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RESEARCH ARTICLE

Typhoon disaster risk zoning for China’s coastal area

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Abstract Previous studies on typhoon disaster risk zoning in China have focused on individual provinces or small-scale areas and lack county-level results. In this study, typhoon disaster risk zoning is conducted for China’s coastal area, based on data at the county level. Using precipitation and wind data for China and typhoon disaster and social data at the county level for China’s coastal area from 2004 to 2013, first we analyze the characteristics of typhoon disasters in China’s coastal area and then develop an intensity index of factors causing typhoon disasters and a comprehensive social vulnerability index. Finally, by combining the two indices, we obtain a comprehensive risk index for typhoon disasters and conduct risk zoning. The results show that the maximum intensity areas are mainly the most coastal areas of both Zhejiang and Guangdong, and parts of Hainan Island, which is similar to the distribution of typhoon disasters. The maximum values of vulnerability in the northwest of Guangxi, parts of Fujian coastal areas and parts of the Shandong Peninsula. The comprehensive risk index generally decreases from coastal areas to inland areas. The high-risk areas are mainly distributed over Hainan Island, south-western Guangdong, most coastal Zhejiang, the coastal areas between Zhejiang and Fujian and parts of the Shandong Peninsula.

Keywords typhoon disaster, risk zoning, comprehensive social vulnerability index, China’s coastal area

1 Introduction

Typhoons, also known as tropical cyclones, may make landfall on China from Hainan in the south to Liaodong in the north. Throughout history, severe and super typhoons have caused extreme disasters in China, resulting in serious damage to infrastructure, property and the agricultural industry, and loss of life (Wang et al., 2006; Zhang et al., 2009). According to statistics from 1949 to 2010, on average, 27.1 typhoons generate each year in the Northwest Pacific and South China Sea, of which 6.9 typhoons land on China. From 2005 to 2015, typhoons in China have caused annual average direct economic losses of 44.78 billion CNY (converted to 2005 values), accounting for 17.4% of the total direct economic losses of meteorological disasters (Zhao et al., 2015). Therefore, it is of significance to build a system for assessing the risk of typhoon disasters in China’s coastal area.

As the basis for typhoon disaster impact assessment, a series of studies were conducted, including the activity characteristics of the impacting and landfalling typhoons, typhoon disaster characteristics and formation regularity (Liang et al., 1995; Xu and Gao, 2005; Xue et al., 2006; Yang et al., 2007; Chen et al., 2009). Following this, some studies assessed the risk of typhoon disasters in China, with more emphasis on semiquantitative research based on disaster data (Cheng and Wang, 2004; Lou et al., 2009; Rezapour and Baldock, 2014). In addition, Lin and Luo (1995) and Kim et al. (2018) assessed the regional typhoon disaster risk and developed forecast models.

The arrival of a typhoon is accompanied by heavy rain and strong winds, which are the factors causing severe disasters. Using the advanced Doppler weather radar, Liu et al. (2011) determined the dynamic and static factors of typhoons to establish a typhoon disaster assessment model. Niu et al. (2011) selected representative indices of typhoon precipitation and typhoon winds to establish a loss assessment model. Vickery et al. (2009), Fang and Shi (2012), and Fang and Lin (2013) reviewed the factors causing tropical cyclone disasters. Huang and Wang (2015) built a quantitative disaster assessment model by analyzing the indicators of the two factors (rainfall and intensity) and typhoon disasters, while some studies only consider the factor causing disasters to determine the risk

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of typhoon disasters (Li et al., 2006; Su et al., 2008; Yang et al., 2010).

Considering the vulnerability component of risk, many factors have been chosen for study, such as population, economic currency, indoor property, gross domestic product and road network (Ding and Shi, 2002; Jiang et al., 2014; Xu et al., 2015; Cao et al., 2016; Mo et al., 2017). Pielke and Landsea (1998) pointed out that increasing population and increasing wealth are the major vulnerability factors contributing to increasing disaster losses. A number of population and economic indices have been established, among which the most widely used is the social vulnerability index of Cutter and collaborators (Cutter et al., 2003; Chen et al., 2011). Chen et al. (2013) selected 29 socioeconomic indicators to design a typhoon disaster vulnerability index method for China.

In recent years, some researchers have conducted studies on risk zoning. For local areas, Yu et al. (2011) divided Hangzhou city into five typhoon rainstorm flooding disaster risk zones. In addition, Lou et al. (2012) divided the risk of typhoon disasters in Zhejiang Province into four parts. For larger ranges, Chen et al. (2011) found that 16 cities could be classified into three grades of hazard in the Yangtze River Delta region. Furthermore, Yin et al. (2013) zoned typhoon disasters in China into nine regions. Most previous studies on typhoon disaster risk assessment have focused on a single province or on smaller areas and do not utilize disaster data at the level of individual counties. Recently, Lu et al. (2018) developed a method for risk zoning of typhoon disasters at the county level for Zhejiang Province. This makes it possible to conduct typhoon disaster risk zoning at the county level for China's coastal areas, which is the main topic of this study. The method can be used to determine a suitable study area according to the disaster data and select the best technical methodology for conducting the study.

To conduct typhoon disaster risk zoning at the county level for China's coastal areas, the remainder of this paper is organized as follows. Section 2 introduces the data and methods. Section 3 discusses the characteristics of typhoon disasters and typhoon precipitation and winds in China's coastal areas. Section 4 builds an intensity index of factors causing typhoon disasters and a comprehensive social vulnerability index. The two indices are combined to obtain a comprehensive risk index and risk zoning is conducted. Section 5 provides a conclusion and discusses the applicability of the method.

