Risk assessment of tropical storm surges for coastal regions of China

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Abstract Storm surges are responsible for much of the damage and loss of life associated with landfalling tropical cyclones (TCs). Thus, understanding the characteristics of risk associated with TC storm surges for the coastal regions of China is of great interest. Based on a comprehensive assessment of hazard indices for TC storm surges and vulnerability indices for coastal counties, we obtained a risk assessment for coastal regions of China as a county-level unit. The hazard index was calculated using a model based on the parameters of a TC landfall frequency index (f) and maximum storm surge elevation (MSSE). The MSSE was calculated from the TC maximum sustained wind and tide gauge records using a regression function. Vulnerability indices were obtained from indices on socioeconomics, land use, the ecological environment, and resilience. From this study, it can be concluded that the hazard level of TC storm surges increases from north to south along the Chinese coast, the vulnerabilities have significant spatial heterogeneity, and coastal regions of China can be divided into four zones of risk level. The results of this study can provide scientific support for marine disaster mitigation and decision making. Additionally, the risk assessment methodology used here for storm surges could be extended and applied to other coastal areas.

1. Introduction

In recent decades, economic damage from tropical cyclones (TCs) around the world has increased dramatically [Weinkle et al., 2012]. The densely populated low-lying coastal zone of China lies on the junction of the Eurasia and Pacific plates and is a region prone to disaster. Coastal areas face multiple storm-related hazards, including floods, storm surges, and erosion, which not only cause great loss of life and property but also hinder local economic development. Among the above, storm surge is the most serious disaster. The southeastern coastal regions of China are usually affected by TCs in the summer and autumn. According to the China Meteorological Administration’s (CMA) data sets of TC tracks from 1949 to 2012, there are on average 7.8 TC landfalls in China annually. The China Marine Disasters Bulletin (available at http://www.soa.gov.cn/zwgk/hygb/zghyzhgb) shows that between 1990 and 2010, on average, storm surge disasters caused economic losses of 10.5 billion Yuan (Renminbi), 148 deaths, and affected 11.5 million people annually. Some of the more intense storm surges brought even worse consequences. For example, the storm surge disaster on 21 August 1994, caused by TC No. 9417 and named “Fred,” hit Zhejiang Province and resulted in damage to 520 km of seawall, 189 towns flooded by seawater, 1216 deaths, direct economic loss of 17.76 billion Yuan, and 2,280,000 people were affected [Le, 2000]. According to data from the National Bureau of Statistics for 2010, the 190 coastal counties contain 14.7% of the population and produce 26.88% of China’s entire gross domestic product (GDP).

Recently, the relationship between global warming and trends in TC activity has become an active focus of research. By defining a power dissipation index (PDI), Emanuel [2005] highlighted that the annual accumulated PDI has increased markedly in the Western North Pacific and North Atlantic basins since the mid-1970s, which has contributed to the upward trend in both longer lifetimes and greater intensities of storms. Research has shown a substantial increase globally in the number of most severe TCs [Elsner et al., 2008; Webster et al., 2005], and the globally averaged intensity of TCs is projected to continue to shift toward stronger storms with an expected increase of 2% to 11% by 2100 [Knutson et al., 2010]. In the East Asia and Pacific region, the area expected to be at risk from future storm surges would increase the most in China (39.4%) [Dasgupta et al., 2009b]. Coincidentally, as ocean-based risks associated with climate change increase,
those areas most at risk are experiencing particularly high population growth [McGranahan et al., 2007]. The rapid economic development and increase in population in these coastal regions exacerbate the risks posed by the above predictions of increased TC activity and the associated storm surges.

