

Article

Risk Assessment of Landfalling Tropical Cyclones in China Based on Hazard Risk Theory

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Abstract: As a frequent hazard, tropical cyclones have a great impact on the social and economic development of China, which is close to the origin of tropical cyclones in the western Pacific Ocean. The primary objective of this study was to construct a comprehensive risk assessment model for tropical cyclone hazards based on natural influencing factors, informing recommendations for hazard prevention and mitigation in affected regions. This research focused on tropical cyclones that made landfall in mainland China and Hainan from 1949 to 2023, utilizing hazard risk theory and classical extreme value theory. The wind speed and rainfall data during the peak cyclone periods (June to October) from 1997 to 2021 gathered from various meteorological stations, as well as altitude and vegetation cover data, were examined. Hierarchical analysis and ArcGIS spatial analysis methods were employed to study the characteristics of the spatiotemporal distribution of landfalling tropical cyclones and the comprehensive risk of tropical cyclone hazards, and the regions of China were delineated according to these methods. The results showed that, during the period from 1949 to 2023, the overall number of landfalling tropical cyclones decreased in a fluctuating manner, while the intensity of the cyclones increased. Furthermore, severe typhoons tended to occur more frequently in the summer than autumn with time, intensifying the challenge to resist short-term hazards. Moreover, the hazard-causing factors in areas affected by tropical cyclones displayed an increasing trend from north to south and from west to east. In detail, the regions sensitive to natural hazards were primarily located in the central part of Liaoning province, Tianjin, central and eastern Hebei province, Shandong province, eastern Henan province, central and northern Anhui province, Jiangsu province, and Shanghai, which are characterized by flat terrain and relatively low vegetation cover. Overall, the comprehensive risk of tropical cyclone hazards showed a geographical distribution that decreases from south to north and from east to west, with coastal cities in provinces such as Hainan, Guangdong, Guangxi, Fujian, and Zhejiang—including Haikou, Zhanjiang, Xiamen, Beihai, and Taizhou—exhibiting the highest levels of risk.

Keywords: tropical cyclone hazard assessment; comprehensive evaluation; geographic information system (GIS); risk assessment



Citation: Xu, J.; Xue, X.; Yang, B.; Wang, W.; Wu, W.; Ji, X. Risk Assessment of Landfalling Tropical Cyclones in China Based on Hazard Risk Theory. *Appl. Sci.* **2024**, *14*, 5126. <https://doi.org/10.3390/app14125126>

Academic Editor: Athanasios Sfetsos

Received: 16 May 2024

Revised: 1 June 2024

Accepted: 6 June 2024

Published: 12 June 2024



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1. Introduction

A tropical cyclone is the generic term for a warm-cored, non-frontal synoptic-scale low-pressure system over tropical or subtropical waters. They encompass three major natural hazards: high winds, torrential rains, and storm surges. These cyclones bring copious amounts of rainfall and violent winds, and the secondary hazards they induce pose significant threats to the safety of lives and property in areas near their landfall [1–3].

Tropical cyclones, characterized by their extensive reach and high frequency, inflict substantial damage to China, a country near the genesis region of these cyclones in the western Pacific [4]. Historical data indicate that approximately 30 tropical cyclones form in the Western Pacific each year, with about 7 of these making landfall in China. On average, these cyclones result in approximately 300 fatalities annually in China and cause direct economic losses amounting to about 44.1 billion yuan per year [5]. Therefore, it is essential to conduct in-depth research on the hazard characteristics of tropical cyclones and to implement effective measures to reduce their occurrence or mitigate their intensity.