2 Data and methods

2.1 Data

2.1.1 Precipitation and wind data

This study uses the daily precipitation data of 2479 stations and the daily wind data of 2419 stations which are distributed throughout China from 1 January, 2004 to 31 December, 2013, provided by the National Meteorological Information Center. The maximum wind speed is the maximum 10 min mean wind speed on the day.

2.1.2 Typhoon disaster and social data

Coastal typhoon disaster data for China were provided by the National Climate Center with county-level resolution recorded for each typhoon. The data include four indicators: direct economic loss, affected population, death toll and affected crop area. The typhoon disaster data of provinces from Meteorological Disaster Yearbooks are used as a quality-control check of the damage data at county level. Table 1 shows typhoon disaster records during 2004–2013 for the 12 coastal provinces and cities in China. There are only three years of records for Liaoning and no records in Hebei, Tianjin and Taiwan. Therefore, the other eight coastal provinces and cities with at least seven years of records — Shandong, Jiangsu, Shanghai, Zhejiang, Fujian, Guangdong, Guangxi and Hainan — were selected as the study area (Fig. 1). Figure 2 shows the distribution of the number of typhoon disaster records in the eight coastal provinces and cities. It can be seen that the junction coastal areas between Fujian and Zhejiang, and between Guangdong and Guangxi have the highest frequency of records.

The social data were obtained from the sixth national population census of China in 2010, including the resident population, household registration population and so on. The socioeconomic data are from the statistical yearbooks of provinces, cities and counties in 2011 provided by the China Economic and Social Development Statistics Database.

2.2 Method

This study develops risk zoning for China's coastal areas using county-level-resolution data following the methods developed by Lu et al. (2018). Preliminary to the results documented here, three technical paths were explored. The first path treats each coastal province as an independent individual for risk zoning and then unifies the zoning results. On the basis of the different typhoon disasters, different economic bases and social population gaps in each province and city, the second path divides the coastal provinces into three regions, South China, South-east China and East China, for risk zoning and then unifies the results. The third route considers the coastal provinces and cities as a whole for risk zoning. Comparing the results of the three paths, it is found that the comprehensive risk zoning result of the third technical path corresponds to the typhoon disaster distribution, and therefore can better indicate the typhoon disaster risk level for each county in

Fig. 1 Study area.

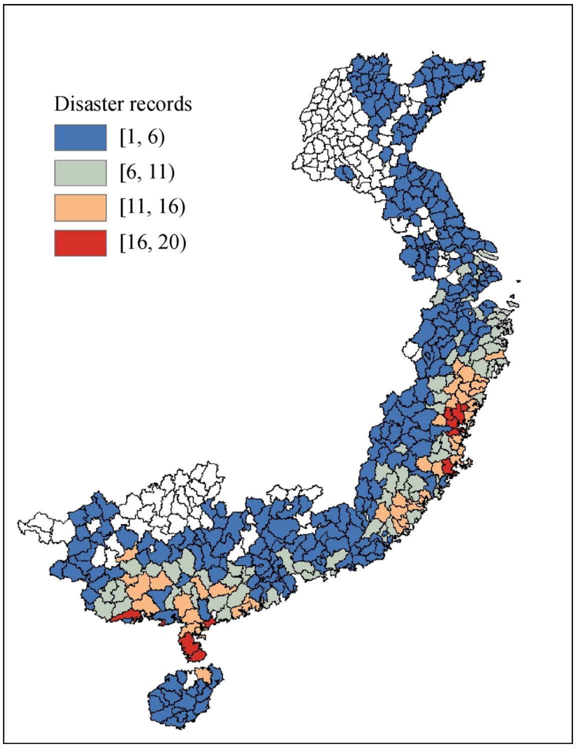


Fig. 2 Number of typhoon disaster records in the study area.

Table 1 Typhoon disaster records during 2004–2013 for the 12 coastal provinces and cities in China

Provinces	Years	Total years
Fujian	2004–2013	10
Guangdong	2004–2013	10
Zhejiang	2004–2012	9
Jiangxi	2005–2013	9
Jiangsu	2004–2009, 2011–2013	9
Shanghai	2004–2009, 2011–2013	9
Shandong	2005–2008, 2010–2013	7
Hainan	2005–2007, 2010–2013	7
Liaoning	2005, 2011, 2012	3
Hebei	None	
Tianjin	None	
Taiwan	None	

China's coastal area. The advantage of the third technical route is mainly the use of unified grading standards, which can reduce the error between provinces on the results of risk zoning. Therefore, this study chooses coastal provinces and cities as a whole to study typhoon disaster risks and zoning.

2.2.1 Objective synoptic analysis technique

Ren et al. (2001, 2007) developed a numerical technique, the objective synoptic analysis technique (OSAT), to identify tropical cyclone precipitation. The OSAT uses the distance from the typhoon center and the closeness and continuity between neighboring stations with precipitation to trace typhoon-influenced rainbelts, which may extend from 500 km to 1100 km from a typhoon center. Lu et al. (2016) developed the method of improved OSAT to identify typhoon winds. Then, in this study we use the OSAT method and the improved OSAT method (Lu et al. 2016) to identify typhoon precipitation and typhoon wind corresponding to individual cases of typhoons using daily station precipitation and wind data. The typhoon precipitation data refers to the accumulated precipitation for a typhoon case, while the typhoon wind data represents the maximum 10-min mean wind speed during a typhoon case. After identifying typhoon precipitation and winds throughout China, 538 stations, which are in the study area, are applied in the study.

2.2.2 Canonical correlation analysis

Canonical correlation analysis (CCA), which was first proposed by Hotelling (1936) for multivariate statistical analysis, is used in this study. The objective of CCA is to relate a set of dependent or criterion variables to another set of independent or predictor variables (Hardoon and Shawe-Taylor, 2009). This study uses CCA to determine the relationship between the affected population and economic loss (first set of variables), and the typhoon precipitation and winds (second set of variables).