As planning for the mitigation of storm surge disasters is an ongoing and continuous process, among the coping strategies to be decided, risk assessment should be primary work undertaken. The assessment of storm surge risk provides the basis for risk mitigation and related decision making [Lin et al., 2010]. Scholars and organizations estimate storm surge risk from different points of view. Webster et al. [2013] assessed storm surge risk from the point of view of human perception. Brecht et al. [2012] combined the most recent scientific and demographic information to estimate the future impact of climate change on storm surges expected to strike coastal populations, economies, and ecosystems. Lin et al. [2010, 2012] applied a model-based risk assessment methodology to investigate the future risk from hurricane storm surge for New York City. They used a coupled statistical/deterministic hurricane model with the hydrodynamic model Sea, Lake, and Overland Surge from Hurricanes and Advanced Circulation to generate a large number of synthetic surge events, then they performed a statistical analysis to estimate the probability density function of storm surge height for New York City. Hallegatte et al. [2011] applied a simplified catastrophe risk assessment to estimate the risk from storm surges under scenarios of sea-level rise for Copenhagen, the capital of Denmark. Apivatanagul et al. [2011] reported a method to estimate the long-term regional hurricane wind and storm surge hazard by analyzing the correlation between wind and surge depths and the spatial correlations of each probabilistic scenario. The Natural Disaster Hotspots report supported by the World Bank, considered storm surge disasters as an important part of its content [Arnold et al., 2006]. Previous research on the assessment of storm surge risk has focused mainly on natural hazards, while the coastal vulnerability of people and property at risk has been inadequately estimated.

In China's coastal area, storm surges are mainly due to TCs that have caused landfall and only a small percentage of surges are caused by extratropical storms. Therefore, we consider only TCs in this study. With the motivation to explore the method of assessment of TC storm surge risk, to identify regions of high risk, and finally, to provide scientific support for marine disaster prevention and mitigation, we apply geographic information system (GIS)-based approaches to estimate the storm surge risk of the coastal zone of China. We combine analyses of vulnerability and hazard to achieve storm surge risk. The vulnerability of the coastal county-level administrative divisions is estimated using a model of coastal vulnerability index assessment, in accordance with the most recently available data on demographic, socioeconomic, land use, and ecological environment information. The degree of hazard is estimated by building an estimation model according to the parameters of TC landfall frequency ($f$) and maximum storm surge elevation (MSSE).

## 2. Method and Data

### 2.1. Risk Assessment Model

The definition of risk in natural disaster-related literature can be classified in two categories: (i) the probability of the occurrence of a hazard that acts to trigger a disaster or a series of events with an undesirable outcome, and (ii) the probability of a disaster or outcome combining the probability of the hazard event with a consideration of the likely consequences of the hazard [Brooks, 2003]. Because of the different perceptions of risk, the risk assessment of storm surge disaster also has two categories: (i) the possible loss induced by the storm surge; these studies are based on the analysis of surge elevation return period and combined coastal terrain data to determine the possible inundation region [Fritz et al., 2009; McInnes et al., 2003], and (ii) areas where there is the possibility of loss of life due to substantial inundation by storm surges; such studies suggest that the storm surge risk includes three aspects: losses caused by disasters [Fritz et al., 2007], the probability of occurrence, and the possible consequences [Lowe et al., 2001]. According to the United Nations Development Programme (2005), natural disaster risk is understood to be the probability of harmful consequences, i.e., expected loss of life, injuries to people, and disruption to property, livelihoods, and economic activity (or environmental damage) resulting from interactions between natural or human-induced hazards and vulnerable conditions. Here we take the risk assessment model proposed by the United Nations Development Programme to estimate the storm surge risk, as shown by formula (1).

\[
\text{Risk} = \text{Hazard} \times \text{Vulnerability} \tag{1}
\]

Obviously, risk assessment work includes two aspects: a vulnerability index assessment of people and property at risk and a hazard index assessment. There are two essential conditions for the realization of risk
from TC storm surges the inundation of the land by the sea, and the tremendous damage due to the strong wind, which indicates biophysical vulnerability and hazard, respectively.

2.2. Hazard Assessment Method and Data Processing

The estimation of storm surge hazards has typically followed two very different approaches. In the first, surge values modeled from historical storms are combined with information on historical storm frequencies to estimate local surge hazards, which is called the historical surge population approach. In the second, surge values modeled from a set of parameterized storms are combined with information on the multivariate probabilities of the storm parameters to obtain similar estimates; this is called the joint probability method. For further information on these two approaches, the reader is referred to Irish et al. [2011]. Many scientists and engineers around the world have assumed that either approach, if properly executed, would yield comparable estimates of the actual hazard levels; therefore, either would be acceptable for application in solving real problems.

2.2.1. Hazard Level of Tropical Storm Surge

The hazard level of one tropical storm surge depends on the magnitude of the MSSE. In a certain region, the larger the surge magnitude is, the greater the inundation is, which leads to a relatively higher hazard level. To explore the relationship of TC strength and storm surge hazard level, we collected information on TCs and storm surge elevation that caused severe damage to the coastal region of China (1989–2010), and on two storm surge catastrophes from the USA and Bangladesh (see Table 1). The regression relationships of MSSE versus central pressure and maximum sustained wind (MSW) of TCs that made landfall is shown in Figures 1a and 1b.

