Evaluation of storm surge hazard along the mainland coast of China

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Abstract

A storm surge hazard indicator was developed based on the storm surge index and high-water index. Based on this indicator, the storm surge hazard along the Chinese mainland coast was evaluated. Storm surges were simulated by the GPU-based high-resolution 2-D hydrodynamic operational storm surge model, driven by ERA5 reanalysis data. High waters were calculated from coastal warning water. The results show that the storm surge hazard of more than 80% of the mainland coast are moderate and low. The coast with a high-level storm surge hazard was distributed at the top area of Hangzhou Bay, in the Pearl River Estuary, along the eastern coast of the Leizhou Peninsula and in the coastal area of Guangxi Province, representing less than 20% of the total coast. In future work, different sea level rise scenarios will be considered in this indicator and method.

1. Introduction

The Chinese coast is very vulnerable to storm surges. The whole coast is affected by storm surges in every season. Since the statistical data were available (The China Marine Disasters Bulletin, available at http://www.mnr.gov.cn/sj/sjfw/hy/gbgg/zghyzhgb/) for 1989, the direct economic losses caused by storm surges (including near-shore wave run-ups) accounted for more than 90% of the total direct economic losses caused by marine disasters on the Chinese mainland. Since 2020, China has implemented a national natural disaster risk survey project, and storm surge risk assessment and zoning is an important category in the marine disaster risk survey.

Risk is a complex outcome that is depicted as a function of the combined effects of hazards, the assets or people exposed to hazard and the vulnerability of those exposed elements (available at https://www.undrr.org/building-risk-knowledge/understanding-risk) according to the United Nations Office for Disaster Risk Reduction (UMDRR). Hazard, as an event or occurrence that has the potential to cause harm to people and/or property (Shepard et al., 2011), is a determining factor when assessing disaster risk (Liu et al., 2014). Hazard evaluation is therefore the preprocess of risk assessment. Return periods of surge heights applied to indicate the risk (Lin et al. 2010) are obviously insufficient. Directly simulating storm surge inundation is a general approach that has been adopted to evaluate storm surge hazards. The inundation range and water depth of the selected category (Shepard, 2011) or of different levels of hurricanes were utilized to evaluate and zone storm surge hazards (Murdukhayeva et al., 2013; Zhang et al., 2016; Li et al., 2017; Shi et al., 2020). However, this approach, as specified in the Chinese storm surge risk assessment at the county scale and below, simply provides assessment results for a small region and requires heavy calculations. Another method is the statistical approach, such as the joint probability method (JPM) (Resio et al., 2009; Rizzi et al., 2017; Niedoroda et al., 2010) or the statistical-deterministic approach (Krien et al., 2015; Krien et al., 2017). However, the factor candidates in statistical approaches are usually simple surge or water height. Since storm surge disasters are mainly caused by inundation or wave-up destruction, two direct physical aspects, storm surge height and high water level, should be considered.

Based on the analytic hierarchy process (AHP), this paper developed a storm surge hazard assessment indicator based on two key natural elements of storm surge disasters: storm surge and high tide level. By using the GPU technique-improved storm surge model and Chinese coastal warning water, the high-resolution storm surge hazard index along the coast of mainland China could be calculated and classified.

2. Storm Surge Hazard Assessment Indicator

According to the AHP, the hierarchical structure model of the storm surge hazard index was established. The model factor layer includes two physical factors: storm surge and high water. If the superposition evaluation model is adopted, the number of hazard indicators is as follows:

$$D_g = w_s * S + w_h * H$$

where S is the storm surge index, H is the highwater index, and w_s and w_h are the weights of the storm surge and high water indices, respectively.

The intensity and frequency of storm surges should be considered in the index. The extreme return period is one of the quantitative indicators that comprehensively reflects the intensity and frequency of events. Therefore, the return value of a short period and a long period were adopted as the index layer of the storm surge factor. The high-water factor directly adopted the water level that would probably cause danger or disaster along the coast, and it was defined as the warning water level in China. In the area without a warning water level, a high water value that historically caused disasters or the elevation value of the area prone to inundation can be selected as the high-water factor.

Table 1
Storm surge hazard assessment indicator

Indicator	Index factor	Index weight	Index layer	Layer weight
Storm surge hazard	Storm-surge	w_s	Short-term return value	w_{s1}
			Long-term return value	w_{s2}
	High-water	w_h	Warning water	w_h

The judgment matrix is constructed as $\begin{pmatrix} a_{ss}a_{sh} \\ a_{hs}a_{hh} \end{pmatrix}$, and the values of a_{ij} represent the importance of the storm surge relative to the high water level, the storm surge relative to the storm surge, the high water level relative to the storm surge, and the high water level relative to the high water level. According to the comparison scale law, a_{ij} is taken in the middle of 1–9 and its reciprocal, usually between 2N-1 and 2n + 1 (n = 1,2,3,4). The scale significance is shown in the Table 2.