2.2.3 Standardization methods

The study uses two standardization methods: Z-score standardization and min–max standardization. The equation of them are as (1) and (2), respectively.

$$Z=\frac{(x-\mu)}{\sigma}, \tag{1}$$

where Z is the standardized value, x is the original value, while μ and are the mean and the standard deviation of x, respectively. Z-score standardization is mainly used in calculating the intensity index of factors (the wind and precipitation) causing typhoon disasters.

Min-max standardization converts the initial value to a decimal between [0, 1]. The Equation is as follows:

$$x_i^*=\frac{x_i-m_i}{M_j-m_j}, \tag{2}$$

where x_i^* is the standardized value, x_i is the original value, $M_j=\max\{x_i\}$ and $m_j=\max\{x_i\}$. Min-max standardization is mainly used in calculating the comprehensive risk index “R” and its two factors “I” and “SoVI.”

2.2.4 Vulnerability assessment

On the basis of the SoVI designed to determine the disaster social vulnerability in the United States, Chen et al. (2013) selected 29 socioeconomic indicators to develop a typhoon disaster vulnerability index method for China’s social and economic environment. This study uses this method to evaluate the vulnerability of the study area and analyzes the spatial distribution of vulnerability in China’s coastal areas.

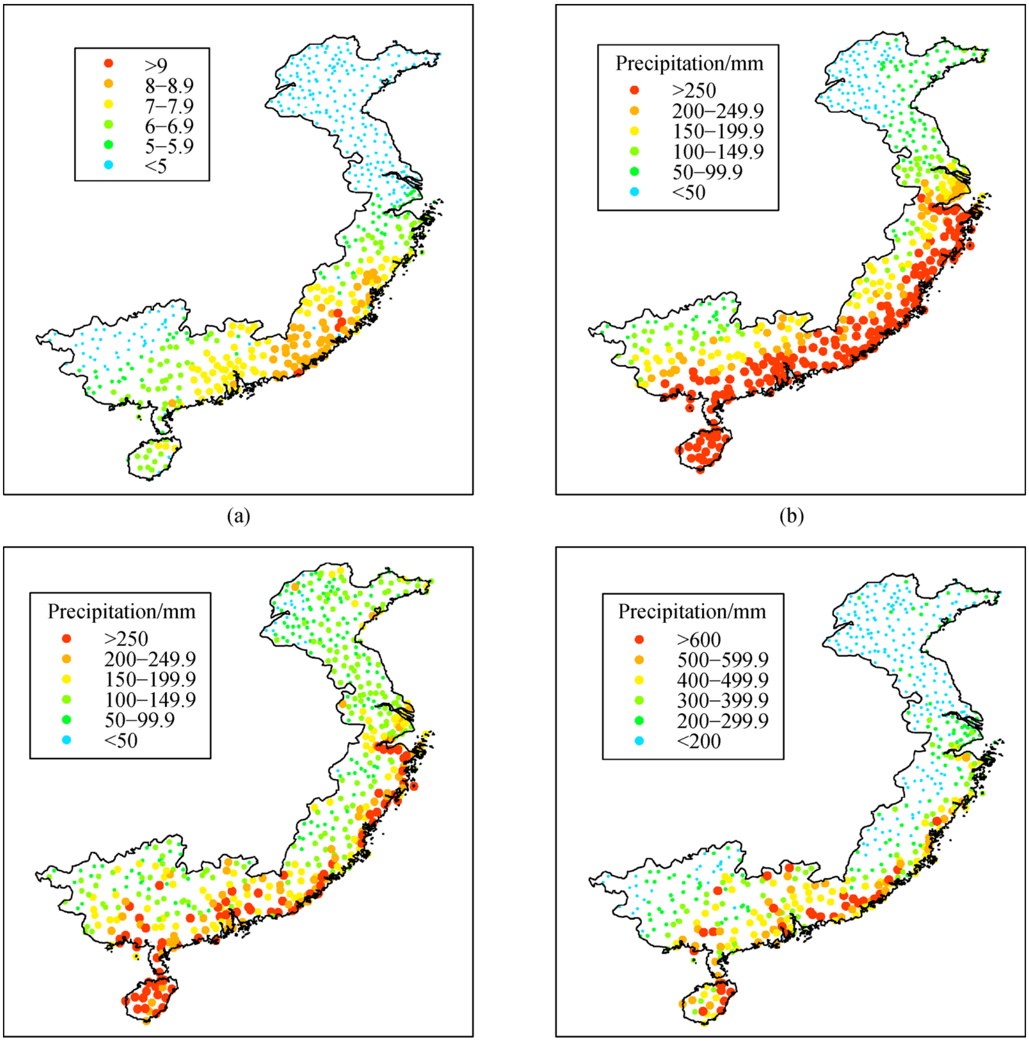
3 Characteristics of typhoon disasters and factors

3.1 Characteristics of factors causing typhoon disasters

The factors causing typhoon disasters are typhoon precipitation, typhoon winds and storm surges (Liang et al., 1995). In this study, two factors, typhoon precipitation and winds, are considered.