Figure 1 shows that the correlation degree of MSSE versus MSW ($R^2 = 0.952$, root-mean-square error (RMSE) = 0.3256) is significantly higher than that of MSSE versus TC central pressure.

### Table 1. Tropical Cyclone Parameters and MSSE

<table>
<thead>
<tr>
<th>No.</th>
<th>TC_Name</th>
<th>TCID</th>
<th>Date</th>
<th>MSW (m/s)</th>
<th>Pressure (hPa)</th>
<th>MSSE (m)</th>
<th>Tide Stations</th>
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</tr>
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<td>29</td>
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<td>909</td>
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<td>62</td>
<td>940</td>
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<td>Chittagong</td>
</tr>
</tbody>
</table>

*The information on the storm surge in Gulfport, USA, caused by Hurricane “Camille” in 1969 is from Needham and Keim [2012], and the information on the storm surge in Chittagong caused by TC “Bhola” is from literature [Das, 1994; Murty and Neralla, 1996]. TCID = tropical cyclone international number. The asterisks (**) are used to represent the international number for tropical cyclone.
Thus, it is reasonable to believe that the MSSE depends on the TC’s MSW when it makes landfall.

### 2.2.2. Hazard Assessment Method

Common sense dictates that for a specific coastal region, the hazard level of TC storm surges depends not only on the magnitude of the TC but also on the frequency of TCs making landfall, which causes the storm surges. The stronger the wind is, the larger the size of the population affected by the TCs making landfall, and the higher the hazard level of the storm surge. We construct a hazard level assessment model, as follows:

$$ h_i = f_i \times \text{MSSE}_i $$  

(2)

where $h = \text{the hazard level score}$, $f = \text{the normalized frequency of the TC during the years of 1949–2012}$ that make landfall, MSSE = maximum storm surge elevation, and $i = \text{the number of the coastal county}$.

To obtain the normalized frequency index $f$ for each coastal county, the TC tracks of 1949–2012 were used to analyze the frequency of crossing the coastline of each coastal county using the spatial analysis tools of ArcGIS 9.3. Finally, we obtained $f$ by normalizing the crossing frequency into the range of 0–1 for the whole coastal regions of China.

As the level of hazard is determined by the frequency of TC landfalls and the MSSE, a model for the assessment of the TC storm surge hazard is established based on the CMA TC best track data set of 1949–2012. The regression relation of MSW with MSSE is shown in Figure 1b. The value of MSSE is normalized into the range of 0–1 and used to calculate hazard level in equation (2).

As mentioned above, the MSSE is determined by the TC MSW when making landfall. Therefore, the spatial pattern of the historical MSSE along the coast can be obtained from the analysis of the spatial pattern of historical TC MSW. The value of the historical spatial pattern of MSSE can be calculated according to the regression equation of MSSE and MSW (see Figure 1b).

### 2.2.3. Data Processing

The information on TCs making landfall during 1949–2012, including the landfall location and time, was obtained from the Shanghai Typhoon Institute of the CMA [Ying et al., 2013]. The CMA TC data set of 1949–2012 was processed into a vector format for analysis in GIS. The track map and point records of TCs that made landfall are shown in Figures 2a and 2b, respectively.

The estimation of the hazard level of the TC storm surge and the data processing are performed as follows:

1. Establish spatial patterns of historical TC MSW. The county/district-level administrative regions are spatially continuous, whereas the records of TC information are composed of discrete points. Therefore, the historical spatial pattern of CMA TC maximum sustained wind, during 1949–2012, needs to be obtained by spatial interpolation. The interpolation operation is performed using the geostatistical analysis tool of ArcGIS 9.3.

2. Obtain the MSW at the time when the TC made landfall for each coastal county using the zonal statistics tool.
3. Obtain the historical MSSE distribution of coastal counties. The MSSE value of each county can be calculated based on the regression function of MSSE and MSW (see Figure 1b).