Table 2
The significance of the judgment matrix element

Assignment	Significance
1	The two elements are equally important
3	Element i is slightly more important than element j
5	Element i is more important than element j
7	Element i is much more important than element j
9	Element i is extremely more important than element j

Taking a_{ss}=a_{hh}=1, a_{sh}=1/5, and a_{hs}=5 separately, the corresponding weights of the index factor were calculated by the root method as W_s=0.309 and W_h=0.691.

The above steps were repeated to construct the judgment matrix of the storm surge index layer. The surge values of the two return periods are equally important; that is, a_{ij} was taken as 1, and the weights were calculated as W_{s1}=0.1545 and W_{s2}=0.1545.

3. Data And Methodology

3.1 Storm surge model

The numerical simulation results can provide the storm surge values for sites along the Chinese coast. Yu (Yu et al., 2002; Dong et al., 2008) developed a high-resolution 2-D hydrodynamic model and used it for operational storm surge predictions in China. Liu (2020) modified the model by using CUDA Fortran to improve the calculation efficiency. This approach is very useful for calculating the long-time scale data in this study. We use a structured grid for the area from 15°N to 42°N and 105°E to 129°E as the computational domain, and this grid coveres all of China’s coastal areas. The grid resolution of the model is 1’. There are 1441 grid cells in the x-direction and 1621 grid cells in the y-direction. The coastal water depth data were obtained by field measurements near the continental shelf. The other bathymetric data were obtained from the General Bathymetric Chart of Oceans 2014 dataset (GEBCO, 30 arc sec resolution) (Weatherall et al. 2015). The two bathymetries were combined and interpolated into the computational grid underlying the model. The bathymetric data used in this study are illustrated in Fig. 1.

3.2 Pressure and wind fields

Pressure variation and wind are the direct forcing factors affecting the storm surge. The accuracy of the input pressure and wind field greatly affects the storm surge model results. The European Centre for Medium-Range Weather Forecasts (ECMWF) released the fifth-generation reanalysis datasets (ERA5), which provide long time series of atmospheric fields at high spatial and temporal resolutions (Hersbach et al., 2019). Dullaart validated the wind speed for eight historical storm surge events globally as well as the surge heights for four of them. The results showed that ERA5 constituted a major improvement over

ERA-Interim (Dullaart et al,2020). Li (Li et al., 2021a) and Tan (Tan et al., 2021) indicated that the ERA5 wind data matched well with the observations of typhoon events in the North and East China Seas. Although Li (Li et al., 2021b) considered that the ERA5 maximum wind speed of typhoons is underestimated in the Northwest Pacific Ocean, the ERA5 datasets represent a preferred storm surge forcing due to their high resolution.

3.3 Storm surge return value calculation

The ERA5 wind and pressure fields were linearly interpolated to the computational grid to force the GPU-based model, and the storm surge heights were retrieved hourly from 1980 to 2019. The maximum annual surge value of each grid along the Chinese mainland coast was taken to form the extreme series of storm surges. The two-parameter Fisher-Tippett Type I (Gumbel, 1958) distribution is commonly recommended in port and coastal engineering design. The Gumbel extreme value distribution was used to fit the annual extreme storm surge value, and then the values were retrieved under a specific return period.

The equation is given by this double exponential function:

$$G\left(x\right)=e^{-e^{-(x-\mu)/\alpha}}$$

where μ is the location parameter, that is, the mode of distribution, and α is the scale parameter, which represents the discreteness of the distribution. These two parameters can be estimated by many methods (Aydin et al.,2015). In this paper, the Gumbel method was used (Gumbel, 1958).

3.4 Warning water level

The warning tide level is a water level threshold that can be used to indicate a regional area may suffer from inundation and disasters if high tide exceeds that threshold. This value is related not only to the local return high tide but also to the local elevation, seawall height and firmness, waves run-up, and local social economy, etc. Thus, the value must be determined using a complex and rigorous calculation process according to the national standard “Specification for warning water level determination”. China has already issued all warning water levels for more than 200 coastal sections of the country. There are four grades of warning level values in each section. The value of the red warning water level refers to the upper limit of the tide level under which the coastal people can live and engineering can operate safely; this value is dominantly determined by the actual construction standard of the coastal seawall. When the water level reaches this value, major storm surge disasters may occur along the coast. Therefore, the red warning value reflects a high water level related to storm surge disasters, but this value also includes the local astronomical tide, the probability of the superposition of a storm surge and astronomical tide, and the local surge disaster-proof capacity. In this study, the newly approved red warning water level values in the coastal section are in reference to the mean sea level (MSL) and local astronomical tide and are adopted as the index factor value of the high water level. For the same high tide value, the lower the warning water level, the greater the disaster, so the reciprocals of the warning water level were taken to participate in the calculation.