According to the annual average typhoon precipitation frequency based on daily precipitation $\geqslant 0.1$ mm for the study area from 2004 to 2013 (Fig. 3(a)), it is found that Fujian and Guangdong are high-frequency regions. The highest frequency appears in Jiuxian Mountains, Fujian Province, with an annual average impact frequency of more than nine events per year. Considering the annual average typhoon precipitation (Fig. 3(b)), the magnitude decreases inland from the coast. The annual average precipitation along the coastline in Shanghai, Zhejiang, Fujian, Guangdong, southern Guangxi and Hainan reaches a maximum level of more than 250 mm. On the basis of comparative analysis of the maximum daily precipitation of typhoons and the maximum accumulated precipitation of typhoons from 2004 to 2013 in the study area (Figs. 3(c) and 3(d)), it is found that extreme precipitation in south China is generally greater than that in southeast China especially for the maximum accumulated precipitation and in Fujian Province. In addition, maximum TC daily precipitation along the coastal line of southeast China is much bigger than that in the inland area. These are consistent with Chen and Ding (1979) on that the Central Mountain Range (CMR) of Taiwan Island generally weakens the intensity of precipitation of a typhoon in Fujian Province, and Qiu et al. (2019) on that the coastal mountains can cause extreme daily precipitation of landfalling typhoon along the coastal line of southeast China.

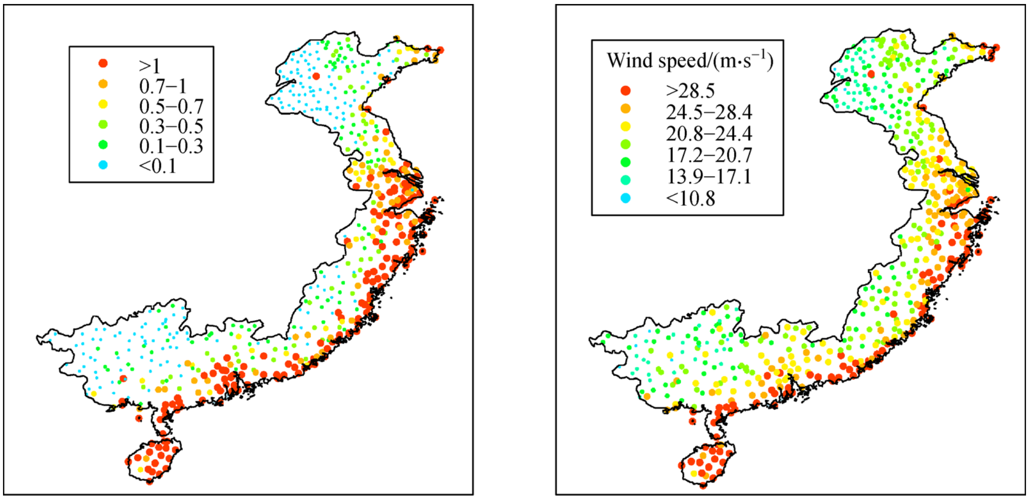
The average number of days with typhoon wind grade 8 or above (wind speed$\geqslant$17.2 m s^{-1}) over the 10 years was counted (Fig. 4(a)). It was found that the Yangtze River Delta, the Pearl River Delta and Hainan Island are most affected by typhoon winds grade 8 or above, with the average exceeding one day. The average number of strong winds days exceeded one day. Moreover, the average number of strong wind days in Weihai City and Yantai City in Shandong Peninsula are also greater than one day. The influences of winds and precipitation are different, and the strong winds in southern Jiangsu last longer than elsewhere. Owing to the protective barrier function of Leizhou



(a) (b)

(c) (d)

Fig. 3 Distribution of typhoon precipitation in the study area from 2004 to 2013. (a) Annual-mean precipitation frequency. (b) Annual-mean precipitation. (c) Maximum daily precipitation. (d) Maximum accumulated precipitation for one typhoon case.



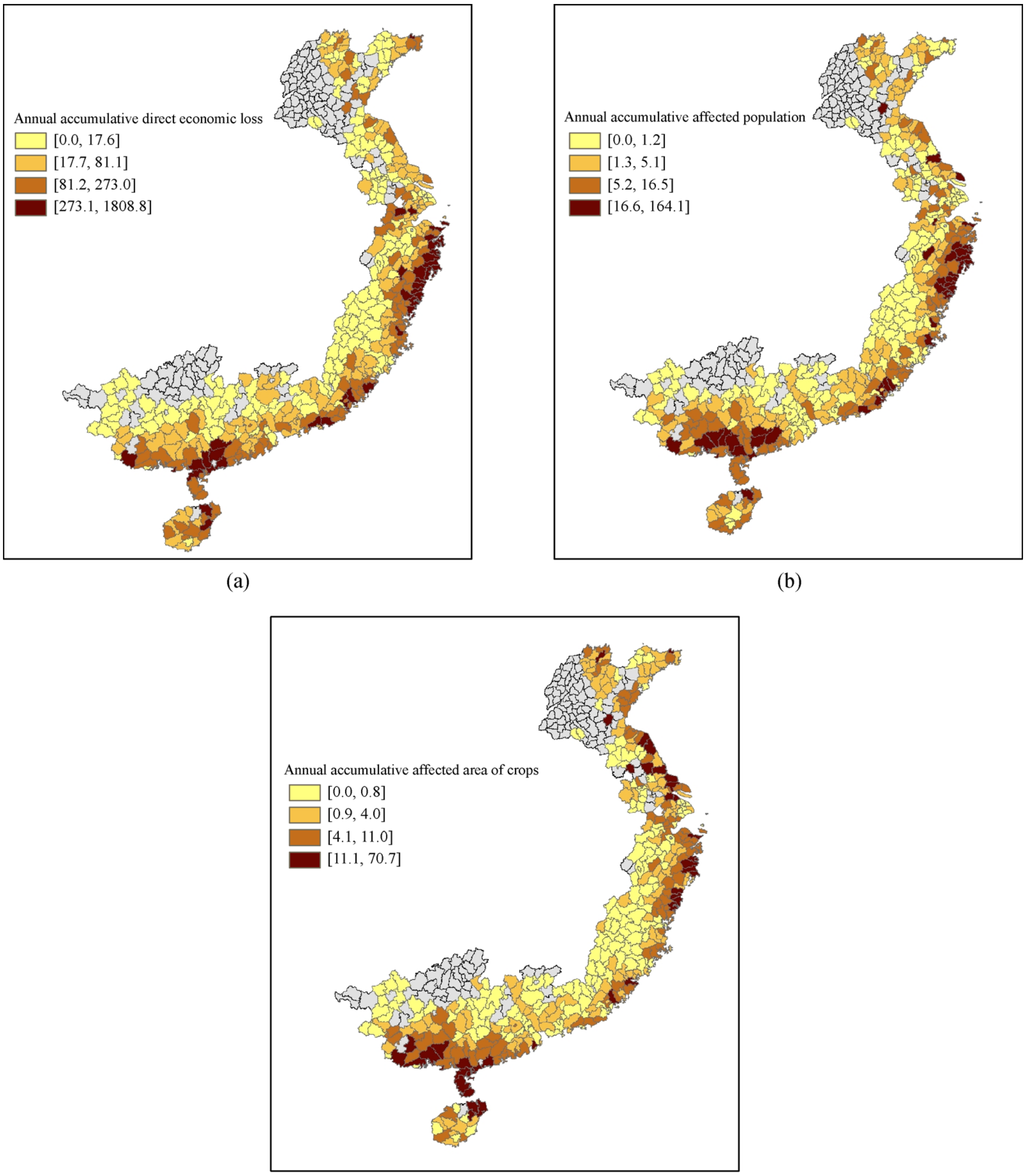
(a) (b)

