the California Coast: 1858–2000, *J. Clim.*, *16*, 982–993, doi:10.1175/1520-0442(2003)016<0982:SVATCC>2.0.CO:2.

Butler, A., J. A. Heffernan, J. A. Tawn, R. A. Flather, and K. J. Horsburgh (2007), Extreme value analysis of decadal variations in storm surge elevations, *J. Mar. Syst.*, *67*, 189–200, doi:10.1016/j.marsys.2006.10.006.

Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett.*, *33*, L01602, doi:10.1029/2005GL024826.

Egbert, G. D., R. D. Ray, and B. G. Bills (2004), Numerical modeling of the global semidiurnal tide in the present day and in the last glacial maximum, *J. Geophys. Res.*, *109*, C03003, doi:10.1029/2003JC001973.

Green, J. (2010), Ocean tides and resonance, Ocean *Dyn.*, *60*, 1243–1253, doi:10.1007/s10236-010-0331-1.

Haigh, I., N. Robert, and W. Neil (2010), Assessing changes in extreme sea levels: Application to the English Channel, 1900–2006, *Cont. Shelf Res.*, *30*, 1042–1055, doi:10.1016/j.csr.2010.02.002.

Hallegatte, S., C. Green, R. J. Nicholls, and J. Corfee-Morlot (2013), Future flood losses in major coastal cities, *Nat. Clim. Change*, *3*, 802–806, doi:10.1038/nclimate1979.

Horsburgh, K. J., and C. Wilson (2007), Tide-surge interaction and its role in the distribution of surge residuals in the North Sea, *J. Geophys. Res.*, *112*, C08003, doi:10.1029/2006JC004033.

Hu, H. M., L. Huang, and G. H. Yang (1992), Recent crustal vertical movement in the Changjiang River delta and its adjacent area [in Chinese with English abstract], *Acta Geogr. Sin.*, *47*, 22–30.

Hu, H. M., L. Huang, and G. H. Yang (1993), Recent vertical crustal deformation in the coastal area of eastern China [in Chinese with English abstract], *Sci. Geol. Sin.*, *28*, 270–278.

Huang, L. R., G. H. Yang, and H. M. Hu (1991), The isostatic datum for studying of the sea level changes along the coast of China, *Seismol. Geol.*, *13*, 8–14.

Jay, D. A. (2009), Evolution of tidal amplitudes in the eastern Pacific Ocean, *Geophys. Res. Lett.*, *36*, L04603, doi:10.1029/2008GL036185.

Johns, B., and M. A. Ali (1980), The numerical modeling of storm surges in the Bay of Bengal, *Q. J. R. Meteorol. Soc.*, *106*, 1–18.

Karim, M. F., and N. Mimura (2008), Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh, *Global Environ. Change*, *18*, 490–500, doi:10.1016/j.gloenvcha.2008.05.002.

Kulkarni, A., and H. von Storch (1995), Monte Carlo experiments on the effect of serial correlation on the Mann-Kendall test of trend, *Meteorologische Zeitschrift*, *4*(2), 82–85.

Marcos, M., M. N. Tsimplis, and A. G. P. Shaw (2009), Sea level extremes in southern Europe, *J. Geophys. Res.*, *114*, C01007, doi:10.1029/2008JC004912.

Marcos, M., A. G. Jord, D. Gomis, and B. Perez (2011), Changes in storm surges in Southern Europe from a regional model under climate change scenarios, *Global Planet. Change*, *77*, 116–128, doi:10.1016/j.gloplacha.2011.04.002.

Méndez, F. J., M. Menéndez, A. Luceño, and I. J. Losada (2007), Analyzing monthly extreme sea levels with a time-dependent GEV model, *J. Atmos. Oceanic Technol.*, *24*, 894–911, doi:10.1175/JTECH2009.1.

Menéndez, M., and P. L. Woodworth (2010), Changes in extreme high water levels based on a quasi-global tide-gauge data set, *J. Geophys. Res.*, *115*, C10011, doi:10.1029/2009JC005997.

Mudersbach, C., T. Wahl, I. D. Haigh, and J. Jensen (2013), Trends in high sea levels of German North Sea gauges compared to regional mean sea level changes, *Cont. Shelf Res.*, *65*,111–120, doi:10.1016/j.csr.2013.06.016.

Pascual, A., M. Marcos, and D. Gomis (2008), Comparing the sea level response to pressure and wind forcing of two barotropic models: Validation with tide gauge and altimetry data, *J. Geophys. Res.*, *113*, C07011, doi:10.1029/2007JC004459.

Pawlowicz, R., B. Beardsley, and S. Lentz (2002), Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE, *Comput. Geosci.*, *28*, 929–937, doi:10.1016/S0098-3004(02)00013-4.

Pickering, M. D., N. C. Wells, K. J. Horsburgh, and A. M. Green (2012), The impact of future sea-level rise on the European Shelf tides, *Cont. Shelf Res.*, *35*, 1–15, doi:10.1016/j.csr.2011.11.011.