4. Finally, the hazard level scores of TC storm surge in the coastal counties of China are calculated by equation (2).

For step 1, because the spatial interpolation methods differ in their assumptions, local or global perspective, and deterministic or stochastic nature [Luo et al., 2008], we compared six interpolation methods: natural neighbor (nn), spline, inverse distance weights (IDW), Kriging, empirical Bayesian kriging (EBK), and local polynomial interpolation (LPI) to select an appropriate method for this study. The RMSE is used to examine the quality of the interpolation results, which can be calculated by formula (3).

\[
\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (\text{MSW}_{\text{max}(i)} - Z_{\text{max}(i)})^2}
\]

where \( n \) is the number of coastal counties, \( \text{MSW}_{\text{max}} \) is the maximum value of the CMA best track data set MSW in county \( i \) that made landfall, \( Z_{\text{max}} \) is the maximum value of the interpolation results in coastal county \( i \). The RMSE for interpolation method of nn, Spline, IDW, Kriging, EBK, and LPI is 4.89, 9.82, 3.82, 8.13, 9.88, 9.84, respectively (for information for RMSE analysis, see supporting information Table S1), from which it can be seen that IDW has the smallest value (3.82). Therefore, we use the IDW method to access the historical TC MSW spatial pattern data.

2.3. Vulnerability Assessment Method and Data Processing

Despite the diversity in concepts of vulnerability, there are two predominant perspectives in its conceptualization [Wu et al., 2002]. The first considers the status of people and property at risk; studies of this point focus on the potential exposure to a physical hazard. The second takes exposure as given and searches for the patterns of differential losses among the people affected. The vulnerability of a hazard-bearing body is a condition or process resulting from physical, social, economic, and environmental factors, which determine the likelihood and scale of damage from the impact of a given hazard. The purpose of vulnerability assessment is to create an index of overall vulnerability from a suite of indicators. However, constructing a vulnerability index would raise several problems in the aggregation of these indicators, including the decision of assigning them weights [Rygel et al., 2006]. In this study, biophysical vulnerability refers to the status of people and property at risk that are exposed to the storm surge hazard. As the status of a system or object is dynamic and constantly changing, this method of defining vulnerability facilitates its dynamic assessment.
The estimation of vulnerability to a storm surge is a complex problem, which includes many aspects: population, economy, industry, agriculture, environment, and ecology [Adger et al., 2005; Dasgupta et al., 2009a]. Among the diversity of people and property at risk, there is to date, no common knowledge on species. With comprehensive consideration of the features affected by the storm surge hazard and the availability of data, the vulnerability assessment indices, including the socioeconomy index, land use index, ecological environment, and resilience index, are listed in Table 2.

Among the vulnerability indexes, the socioeconomic index, which includes the population, economy, infrastructure, and the level of development of the society, is the basis of vulnerability. The land use index indicates the property that is exposed to the storm surge hazard, which accounts for the direct property loss due to the storm surge. The ecological environment is sensitive to the storm surge hazard. Contrary to vulnerability, the resilience index is also considered. Faced with a storm surge disaster, we can increase adaptive capacity by purposeful action, such as building seawalls and establishing special funds from local revenue for disaster prevention and mitigation. The vulnerability index elements are sorted by the units of county-level administrative divisions and the value of vulnerability index elements (refer to supporting information Table S2).

The vulnerability index can be divided into detailed elements, which are sensitive to the storm surge hazard. Although we are using the best available data for estimating the vulnerability of coastal counties, we should acknowledge at the outset several limitations in the analysis. First, there is the absence of both coastal infrastructure (e.g., nuclear power plants and offshore oil platforms), which is most sensitive to storm surge disasters, and coastal zone management (e.g., the height of seawalls and coastal shelterbelts), which restricts the analysis of the man-made resilience capacity to storm surge.

Among the diversity of methods for vulnerability assessment [Ramieri et al., 2011], the model of coastal vulnerability index (CVI) proposed by Gornitz is thought to be an appropriate method for most vulnerability assessments of coastal hazards [Gornitz et al., 1997, 1994]. Here we construct a vulnerability assessment model for people and property at risk by modifying the CVI method. The CVI on storm surge (CVISS) is calculated by formula (4).

\[
CVISS = \frac{A \times L \times E}{k}
\]  

where \(A\), \(L\), \(E\), and \(k\) represent the socioeconomic index, land use index, ecological environment index, and resilience index, respectively.