In the past, research on the risk assessment of tropical cyclones has garnered considerable attention from scholars both domestically and internationally, with many studies focusing on the point of landfall [1,6,7]. At the same time, under the influence of factors such as the origin, intensity, and landfall location of tropical cyclones, the path of tropical cyclones can change dynamically [8], and the surrounding areas will be affected, so the risk assessment should not be limited to the range of landfall sites. In 2023, affected by the powerful typhoon “Doksuri”, regions as far as a thousand miles away from the landfall site, including Beijing and Henan Province, experienced the year’s most significant rainfall [9]. In the field of tropical cyclone risk assessment, the selection of the research scale—such as provincial or national level—significantly influences the choice of assessment indicators and the risk assessment methods used [7,10]. Therefore, a comprehensive evaluation of the impact of tropical cyclones across multiple provinces emphasizes the necessity to establish a robust tropical cyclone hazard assessment system. This system aims to safeguard people’s lives and property, as well as to enhance natural hazard resilience, both of which can be expected to continue to receive sustained attention.

As research continues to deepen, methods for assessing the risk of tropical cyclones are being continually enriched and refined toward precision and quantification by scholars. Shi, P.J. has broadly conducted detailed assessments focused on three elements: hazard-causing factors, hazard-prone environments, and carriers [11]. Building on this, Ding, Y. proposed a fuzzy risk assessment model for typhoon hazards [12]. Shi, J. has established a hazard loss assessment model by selecting meteorological hazard-causing factors such as maximum wind speed, extreme wind speed, total precipitation, and daily rainfall from local weather stations, and correlating these with indices of human casualties, agricultural damage, and house collapses [13]. However, the above scholars did not consider the impact of the environment on the risk, especially in terms of how the topographic conditions in various regions can change the dynamic path of tropical cyclones. Several scholars, based on different spatial scales (e.g., nationwide, provincial, and regional levels), have conducted in-depth studies on the temporal and spatial distribution of precipitation caused by typhoons, environmental conditions, and cloud types through analyzing both current and historical typhoon data [14–16]. Zhao, S.J. approached natural hazard risk assessment methodologies from the perspective of their driving forces, categorizing the methods into three main criteria: indicators, data, and scenarios for driving assessments [17]. Zhang X.Y. focused on Guangdong Province, analyzing the correlations between hazard indices and the maximum daily rainfall and highest wind speeds recorded during typhoons [18]. Lee et al. employed a combination of Bayesian models and spatial conditional regression models to analyze the relationship between typhoon locations and cumulative rainfall during typhoon periods in Taipei City [19]. However, when only a single factor is considered in risk assessment, such as the precipitation index used by most of the above scholars, the risk of tropical cyclones may be underestimated.

Existing research indicates that risk assessments of tropical cyclone hazards predominantly focus on high-intensity events such as typhoons. These studies often assess individual typhoons and provincial areas, with less emphasis on larger-scale research. Additionally, as tropical cyclones continue to move inland after making landfall, their impact extends beyond coastal cities to inland regions—an aspect that has not been sufficiently explored spatially.

In light of the shortcomings in previous research, this study is based on tropical cyclones that made landfall in mainland China and the Hainan region in the period from 1949 to 2023. Utilizing hazard risk theory and classical extreme value theory, this research focuses on data obtained from various meteorological stations from 1997 to 2021 during the peak cyclone period (June to October). This includes wind speed, rainfall, collected elevation, and vegetation cover data. Analytical techniques such as the Analytic Hierarchy Process and ArcGIS spatial analysis are employed to analyze the spatiotemporal distribution of landfalling tropical cyclones, assess the comprehensive risk of tropical cyclone hazards, and delineate risk regions. The primary aim of this study is to construct a comprehensive risk assessment model for tropical cyclone hazards based on natural influencing factors, thereby providing references for hazard prevention and mitigation in affected areas.

2. Materials and Methods

2.1. Data

The dataset was sourced primarily from the Cma Tropical Cyclone Data Center, China Meteorological Data Service Centre, Resource and Environmental Science Data Platform, EarthData. Detailed descriptions of the data can be found in Table 1. Figure 1 displays the spatial distribution and elevations of the meteorological stations involved.

Table 1. Source and purpose of data.