Fig. 4 Same as Fig. 3, but for typhoon winds. (a) Annual-mean typhoon wind days (with wind force equal to grade 8 or above). (b) Maximum wind speed.

Peninsula and Hainan Island, the number of days affected by strong winds in Guangxi is relatively less. The annual-mean typhoon wind days and the maximum daily wind speed (Figs. 4(a) and 4(b)) show similar distributions across the study area, with the high-values and low-values coinciding in the two plots. The longer is the duration, the higher is the probability of extreme wind speeds. The maximum wind area is mainly distributed along the coast area, with a decrease toward inland.

3.2 Characteristics of typhoon disasters

Taking into account missing years of disaster records in some provinces, the annual average accumulative disaster damage is selected as the indicator for disaster analysis. Figure 5 shows the distribution of annual average accumulative damage including direct economic losses, affected population and affected crops caused by typhoons in China's coastal area during 2004–2013, and it is found that the overall trend of the three accumulative disasters decreases from the coast to inland areas. Figures 5(a), 5(b) and 5(c) all display that during 2004–2013, southern Guangxi, south-western Guangdong, coastal areas of Zhejiang, eastern Hainan, the coastal areas between Zhejiang and Fujian and between Fujian and Guangdong, and parts of the coastal Jiangsu were severely affected by



(a)

(b)

(c)

Fig. 5 Distribution of annual average accumulative damage in the study area. (a) Annual average accumulative direct economic loss (unit: million yuan). (b) Annual average accumulative affected population (unit: ten thousand persons). (c) Annual average accumulative affected area of crops (unit: thousand hectares).

typhoons, with high values of annual average accumulative direct economic loss, affected population, and affected crops. In contrast, such as the Pearl River Delta and Shanghai, which have high GDPs and large populations, experienced slight typhoon disaster with low values of annual average accumulative direct economic loss, affected population, and affected crops during the period.

4 Risk assessment and zoning of typhoon-induced disasters

4.1 Intensity index of factors causing typhoon disasters

The intensity of the factors causing typhoon disasters indicates the extent of the impact of typhoon disasters. In this study, we combine historical disaster data with the corresponding typhoon winds and precipitation data to develop an intensity index of factors causing typhoon disasters. CCA was carried out for the accumulated precipitation and the daily maximum wind speed (first field) versus the direct economic loss and the affected population for each typhoon in each county (second field), as shown in Table 2. According to the size of typical correlation coefficients, the degree of influence of typhoon precipitation and winds on the affected population or economic loss are determined. Although the typical correlation coefficients are not large, they pass the significance test for both typhoon precipitation and winds, so they can be used as weight coefficients. Whether the form of disaster is the affected population or the direct economic loss, typhoon winds have a greater impact than typhoon precipitation. By averaging the typical correlation coefficients of the disaster-causing form, the weight coefficients of typhoon winds and precipitation for the intensity index are obtained. The typhoon precipitation weight coefficient is 0.529, and the wind weight coefficient is 0.726. Considering the complexities of impacts of typhoon precipitation and winds on disaster, the precipitation weight coefficient being less than the wind weight coefficient doesn't mean that the impact of wind is more significant. It only means that in China's Coastal Area and on average, from the angle of linear relationships, the contribution of winds to disaster is greater than precipitation.

Consistent with the above statistics and weight calculation results, an intensity index of factors causing typhoon disaster was defined as follows:

$$I = Ax + By, \tag{3}$$

where I is the intensity index of factors causing typhoon disasters, A and B are the typhoon precipitation and wind weight coefficients, x is the standardized accumulated typhoon precipitation and y is the standardized maximum wind speed.

The intensity index of factors causing typhoon disasters in each county in the study area was calculated for 2004 to 2013, and the index was ranked by percentile (Fig. 6). The index generally decreases from the coast to inland meaning that the coastal areas are more affected by typhoon than the inland areas. The high-value areas are mainly distributed in counties locating on the coastline with the maximum intensity values in most coastal areas of both Zhejiang and Guangdong, and parts of Hainan Island.