4. Results

4.1 Distribution of storm surge return values along the coast of mainland China

Based on the methods described above, the return values of storm surges along the Chinese mainland were calculated. We use the value of 5-year return period to represent the short-term period (high-frequency occurrence) value of storm surges and the value of the 50-year return period to represent the long-term period (low-frequency occurrence) value. The figure below shows that the areas of the top of the three bays in the Bohai Sea, the Yangtze River Estuary and Hangzhou Bay, the Pearl River Estuary and the eastern coast of the Leizhou Peninsula experienced more serious storm surges. The return value of the 5-year storm surge is more than 1 m, and that of the 50-year storm surge is more than 2 m. The differences between these two return period values are more than 1 m in the areas from Hangzhou Bay to the north central part of Zhejiang Province and most areas from the Pearl River Estuary to the eastern coast of the Leizhou Peninsula, with an increase of more than 50%, indicating that these areas are more likely to encounter higher storm surges and may experience serious hazards.

4.2 Distribution of warning water levels along the coast of mainland China

The red warning water value (Fig. 5, left) from the unified elevation datum for the South China mainland coast is generally higher than that of the north due to the contribution of astronomical tide, and it was lowest in the vicinity of the nontidal point in Bohai, which is related to the lower tidal level in the area. On the southern Jiangsu, Shanghai, Zhejiang and Northern Fujian coasts, as well as on the eastern coast of the Leizhou Peninsula, the value is higher, and the highest value occurred in Shanghai for. After removing the influence of the tide level and sea level, the definite red warning value (Fig. 5, right) along the coast of Shanghai is still the highest, indicating that the coastal defense ability of Shanghai is strong, and a higher water level can cause coastal storm surge disasters in this region. The definite red warning values increase along the southwest coast of Bohai Bay, the coast of eastern Guangdong and the coast of Hainan Island. These areas also require higher water levels to cause storm surge disasters. The areas where the definite red warning value decreases include the eastern coast of the South Bank of Liaodong Peninsula, the coast of Zhejiang and the coast from the West Bank of Leizhou Peninsula to Guangxi Province. The defense capacity of these areas is weak, and the lower water level can cause storm surge disasters.

4.3 Distribution and zoning of the storm surge risk index along the coast of mainland China

We standardized the above three layers indices-two return period surge values and the definite warning water level—with min-max normalization as follows:

$$Q_i = \frac{p_i - min(p_i)}{max(p_i) - min(p_i)}$$

where p is the index value, Q is the standardized value, and i is the number of grid data.

Then, the storm surge hazard index along the Chinese mainland was calculated based on the storm surge hazard assessment formula. Based on its distribution (Fig. 4, left), the three bay tops of the Bohai Sea, the top of Hangzhou Bay, the Pearl River Estuary, the East Bank of Leizhou Peninsula, the coast of Guangxi Province, and the tops of some bays in Zhejiang and Guangdong Province have a high storm surge hazard index and are more likely to experience storm surge hazards. Among them, Bohai Bay, Laizhou Bay, the top of Hangzhou Bay and the eastern coast of the Leizhou Peninsula are mainly at risk due to the probability of a larger storm surge, while the coastal areas of Guangxi Province and Liaodong Bay are at risk due to the weak local defense capacity against a storm surge.

According to the cumulative frequency distribution of storm surge hazard indices, the level of storm surge hazard along the Chinese mainland was divided into four grades (Table 3), from very high to low, corresponding to 1 to 4. According to its distribution (Fig. 4, right), the storm surge hazard is quite moderate in most parts of the Chinese mainland coastal area, with more than 60% of grid points having a value of level 3. The storm surge hazard level is low in the southern part of Shandong Peninsula, southern Zhejiang, Hainan Island and southwestern coast of the Leizhou Peninsula and high in Bohai Bay, Laizhou Bay, Hangzhou Bay, the Pearl River Estuary, the eastern coast of Leizhou Peninsula and the coastal area of Guangxi Province. In these high-level hazard probability areas, the top area of some bays has a very high storm surge hazard level but covered less than 0.7% of the total coastal grid points.

Table 3
Classification of storm surge hazard

Index value	$0 < x \leq 0.1$	$0.1 < x \leq 0.2$	$0.3 < x \leq 0.2$	$0.3 < x$
Level	4 (low)	3 (moderate)	2 (high)	1 (very high)

5. Conclusions And Discussion

In this paper, a storm surge hazard assessment index is established by using the AHP, and two key factors related to storm surge disasters—storm surge and high water level are considered. The return value, which reflects both strength and frequency, is used as the storm surge factor, and the warning tide level representing the possible storm surge disaster along the coast is used as the high-water level factor. The extreme storm surge series was simulated based on a GPU tech-based high-resolution 2-D hydrodynamic operational storm surge model, driven by ERA5 datum with the highest temporal and spatial resolutions of the ECMWF. The definite red warning water level in mainland Chinese coastal areas, representing the probability of a storm surge disaster issued by China, was used as the high-water level factor. The storm surge hazard indices along the Chinese mainland coast were calculated, and the results showed that the hazard of storm surge in most coastal areas of China is moderate, and in Bohai Bay, Laizhou Bay, Hangzhou Bay, the Pearl River Estuary, the eastern coast of the Leizhou Peninsula and most coastal areas of Guangxi Province, it is high. In these high-level areas, the tops of some bays had the very high level of storm surge hazard.