Data	Source	Content	Purpose
The CMA-STI Tropical Cyclone Best Track Data [20,21]	Cma Tropical Cyclone Data Center “ http://tcdata.typhoon.org.cn/ ” (accessed on 12 July 2023)”	Best track and intensity of landfalling tropical cyclones from 1949 to 2023	Analysis of regions affected by historical tropical cyclone paths
Meteorological Station Observation Records	China Meteorological Data Service Centre “ http://data.cma.cn/ ” (accessed on 19 January 2023)”	The accumulated precipitation of each station at 20–20 h every day and the average wind speed of 10 min at an hourly height of 10 m from 1997 to 2021	Risk data of hazard factors
Topographic Elevation Data	Resource and Environmental Science Data Platform “ https://www.resdc.cn/ ” (accessed on 19 January 2023)”	Longitude, latitude, and terrain with 90 m spatial resolution	Natural carrier sensitivity data
MOD13A1 Product Data	EarthData “ https://search.earthdata.nasa.gov/ ” (accessed on 20 May 2023)”	The year 2019 has 16-day intervals and 500 m NDVI spatial distribution data	Natural carrier sensitivity data

2.2. Study Area

In this study, the methodology for determining the landfall locations of tropical cyclones was re-evaluated and refined. It is determined that a tropical cyclone has made landfall when its path intersects with administrative boundaries, based on the cyclone’s optimal trajectory. The point of intersection is deemed the exact landfall location, and the administrative region where this point lies is defined as the landfall area [22]. Considering the broad impact zones of tropical cyclones, even those not passing directly can substantially affect nearby cities. According to the reviewed literature, regions within 220 km are significantly impacted by tropical cyclones [23]. Consequently, this study identified cities within a 220-km radius as being within the cyclone’s impact zone, and defines the administrative districts of these cities as impact areas.

This study filtered the CMA-STI optimal trajectory dataset of tropical cyclones from 1949 to 2023, selecting landfall points on the Chinese mainland and Hainan to identify the historical paths and impact areas of these cyclones. Figure 2 shows the landfall statistics of tropical cyclones in China from 1949 to 2023.

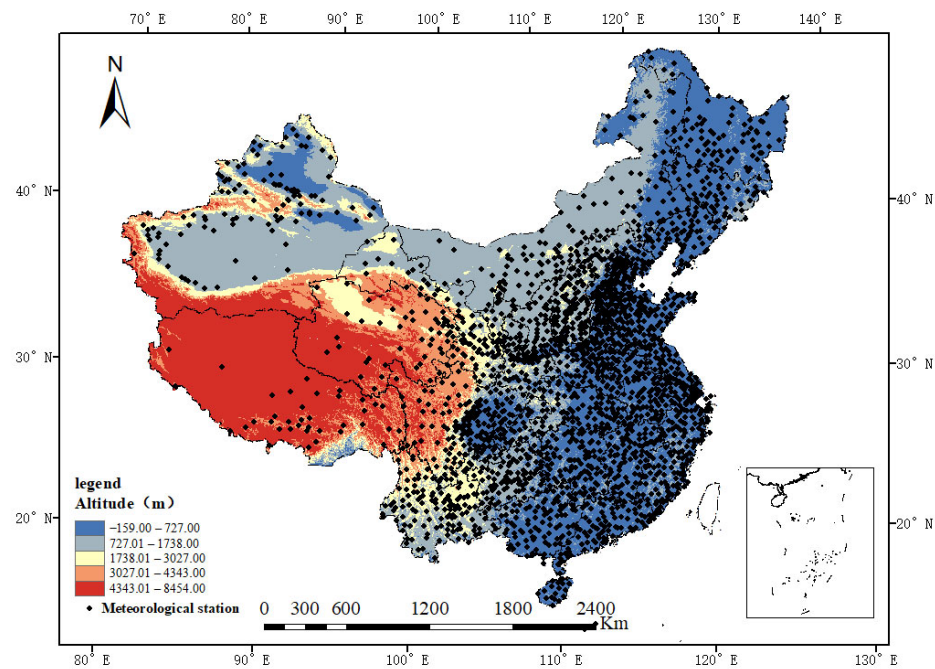


Figure 1. Spatial distribution of 2340 meteorological stations.