To make the vulnerability assessment more reasonable and spatially refined, the coastal regions of China are divided into county and district units. The data for the vulnerability indicators are collected by the estimated units. A vulnerability indicators form is constructed and the vulnerability indicators data are standardized according to Table 2.
These vulnerability indices are calculated based on the elements that account for the indices. As an example, the socioeconomic index \( A_i \) is calculated as follows:

\[
A_i = \frac{1}{n} \sum_{j=1}^{n} a_{i,j}
\]

\[
a_{i,j} = 0.5 + 0.5 \times \frac{x_{i,j} - x_{i,j\text{min}}}{x_{i,j\text{max}} - x_{i,j\text{min}}}
\]

where \( A_i \) is the socioeconomic index of county \( i \), \( n \) is the number of socioeconomic elements, \( a_{i,j} \) is the score of element \( j \) in county \( i \) calculated by (6), \( x_{i,j} \) is the value of each element, and \( i \) and \( j \) represent the number of counties and elements in each county, respectively. There are many methods of weight assignment (e.g., principle analysis, expert consultation, analytical hierarchy process) for the vulnerability index [Brooks et al., 2005]; however, none is yet recognized as the best or most scientific. Therefore, we do not consider the weights of each vulnerability index in this study, and instead, we define the range of values of the vulnerability elements as 0.5–1.

### 2.4. Risk Assessment

The results of the assessment of vulnerability on the people and property at risk and hazards on TC storm surges were normalized to the range of 0–1, according to the following formulas, respectively.

\[
V_i = \frac{CVI_{SS(i)} - CVI_{SS\text{min}}}{CVI_{SS\text{max}} - CVI_{SS\text{min}}}
\]

\[
H_i = \frac{h_i - h_{i\text{min}}}{h_{i\text{max}} - h_{i\text{min}}}
\]

where \( CVI_{SS(i)} \) is the assessment result of coastal county \( i \), calculated by (4) and \( h_i \) is the hazard score of coastal county \( i \), calculated by (2), as described previously.

The risk of TC storm surge for the coastal counties of China can be obtained by formula (1), as previously mentioned, based on the assessment of vulnerability on people and property at risk and hazards on tropical storm surges.

### 3. Results

The final assessment results of vulnerability on people and property at risk, hazard on TC storm surges, and TC storm surge risk for coastal counties of China are shown in Figures 3a–3c, respectively. This paper estimated the TC storm surge risk for the coastal counties of China based on the assessment of \( CVI_{SS} \) and TC storm surge hazard for these coastal counties. The detailed results of this study are presented in the following.

#### 3.1. Estimates of Storm Surge Hazards

The spatial distribution of TC track frequency index \( f \) and MSSE are shown in Figures 4a and 4b, respectively. As shown in Figure 4a, the frequency of historical TCs in the coastal zone of China decreases gradually from south to north, but is extremely high along the coast of Hainan province and the western coastal counties of Guangdong province. The value of MSSEs caused by TCs in the coastal counties of China are shown in Figure 4b; the value is over 2.5 m in the middle coastal counties of Zhejiang province, northern Fujian province, Lufeng, the Leizhou Peninsula in Guangdong province, and the northern and southern parts of Hainan province.

The hazard value on TC storm surge is calculated according to equations (2) and (8), and the result is shown in Figure 4b. Similar to the distribution of TC frequency, the hazard level of TC storm surge in the coastal counties decreases gradually from south to north. The districts and counties with the highest hazard are located in Leizhou Peninsula in Guangdong province and in the southern and northern coastal areas of Hainan province.

#### 3.2. Vulnerability Assessment

By using the above assessment model, the values of socioeconomic index, land use index, ecological environment index, and resilience index can be calculated separately, and the results are shown in Figure 5.
The counties with the highest level of socioeconomic vulnerability are Dalian in Liaoning province, Binhai district in Tianjin, Pudong district in Shanghai, and the coastal counties in the Pearl river estuary (see Figure 5a). The highest vulnerability level of the land use index is distributed in the coastal counties of Liaoning, Tianjin, Shandong, Jiangsu, and Guangdong, and northeastern parts of Hainan province (see Figure 5b). The highest vulnerability level of the ecological environment index is distributed in some coastal regions (Figure 5c).

Figure 3. (a) Assessment results of vulnerability on people and property at risk, (b) hazard on TC storm surges, and (c) TC surge risk for coastal counties and districts of China. The levels of vulnerability (Figure 3a), hazard (Figure 3b), and risk (Figure 3c) are starting lower to higher (0 is the lowest level and 1.0 is the highest).