Pirazzoli, P., S. Costa, U. Dornbusch, and A. Tomain (2006), Recent evolution of surge-related events and assessment of coastal flooding risk on the eastern coasts of the English Channel, *Ocean Dyn.*, *56*(5–6), 1-15, doi:10.1007/s10236-005-0040-3.

Pirazzoli, P. A., H. Regnauld, and L. Lemasson (2004), Changes in storminess and surges in western France during the last century, *Mar. Geol.*, *210*, 307–323, doi:10.1016/j.margeo.2004.05.015.

Pugh, D. J. (1987), *Tide, Surge and Mean Sea Level. A Handbook for Engineers and Scientists*, 472 pp., John Wiley, Chichester, U. K.

Ratsimandresy, A. W., M. G. Sotillo, J. C. Carretero Albiach, E. Álvarez Fanjul, and H. Hajji (2008), A 44-year high-resolution ocean and atmospheric hindcast for the Mediterranean Basin developed within the HIPOCAS Project, *Coastal Eng.*, *55*, 827–842, doi:10.1016/j.coastaleng.2008.02.025.

Shaw, J., C. L. Amos, D. A. Greenberg, C. T. O'Reilly, D. R. Parrott, and E. Patton (2010), Catastrophic tidal expansion in the Bay of Funday, Canada, *Can. J. Earth Sci.*, *47*, 1079–1091, doi:10.1139/E10-046.

Tsimplis, M. N., and P. L. Woodworth (1994), The global distribution of the seasonal sea level cycle calculated from coastal tide gauge data, *J. Geophys. Res.*, *99*, 16,031-16,039, doi:10.1029/94JC01115.

Uehara, K., J. D. Scourse, K. J. Horsburgh, K. Lambeck, and A. P. Purcell (2006), Tidal evolution of the northwest European shelf seas from the Last Glacial Maximum to the present, *J. Geophys. Res.*, *111*, C09025, doi:10.1029/2006JC003531.

von Storch, H., and H. Reichardt (1997), A scenario of storm surge statistics for the German Bight at the expected time of doubled atmospheric carbon dioxide concentration, *J. Clim.*, *10*, 2653–2662, doi:10.1175/1520-0442(1997)010<2653:ASOSSS>2.0.CO;2.

von Storch, H., and F. W. Zwiers (1999), Statistical analysis in climate research, United Kingdom at the University Press, Cambridge.

von Storch, H., and K. Woth (2008), Storm surge: Perspectives and options, *Sustainability Sci.*, *3*, 33–43, doi:10.1007/s11625-008-0044-2.

Weisse, R., D. Bellafiore, M. Menéndez, F. Méndez, R. J. Nicholls, G. Umgiesser, and P. Willems (2014), Changing extreme sea levels along European coasts, *Coastal Eng.*, *87*, 4–14, doi:10.1016/j.coastaleng.2013.10.017.

Woodworth, P. L. (2010), A survey of recent changes in the main components of the ocean tide, *Cont. Shelf Res.*, *30*, 1680–1691, doi:10.1016/j.csr.2010.07.002.

Woodworth, P. L., and D. L. Blackman (2002), Changes in extreme high waters at Liverpool since 1768, *Int. J. Climatol.*, *22*, 697–714, doi:10.1002/joc.761.

Woodworth, P. L., and D. L. Blackman (2003), Evidence for systematic changes in extreme high water since the mid-1970s, *J. Clim.*, *17*, 1190–1197, doi:10.1175/1520-0442(2004)017<1190:EFSCIE>2.0.CO;2.

Woodworth, P. L., and D. L. Blackman (2004), Evidence for systematic changes in extreme high waters since the mid-1970s, *J. Clim.*, *17*, 1190–1197, doi:10.1175/1520-0442(2004)017<1190:EFSCIE>2.0.CO;2.

Woodworth, P. L., R. A. Flather, J. A. Williams, S. L. Wakelin, and S. Jevrejeva (2007), The dependence of UK extreme sea levels and storm surges on the North Atlantic Oscillation, *Cont. Shelf Res.*, *27*, 935–946, doi:10.1016/j.csr.2006.12.007.

Woth, K. (2005), North Sea storm surge statistics based on projections in a warmer climate: How important are the driving GCM and the chosen emission scenario?, *Geophys. Res. Lett.*, *32*, L22708, doi:10.1029/2005GL023762.

Woth, K., R. Weisse, and H. von Storch (2006), Climate change and North Sea storm surge extremes: An ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models, *Ocean Dyn.*, *56*, 3–15, doi:10.1007/s10236-005-0024-3.

Zhang, K., B. C. Douglas, and S. P. Leatherman (2000), Twentieth-century storm activity along the US east coast, *J. Clim.*, *13*, 1748–1761, doi:10.1175/1520-0442(2000)013<1748:TCSAAT>2.0.CO;2.

Zhang, W. Z., F. Shi, H. S. Hong, S. P. Shang, and J. T. Kirby (2010), Tide-surge interaction intensified by the Taiwan Strait, *J. Geophys. Res.*, *115*, C06012, doi:10.1029/2009JC005762.