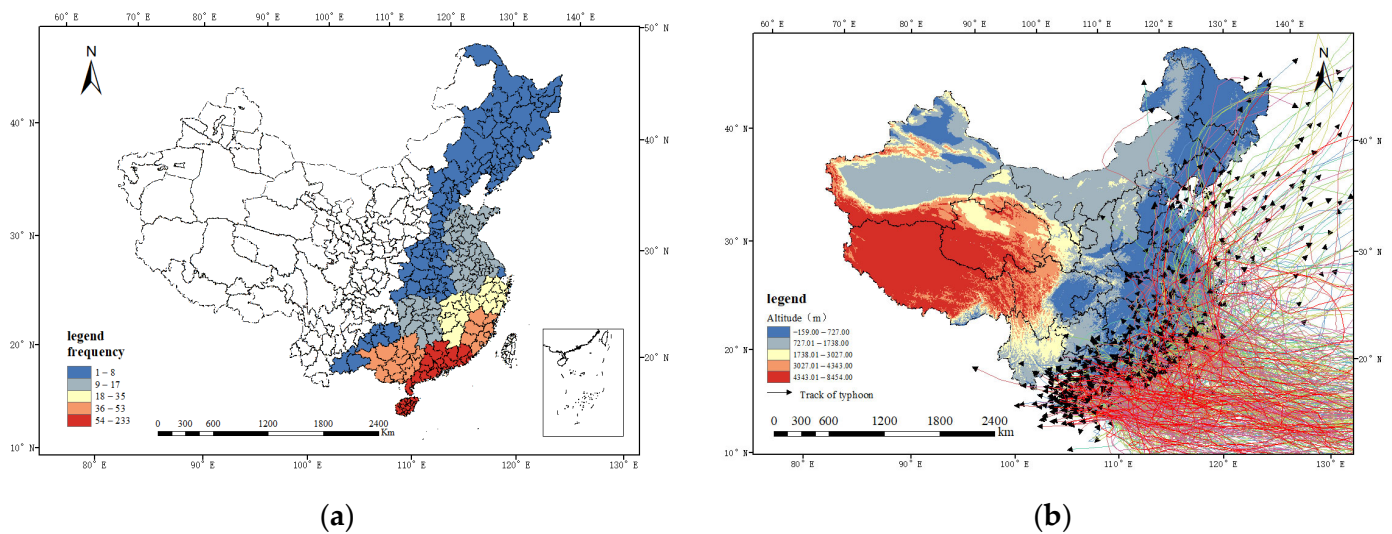


Figure 2. The landfall statistics of tropical cyclones in China from 1949 to 2023. (a) Frequency of affected areas. (b) Landing path.

As depicted in Figure 2, between 1949 and 2023, a total of 19 provinces and cities in China, including Beijing, Anhui, Fujian, Guangdong, Hubei, Heilongjiang, Henan, Hebei, Jilin, Jiangsu, Jiangxi, Hunan, Liaoning, Shandong, Shanghai, Tianjin, Zhejiang, Guangxi, and Hainan, along with selected cities in Inner Mongolia, Guizhou, and Eastern Yunnan, were impacted by tropical cyclones. Figure 3, incorporating statistics on the frequency and paths of these impacts, delineates the regions in China affected by tropical cyclones, covering 1482 meteorological stations.