The evaluation index and methodology established in this paper provide a relatively unified standard for storm surge hazard assessment and comparison and can be applied to coastal regions worldwide. Since climate change has been considered in risk assessment (Shaperd et al., 2011; Murdukhayeva et al., 2013; Rizzi et al., 2017), this method can take sea level rise into account by deepening the bathymetry and mean sea level and changing the astronomical tide; these approches will be conducted in our future research.

Declarations

Statements and Declarations:

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Figures

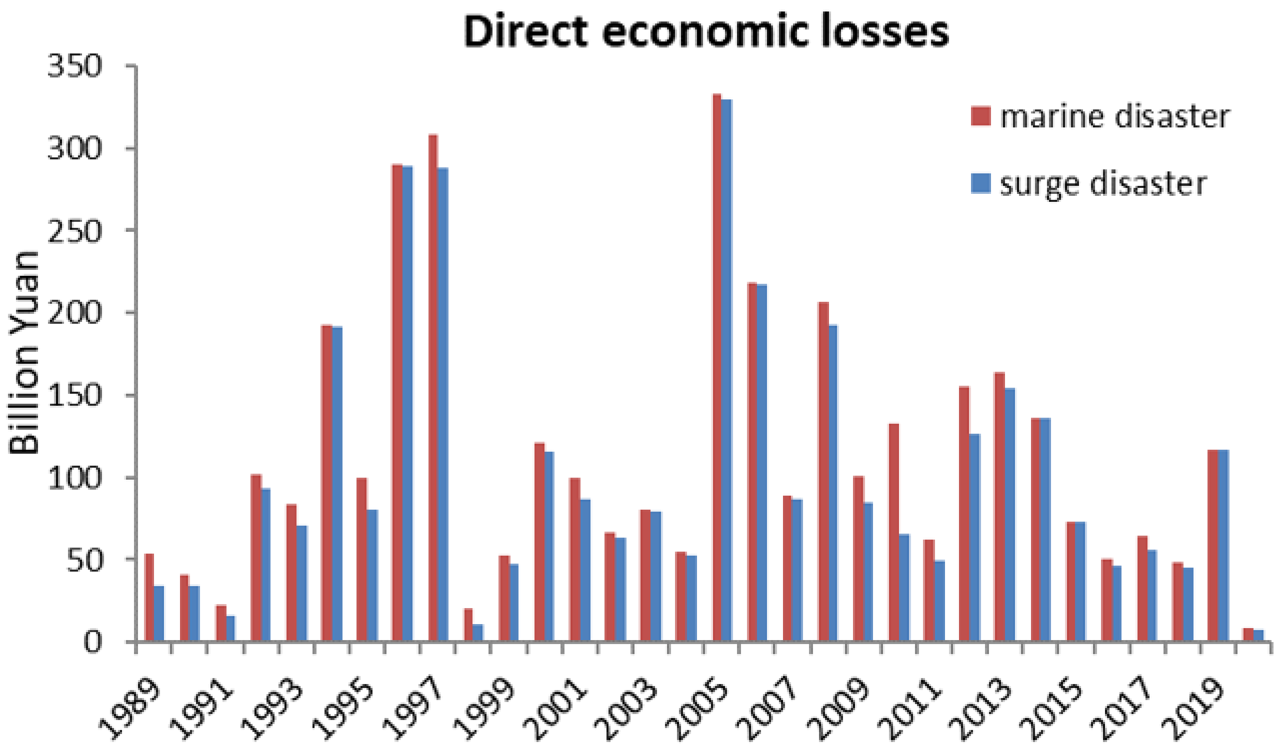

Figure 1

The annual direct economic losses caused by marine and storm surge disasters

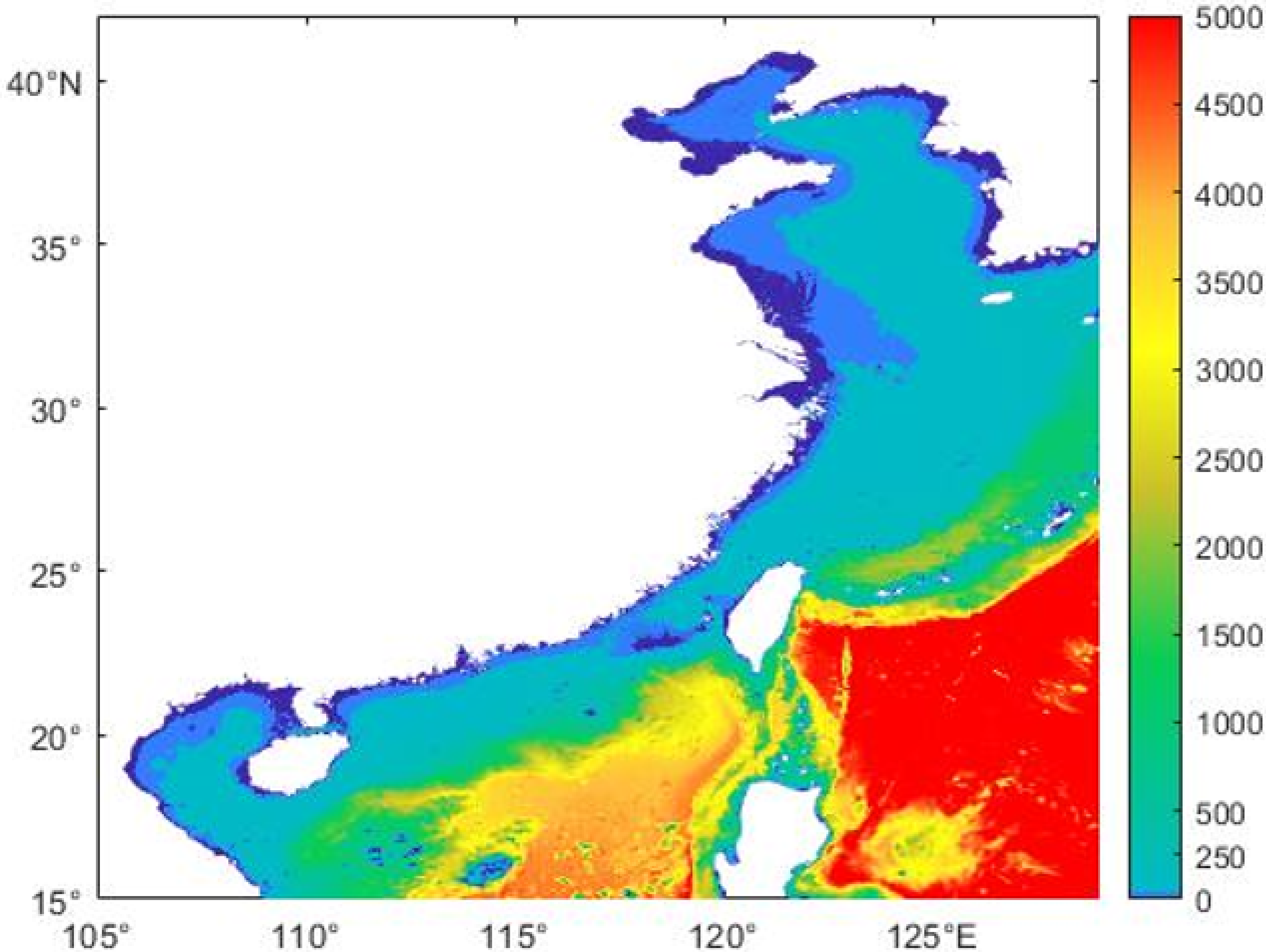

Figure 2

Model domain and bathymetry

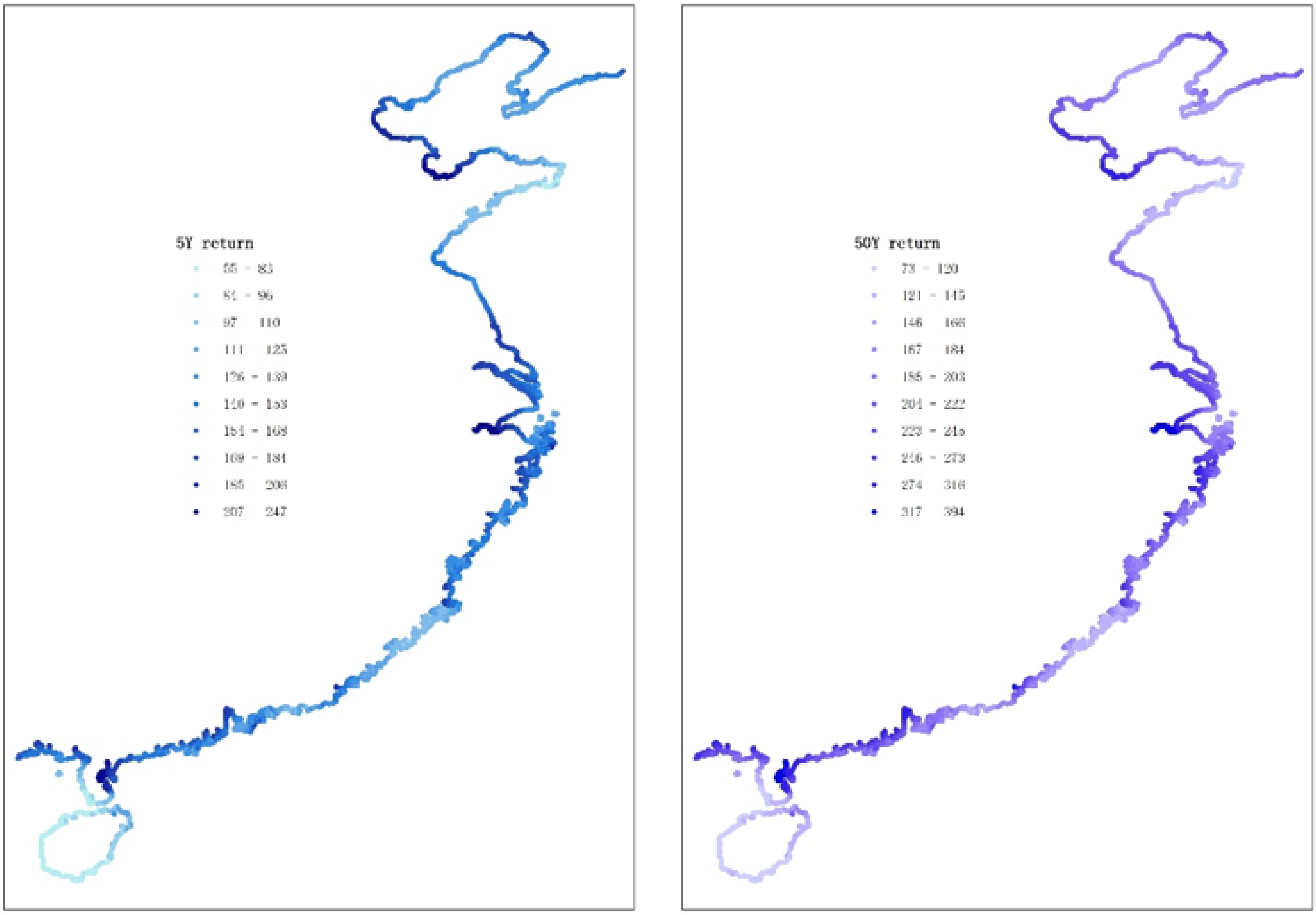

Figure 3

Distribution of storm surge return values along the coast of mainland China

(left: 5-year period, right: 50-year period)