4.2 Comprehensive social vulnerability index

The disaster-bearing body mainly refers to the population, property, natural environment, and so on. A disaster situation occurs when a typhoon causes human casualties, economic losses and damage to the natural environment. The SoVI designed by Chen et al. (2011, 2012) is used to analyze the spatial distribution of social vulnerability in China's coastal area. From the national population information, 29 indicators affecting social vulnerability (Table 3) were selected to investigate the vulnerability distribution in China's coastal areas, for example, median age, population density, family size, etc. By performing PCA on 29 indicators followed by Kaiser-normalized orthogonal rotation, seven principal components with an eigenvalue greater than 1 are obtained (Table 4). Finally, each principal component is classified by an explanatory factor in the rotated component matrix.

The total variance of the first component is about 37.3%. The explanatory factors include per capita disposable income, population density, and so on. For example, when income (UBINCM) increases, the average number of rooms for a family (PHROOM) decreases, the dependency ratio (QDEPEND) decreases, the ability of society to resist disasters becomes stronger and the vulnerability becomes lower. Therefore, the first component has a negative effect and the sign is negative. The total variance of the second component is 13.1%. The explanatory factors include education, medical conditions, and related parameters. When education and medical conditions are good, awareness of disaster prevention and mitigation is

Table 2 Results of the CCA for typhoon precipitation and winds

Disasters	Canonical correlation coefficient	Canonical variable coefficient	
		Typhoon precipitation	Typhoon wind
Affected population	0.29	0.556	0.704
Direct economic loss	0.355	0.502	0.748
Analysis result	The typhoon precipitation weight coefficient A = 0.529		

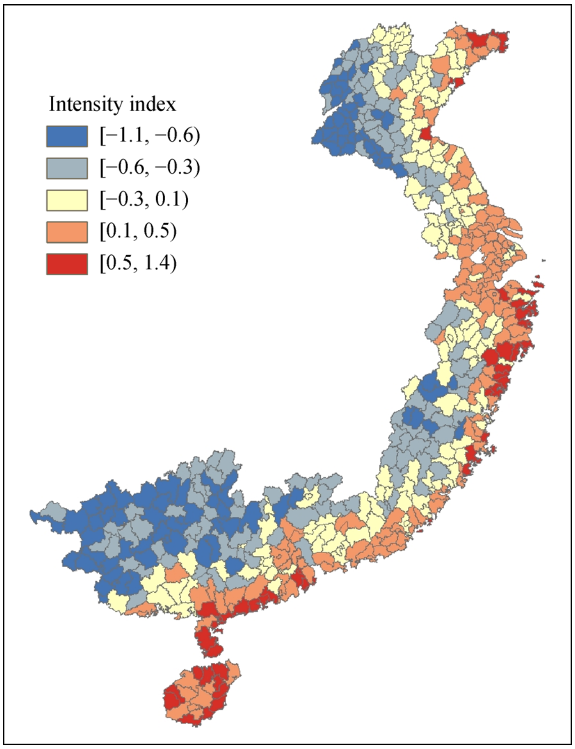


Fig. 6 Distribution of intensity index of the factors causing typhoon disasters in the study area.

enhanced, and social vulnerability is reduced. Therefore, the second component is negative and the sign is negative. The third component contributes 7.5% of the total variance, which mainly represents housing conditions and the agricultural situation. This component is negative. The total variance of the fourth component is 6.1%, which mainly includes the proportion of women and age. When the proportion of women and the average age increases, the social vulnerability increases; therefore, this component is positive. The total variance of the fifth component is 5.5%. The explanatory factors are ethnic minorities and low-income populations. When the population of low-income population increases, it indicates that the economy and society are declining and the ability to resist disasters is decreasing. Therefore, this component has positive effects. The total variance of the sixth component is 4.1%, which mainly includes illiteracy and no bathing facilities in houses. When the proportion of illiterate residents increases, housing condition is poorer and the vulnerability increases. Therefore, this component has a positive effect. The total variance of the seventh component is 3.4%. The explanatory factor is the size of the household. As the size of the household becomes larger, the capacity of houses to withstand disasters is strengthened. Therefore, this component is negative and the sign is negative.

In summary, the total variance explained by these seven components is up to 77%, which can be used to represent

Table 3 The 29 socioeconomic indicators selected by the SoVI method (Lu et al., 2018)

	Name	Variables
1	UBINCM	Per capita disposable income of urban residents (yuan)
2	QFEMALE	Percentage of females (%)
3	QMINOR	Percentage of minorities (%)
4	MEDAGE	Median age
5	QUNEMP	Unemployment rate (calculate-unemployed population/(unemployed + total population)
6	POPDEN	Population density
7	QUBRESD	Percentage of urban population (%)
8	QNONAGRI	Percentage of nonagricultural household population (%)
9	QRENT	Percentage of households that live in rented houses (%)
10	QAGREMP	Percentage of employees working in primary industries and mining (%)
11	QMANFEMP	Percentage of employees working in secondary industries (%)
12	QSEVEMP	Percentage of employees working in tertiary industries (%)
13	PPUNIT	Household size (people per household)
14	QCOLLEGE	Percentage of population with a college degree (25 years old and older)
15	QHISCH	Percentage of population with a high school diploma (20 years old and older)
16	QILLIT	Percentage of illiterate people (15 years old and older)
17	POPCH	Population growth rate (2000–2010)
18	PHROOM	Average number of rooms per household (rooms per household)
19	PPHAREA	Per capita housing construction area (m^2 per person)
20	QNOPIPWT	Percentage of premises without tap water (%)
21	QNOKITCH	Percentage of premises without a kitchen (%)