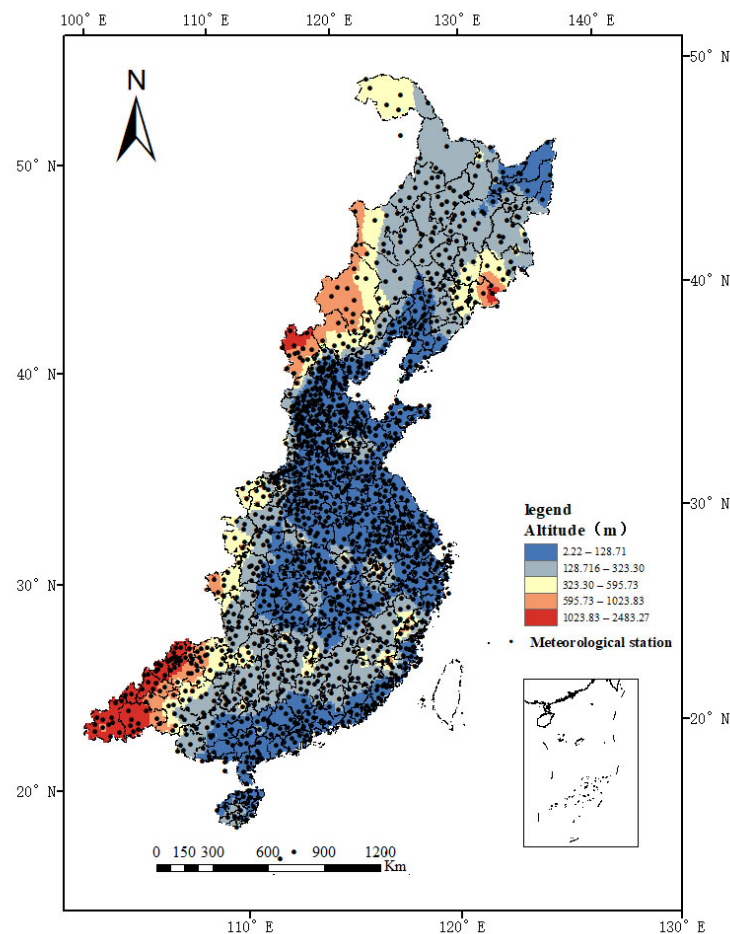


Figure 3. Distribution of Areas and Meteorological Stations in China Affected by Tropical Cyclones.

2.3. Methodology

2.3.1. Integrated Risk Assessment Theory for Tropical Cyclone Hazards

The theory of tropical cyclone hazard risk assessment derives from the inherent characteristics of tropical cyclones and entails the systematic exploration and study of factors that might influence the severity of these hazards. It considers both the hazard posed by cyclone-inducing factors and the sensitivity of natural carriers. There is a direct proportionality between the risk of a tropical cyclone and both the hazard level of its inducing factors and the sensitivity of the carriers—the higher these indices, the more significant the potential impact on the affected regions [24,25]. For this study, the features of these components were synthesized, appropriate indicators were selected, and models were constructed, allowing for a comprehensive evaluation and analysis.

2.3.2. Analytic Hierarchy Process

The Analytic Hierarchy Process (AHP), which most commonly applied in tropical cyclone hazard risk assessments when compared with other methods, was developed in the 1970s by Professor Thomas L. Saaty. This method has a simple and accurate calculation process and integrates qualitative and quantitative analyses, fundamentally deconstructing complex issues into various levels and indicators to streamline the problem-solving process [26]. At each hierarchical level, indicators are evaluated in a pairwise manner according to predefined rules, creating a judgment matrix that assigns weights to each indicator based on their significance with respect to overarching factors [27]. This approach not only aids in decision-making, but is also employed in this study to calculate the indicator weights.

2.3.3. ArcGIS Spatial Analysis

As tropical cyclones have distinctive spatial characteristics, employing Geographic Information Systems (ArcGIS) for the management and analysis of spatial data is highly effective. This method utilizes spatial interpolation techniques such as Inverse Distance Weighting (IDW) and ANUSPLIN to expand point data from meteorological stations into areal representations. Primarily through raster overlay, multiple raster data layers are combined using specific mathematical operations to create a new raster data system. Additionally, overlaying visual information and vector layers enhances the precision of risk assessments and facilitates data visualization.

1. Inverse Distance Weighting

The Inverse Distance Weighting (IDW) method operates on the premise that the influence of each data point diminishes with increasing distance from the interpolation point. This approach is particularly effective in capturing local variations when the data points are densely and uniformly distributed [28]. IDW is favored for its straightforwardness and operational ease, accounting for both distance and direction in its calculations. Nonetheless, its performance can be significantly affected by the characteristics of the dataset itself.