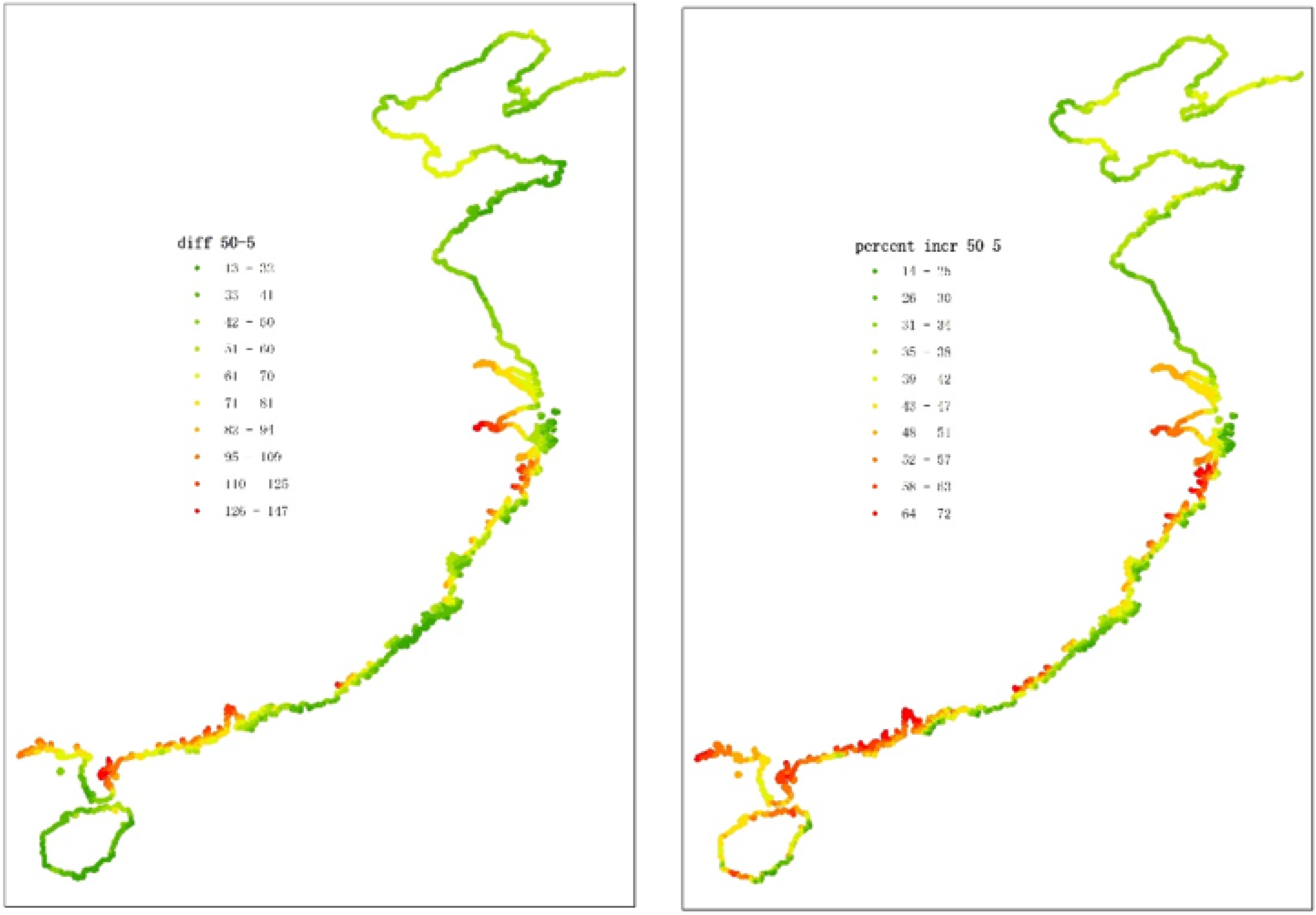

Figure 4

Distribution and percentage of storm surge return value differences over 5 years and 50 years along the coast of mainland China