(*Continued*)

	Name	Variables
22	QNOTOILET	Percentage of premises without a toilet (%)
23	QNOBATH	Percentage of premises without a bath (%)
24	HPBED	Number of beds per 1000 people in health care institutions
25	MEDPROF	Number of medical personnel per 1000 people
26	QPOPUD5	Percentage of people under 5 years old
27	QPOPAB65	Percentage of population over 65 years old
28	QDEPEND	Population dependency ratio (%)
29	QSUBSIST	Percentage of population covered by subsistence allowances (%)

Table 4 The seven principal components extracted by principal component analysis

Component	Name	Contribution rate/%	Sign	Number of drivers	Drivers(coefficient)
1	Income、Average number of rooms per household and Population dependency ratio	37.3%	–	9	PHROOM(–0.75) QDEPEND(–0.726) QPOPUD5(–0.66) UBINCM(0.632) QRENT(0.625) POPDEN(0.608) QAGREMP(–0.562) QMANFEMP(0.515) QUBRESD(0.511)
2	Education and Medical treatment	13.1%	–	7	HPBED(0.858) MEDPROF(0.801) QHISCH(0.732) QCOLLEGE(0.719) QSEVEMP(0.574) QNONAGRI(0.54) QUBRESD(0.526)
3	Housing conditions and Agriculture	7.5%	–	5	QNOBATH(–0.765) QUNEMP(0.676), QAGREMP(–0.642), QMANFEMP(0.622) QNOPIPWT(–0.573)
4	Female proportion and Age	6.1%	+	4	QPOPAB65(0.878) MEDAGE(0.848) QFEMALE(0.677) POPCH(–0.537)
5	Minority and Low-income population	5.5%	+	2	QMINOR(0.803) QSUBSIST(0.719)
6	Illiteracy and Housing conditions	4.1%	+	3	QNOKITCH(0.704) QILLIT(0.612) QNOTOILET(0.582)
7	Household size	3.4%	–	2	PPUNIT(0.829) QNONAGRI(0.592)

Notes: 1) "Drivers" are part of 29 factors, which are absolute values of coefficients greater than 0.5. And 29 factors all contribute to every component. The value in a bracket, which is a coefficient, indicates the contribution of a factor to the component. 2) "Sign" indicates the effect of the component on vulnerability.

the social vulnerability in the study area. The comprehensive SoVI in the study area is defined as:

$$\begin{aligned} \mathrm{SoVI} = & -\mathrm{component1} - \mathrm{component2} - \mathrm{component3} \\ & + \mathrm{component4} + \mathrm{component5} \\ & + \mathrm{component6} - \mathrm{component7}. \end{aligned} \tag{4}$$

The comprehensive social vulnerability index (Fig. 7) represents the potential for loss for different locations when suffering the same typhoon. The lower the value, the greater the disaster tolerance of the city. Figure 7 shows that vulnerability generally increases from the coast to inland. The maximum values of the vulnerability index are mainly in the north-west of Guangxi, parts of Fujian coastal areas and parts of the Shandong Peninsula. Further

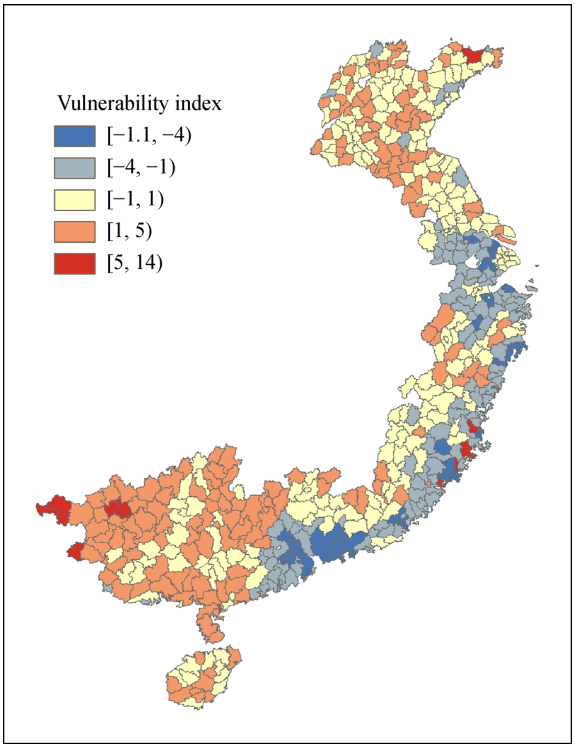


Fig. 7 Distribution of comprehensive SoVI in the study area.

analyses reveal that, the gross domestic product of Guangxi Zhuang Autonomous Region is lower than that of the other seven provinces and the economic foundation is weak. Relative to economically developed areas, the educational and medical conditions are relatively poor, and the disaster prevention and mitigation ability is weak, so the vulnerability is high.

4.3 Comprehensive typhoon disaster risk index and zoning for each county

The typhoon disaster risk assessment system is a complex system consisting of the intensity index of factors causing typhoon disasters, the vulnerability of the disaster-bearing body and the environment. However, this study does not consider the impact of the environment.

There are two steps to obtain the disaster risk index. First, the min–max standardization has been applied for the factor intensity index I and the comprehensive vulnerability SoVI to gain I* and SoVI*. Then the disaster risk index is obtained as follows (Lu et al., 2018):

$$R = \mathrm{I}^{*} \times \mathrm{SoVI}^{*}, \tag{5}$$

where the greater the comprehensive typhoon disaster risk index, the higher the possibility of typhoon disasters.

The comprehensive typhoon disaster risk index is divided into five levels by the natural discontinuity classification method in Arcgis, including Low risk, Medium-low risk, Medium risk, High-medium risk and High risk (Table 5). China’s coastal typhoon disaster risk zoning for the period 2004 to 2013 is presented in Fig. 8.