The counties with the highest level of socioeconomic vulnerability are Dalian in Liaoning province, Binhai district in Tianjin, Pudong district in Shanghai, and the coastal counties in the Pearl river estuary (see Figure 5a). The highest vulnerability level of the land use index is distributed in the coastal counties of Liaoning, Tianjin, Shandong, Jiangsu, and Guangdong, and northeastern parts of Hainan province (see Figure 5b). The highest vulnerability level of the ecological environment index is distributed in some coastal regions (Figure 5c).

Figure 4. (a) Map of historical TC normalized frequency index \( f \) and (b) map of MSSE calculated by regression of MSSE versus TC MSW. The frequency index \( f \) starts lower to higher (0 ~ 1).
counties of Hebei, Tianjin, Jiangsu, Guangdong, and Guangxi provinces (see Figure 5c). The highest vulnerability level of hazard resilience ability is shown in Figure 5d.

The estimated comprehensive vulnerability result on people and property at risk in county-level units is reflected in Figure 3a. The coastal counties with the highest vulnerability are Dalian in Liaoning province, Tianjin, Kenli and Hekou district in Shandong province, Rudong in Jiangsu province, Fuping in Fujian province, Shantou and Leizhou in Guangdong province, Fangchenggang in Guangxi province, and Wenchang in Hainan province.

Figure 5. Map of assessment results of vulnerability index. (a) Socioeconomic vulnerability (A), (b) vulnerability on land use (L), (c) ecological environment vulnerability (E), and (d) resilience (K). These vulnerability indices start lower to higher (0.5–1.0).
3.3. Risk Assessment
Based on the tasks of vulnerability assessment on people and property at risk and hazard on TC storm surge, the risk on TC storm surge is realized. The value of the risk is shown in Figure 3c.

Among the coastal provinces of China, the TC storm surge risk of Zhejiang, Fujian, Guangdong, and Hainan is significantly higher than for the others. On the county and district level, Wenchang, Haikou, and Sanya in Hainan province, and counties located in Leizhou Peninsula and Zhanjiang in Guangdong province have the highest risk level.

The coastal regions of China can be divided into four areas according to the risk assessment results. The coastal regions of Guangxi, Hainan, and the western coastal regions of Guangdong are in the first group with the highest risk levels. The coastal region from Hangzhou Bay south to the Pearl River estuary is the second group with a slightly lower risk level. The region from Shanghai to the Shandong Peninsula and Dalian located at the south of the Liaodong Peninsula is the third group with low risk levels, and the other regions comprise the fourth group with the lowest risk level.

4. Conclusions
Risk assessment of TC storm surges for coastal regions of China is carried out by a combined analysis of vulnerability for people and property at risk and hazard of TC storm surges. It employs the TC track frequency index based on CMA TC data set of 1948–2012 and a defined MSSE to estimate the hazard of TC storm surges, and it employs 16 elements including socioeconomic, land use, ecological environment, and resilience categories to calculate the vulnerability for coastal counties of China. The results indicate that the TC storm surge risk level is increasing significantly from Liao (northeast) to Hainan (southwest). Specifically, coastal counties in the province of Fujian, Guangdong are subject to the highest risk, and counties in the province of Fujian and Zhejiang are subject to higher risk. Without the appropriate mitigation measures, large amounts of people, infrastructure, and land would exposed to coastal flooding from TC storm surges. A national risk assessment is necessary to reduce the negative effects of TC storm surges. Since the risk is determined by the vulnerability of people and property at risk and the hazard of TC storm surges, a proper coastal zone management could be initiated before such problem become irreversible. This study could provide a scientific basis for China’s marine disaster risk management. As reported in literatures, the activities of TCs are affected by climate change [Elsner et al., 2008; Emanuel, 2005; Webster et al., 2005]; therefore, further work should be carried out to consider both aspects, one is the future climate environment (such as the changing magnitude and frequency of TCs and sea-level rise), the other is rapid urbanization and too many people have settled in the Chinese coastal regions. Subject to the availability of comprehensive data, it is important to recognize and consider limitations and shortcomings in the methodology. When considering risk assessment for a smaller regional scale, additional factors (e.g., topography) would need to be considered.

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