The mathematical formulation for the Inverse Distance Weighted (IDW) method is presented in Equation (1) [29]:

$$\hat{Z}_0 = \sum_{i=0}^1 (Z_i W_i) \quad (1)$$

where $\hat{Z}_0$ is the estimated value at the point (x_0, y_0) , W_i signifies the ratio of weights between the interpolation point and the various data points, and n represents the total number of interpolation points.

The computation of the weight coefficient W_i is crucial to the IDW methodology, typically defined by Equation (2).

$$W_i = \frac{f(d_{ej})}{\sum_{j=1}^n f(d_{ej})} \quad (2)$$

where n denotes the quantity of known data points. The function $f(d_{ej})$ articulates the established distance d_{ej} between these data points and the interpolation points. It employs a widely adopted formula for weight calculation, referred to as Equation (3).

$$f(d_{ej}) = \frac{1}{d_{ej}^b} \quad (3)$$

where b acts as a fixed constant; when this constant is set to 1 or 2, the method is converted into inverse distance weighting interpolation or inverse distance squared weighting interpolation, respectively.

2. ANUSPLIN Spatial Interpolation

ANUSPLIN employs the theory of planar smoothing splines and integrates various influencing factors as covariates to facilitate the analysis and interpolation of multivariate data [28]. This model has been extensively validated for its ability to maintain a balance between the accuracy and smoothness of the interpolation surface. The formula for the theoretical model is specified in Equation (4) [30].

$$G_i = f(x_i) + c^T y_i + h_i \quad (4)$$

where G_i denotes the dependent variable for spatial data points, y_i serves as the independent covariate, c refers to the coefficient across n dimensions, and h_i is the random error associated with the independent variables, which is expected to equal zero.

ANUSPLIN spatial interpolation characterizes the variability of variables across a region. This method does not inherently convey spatial resolution; rather, it primarily entails the substitution of numerical data and influencing factors into a polynomial equation for resolution.

2.3.4. Data Standardization

This analysis utilizes various indicators sourced from multiple datasets, which exhibit significant differences in terms of attributes, scales, and magnitudes. Analyzing tropical cyclone hazards with these raw indicators tends to disproportionately amplify the influence of high numerical values while diminishing those of lower ones, thereby compromising the accuracy of the results. To address this, the data were rescaled proportionally and divested of their original units to fit within a specified range, thus converting them into unitless, standardized numbers. This study adopts deviation standardization for the indicators, ensuring that outcomes are confined to the [0, 1] range [31].

When X'_i serves as a positive evaluation indicator, standardization is conducted according to Equation (5):

$$X'_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}} \quad (5)$$

When X'_i serves as a negative evaluation indicator, standardization is conducted according to Equation (6):

$$X'_i = \frac{X_{\max} - X_i}{X_{\max} - X_{\min}} \quad (6)$$

where X'_i is the standardized evaluation value for the i^{th} indicator, and $X_{\max}$ and $X_{\min}$ represent the maximum and minimum standard values, respectively, for this indicator.

2.3.5. Processing of Evaluation Indicators and Calculation of Weights

1. The Hazard of Hazard-Causing Factors

Generally speaking, tropical cyclones encompass three natural hazards: high winds, heavy rain, and storm surges. This study selected average daily wind speed, average daily maximum wind speed, and average daily rainfall as indicators to assess the risk posed by hazard-causing factors. Utilizing the National Meteorological Science Data Center's hourly observational data, we filtered out 1482 meteorological stations impacted by landfalling tropical cyclones over a period of 24 years (i.e., from 1997 to 2021), comprising 288 months. These stations were analyzed for average daily wind speeds, maximum wind speeds, and rainfall. Indicator weights were determined using the AHP and, as the IDW interpolation method is simple and convenient to operate, it was used to interpolate wind speed data. The amount of rainfall is closely related to terrain and, so, the longitude and latitude of data stations were used as the principal variable of the average daily rainfall index, and the terrain was used as the covariable to perform ANUSPLIN interpolation. The risk associated with these hazard-causing factors was quantified using a weighted calculation, as presented in Equation (7).

$$H = \sum_{i=1}^n w_i H_i \quad (7)$$

where H denotes the level of risk posed by hazard-causing factors, w_i is the weight assigned to each corresponding secondary indicator, and H_i measures the influence of each indicator. The greater the value of H , the higher the risk, increasing the susceptibility of the area to tropical cyclone hazards.