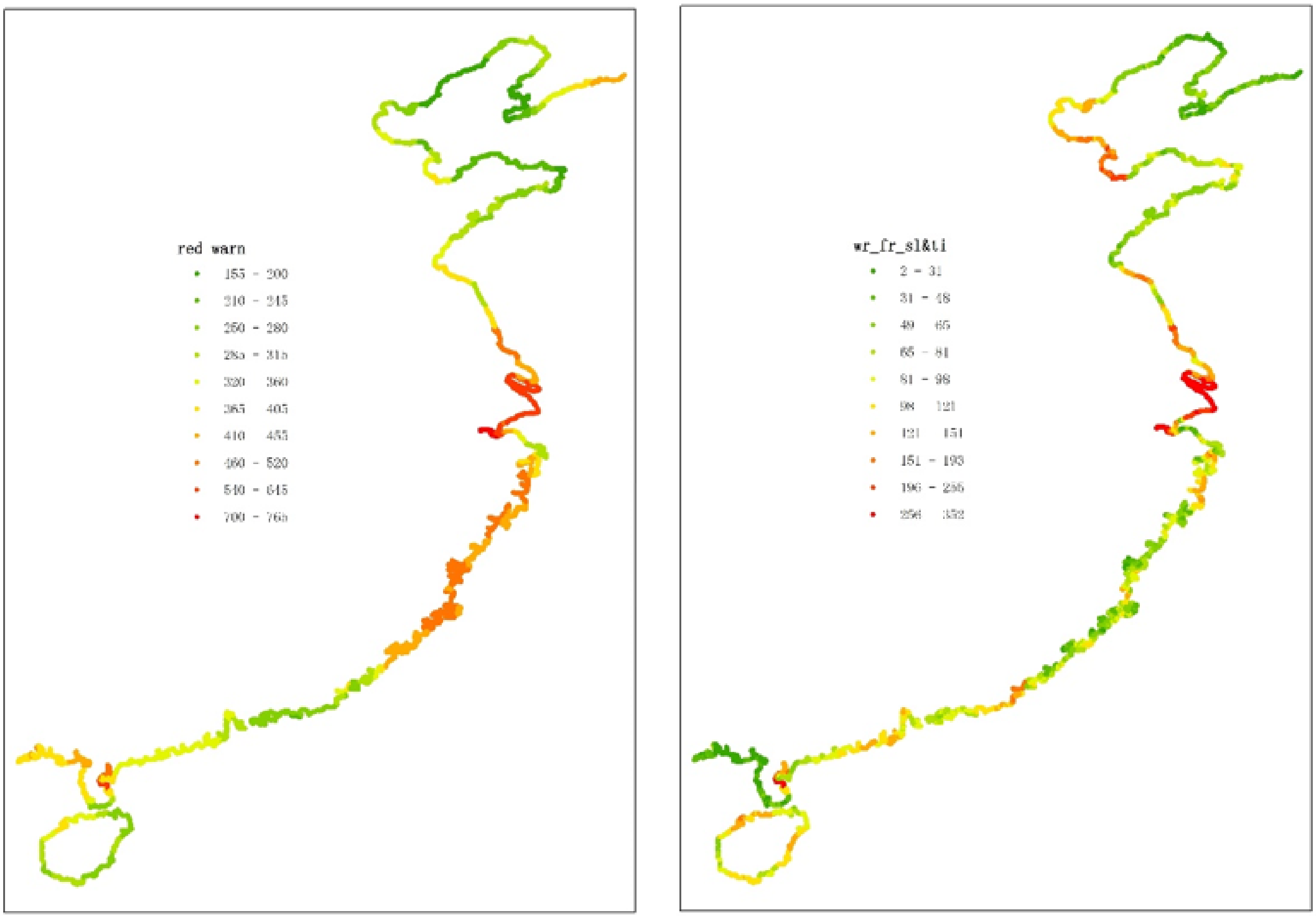

Figure 5

Distribution of the red warning water level along the coast of mainland China

(left: red warning value; right: definite red warning value)