Figure 8 shows that the overall risk decreases from the coast to inland.The high-risk areas are mainly located in most Hainan Island, southwestern Guangdong, most coastal Zhejiang, the coastal areas between Zhejiang and Fujian and parts of the Shandong Peninsula. The low-risk areas are mainly distributed in the central and northern parts of Guangxi and the inland areas of western Shandong. Comparison with the historical distribution of disasters shows that this index can comprehensively indicate the distribution of risks when coastal areas are under the influence of typhoon disasters. The direct economic losses and casualties have a good correspondence with high and low risk in the provinces of Zhejiang, Fujian and Guangdong. The high-risk areas of Hainan Province and Jiangsu Province correspond to the distribution of disasters impacting the agricultural sector. The figure verifies that the factors causing typhoon disasters are not the only determiners of typhoon disaster. By combining the intensity index of factors causing typhoon disasters with social vulnerability, a comprehensive risk index can accurately indicate the risk of typhoon disaster.

5 Summary and discussion

Typhoon disaster risk zoning is conducted at the county level for China’s coastal area using precipitation and wind data, and typhoon disaster and social data from 2004 to 2013. The main results can be drawn as follows:

First, typhoon precipitation and wind are considered as the two main factors causing typhoon disasters in this study. Based on the two factors, an intensity index (I) of factors has been established. The index generally decreases from the coast to inland, while the maximum intensity areas are mainly the most coastal areas of both Zhejiang and Guangdong, and parts of Hainan Island.

Second, based on 29 indicators affecting social vulnerability, the comprehensive social vulnerability index, SoVI (Chen et al., 2011), is applied to analyze the disaster tolerance for the study area affected by typhoons. The vulnerability generally increases from the coast to inland, with the maximum SoVI values in the north-west of Guangxi, parts of Fujian coastal areas and parts of the Shandong Peninsula.

Table 5 Comprehensive risk index classification

Grade	Low risk	Medium-low risk	Medium risk	High-medium risk	High risk
Risk index	$0 \leqslant R < 0.13$	$0.13 \leqslant R < 0.22$	$0.22 \leqslant R < 0.32$	$0.32 \leqslant R < 0.45$	$R \geqslant 0.45$

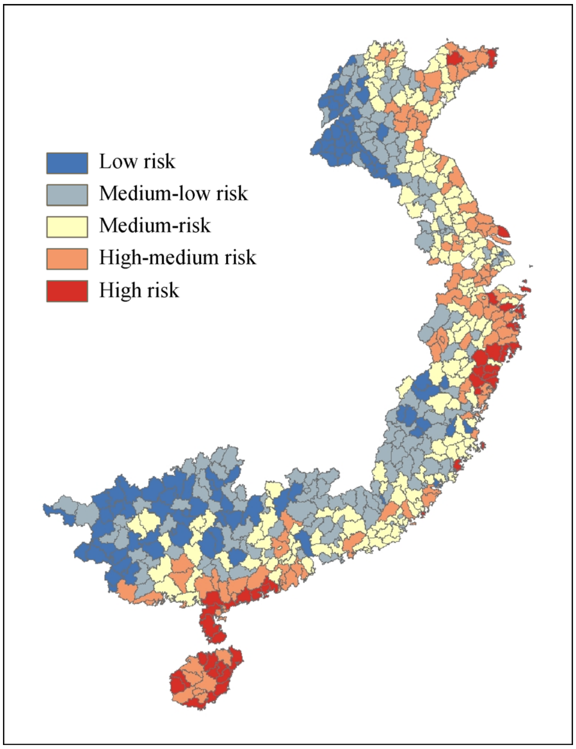


Fig. 8 Risk zoning of typhoon disasters for each county in the study area.

Third, combining the intensity factor index and the comprehensive social vulnerability index, a comprehensive risk index $R=I*SoVI$ (Lu et al., 2018) is applied to assess the risk of typhoon disasters for China’s coastal provinces. Results show that the overall risk decreases from the coast to inland, with the high-risk areas being Hainan Island, south-western Guangdong, coastal Zhejiang, the coastal areas between Zhejiang and Fujian and parts of the Shandong Peninsula.

As explored in this article, it is shown that the method applied in this study is suitable for assessing the typhoon disaster risk. We have compared the risk results of Zhejiang Province in this study with Lu et al. (2018). In general, the zoning levels of typhoon disaster risk assessment are relatively consistent in Zhejiang Province. The southeast coastal areas are at high risk, especially the boundary regions between Zhejiang and Fujian, and Taizhou and Wenzhou cities.

Despite this method shows a good applicability, there are still some issues worth discussing. The first is that the length of typhoon disaster data may mainly determine the results. For example, the Pearl River Delt, which has a large population and high GDP in the costal Guangdong, belongs to low or medium-low risk area. Even though the time period 10 years (2004–2013) is not an ideal length for doing typhoon risk zoning analysis, the state of serious lack of typhoon disaster data especially high resolution data makes this study be the first work for typhoon disaster risk zoning for China’s coastal area at the county level. Considering the limited representativeness of the data during the time period, the results in this study may have some uncertainty, especially regarding to the frequent occurrence of typhoon disasters in South China in recent years. In addition, as storm surge data are unavailable in this study, the results in this study doesn’t include the impact of storm surge. If storm surge data are taken into consideration, the risk results might change in the some areas along the coastline. Moreover, the risk zoning results in this study are completely based on observational data without any manual intervention. For high-risk areas, if the government takes corresponding disaster prevention and reduction measures, the risk and the disaster loss are believed to be reduced.

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