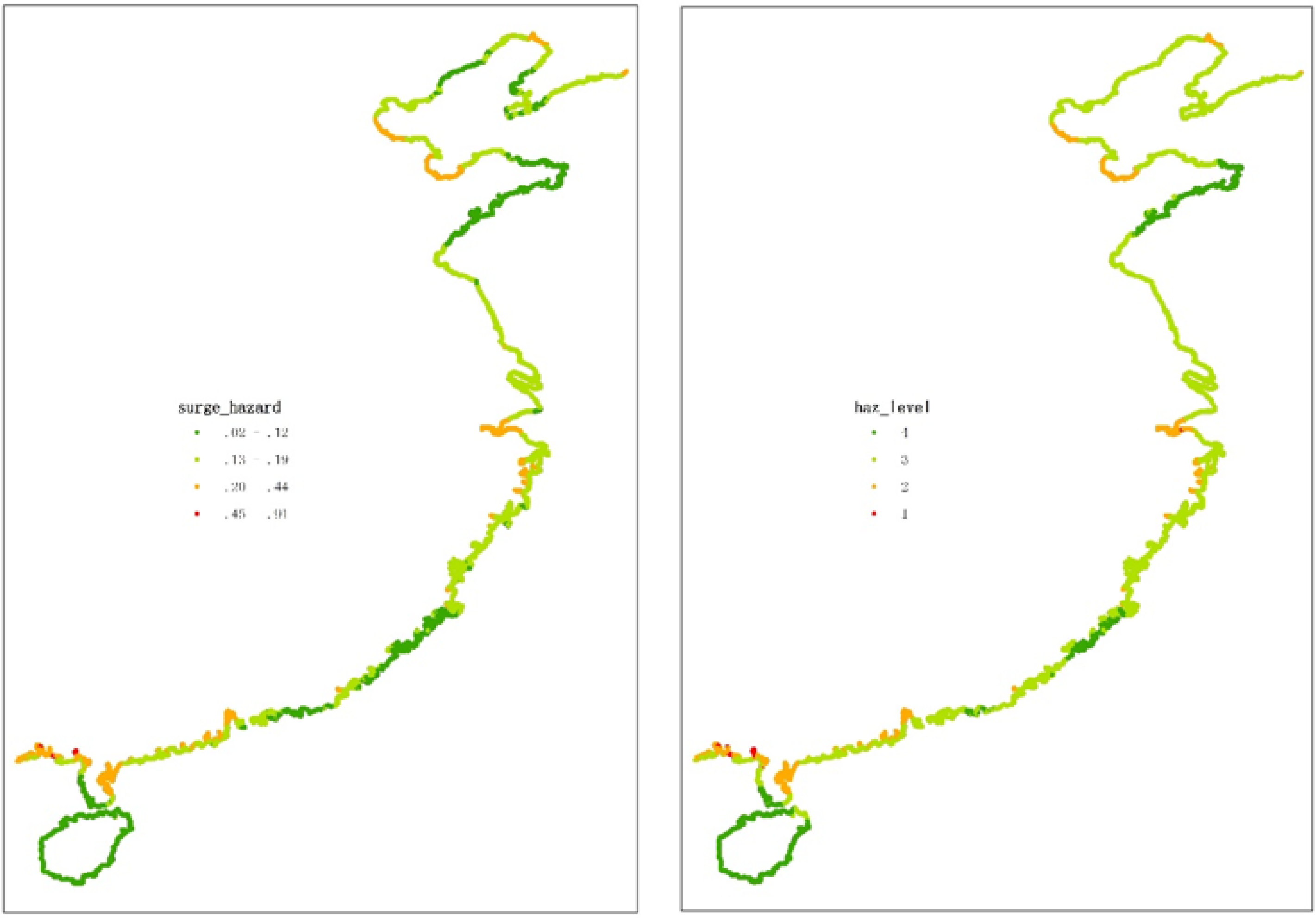

Figure 6

Distribution and zoning of the storm surge risk index

(left: index value; right: hazard level)