2. Sensitivity of Natural Carriers

During the development of tropical cyclones, the terrain changes and ground roughness in the path area will affect the change in its dynamic path and gradually weaken its intensity. In this study, topographic elevation and vegetation coverage were chosen as

indicators to evaluate the sensitivity of natural carriers. The vegetation coverage f_c was computed from NDVI distribution data according to Equation (8) [32]. Following this, the AHP was utilized to determine the weights of these indicators, and the sensitivity of the natural carriers was quantified through the weighted calculation specified in Equation (9).

$$f_c = \frac{NDVI - NDVI_{soil}}{NDVI_{VEG} - NDVI_{soil}} \times 100\% \quad (8)$$

where $NDVI_{soil}$ denotes the NDVI value corresponding to purely bare soil pixels, replaced by the NDVI value that appears at a cumulative frequency of 0.5%; meanwhile, $NDVI_{VEG}$ denotes the NDVI value for purely vegetated pixels, replaced by the NDVI value observed at a cumulative frequency of 99.5%.

$$N = \sum_1^n w_f N_f \quad (9)$$

where N represents the sensitivity of natural carriers, w_f denotes the weights assigned to the respective secondary indicators, and N_f measures the impact level of each indicator. An increased N value indicates higher sensitivity, resulting in a reduced impact of tropical cyclone hazards within the area.

3. Integrated Risk of Tropical Cyclone Hazards

This study integrates various evaluation indicators for both the hazard level of hazard-causing factors and the sensitivity of natural carriers. The calculation results for these indicators are presented in Table 2. The formula for calculating the comprehensive risk of tropical cyclone hazards is (10):

$$CRTY = \sum_{k=0}^n C_k W_k \quad (10)$$

where $CRTY$ represents the comprehensive risk of tropical cyclone hazards. A higher $CRTY$ value indicates a greater overall risk, whereas a lower value indicates a lesser risk. C_k denotes the impact level of each indicator at the indicator layer, and W_k signifies the weight of each indicator in the overall ranking.

Table 2. Selection of Evaluation Indicators and Weight Calculation.

Primary Index	Single Sort Weight	Positive/Negative Indicators	Secondary Index	Single Sort Weight	Positive/Negative Indicators	Total Sort Weight
The Hazard of Hazard-Causing Factors	0.67	Positive	Average Daily Rainfall	0.68	Positive	0.45
			Average Daily Wind Speed	0.19	Positive	0.13
			Average Daily Maximum Wind Speed	0.13	Positive	0.09
Sensitivity of Natural Carriers	0.33	Positive	Terrain Elevation	0.83	Negative	0.28
			Vegetation Coverage	0.17	Negative	0.05

3. Results and Discussion

3.1. Analysis of the Characteristics of Tropical Cyclone Hazards in China

3.1.1. Temporal Distribution Characteristics of Landfalling Tropical Cyclones

A polynomial fit was applied to the tropical cyclone landfall data from 1949 to 2023, with the comparative data shown in Figure 4a. The data indicate that the frequency of tropical cyclone landfalls in China exhibited an oscillatory pattern. Over the 75-year period,

a total of 661 tropical cyclones made landfall, with an average of 8.8 landfalls per year. The overall trend shows a fluctuating decline around this average frequency, with an oscillation period of approximately four years. Since 1986, the frequency of tropical cyclone landfalls in China has generally remained below the average. Between 2011 and 2023, except for 2013 and 2018 (which saw 10 and 12 landfalls, respectively), the number of landfalling tropical cyclones each year ranged from 6 to 9. This result is consistent with previous research on historical tropical cyclone landfalls [33].

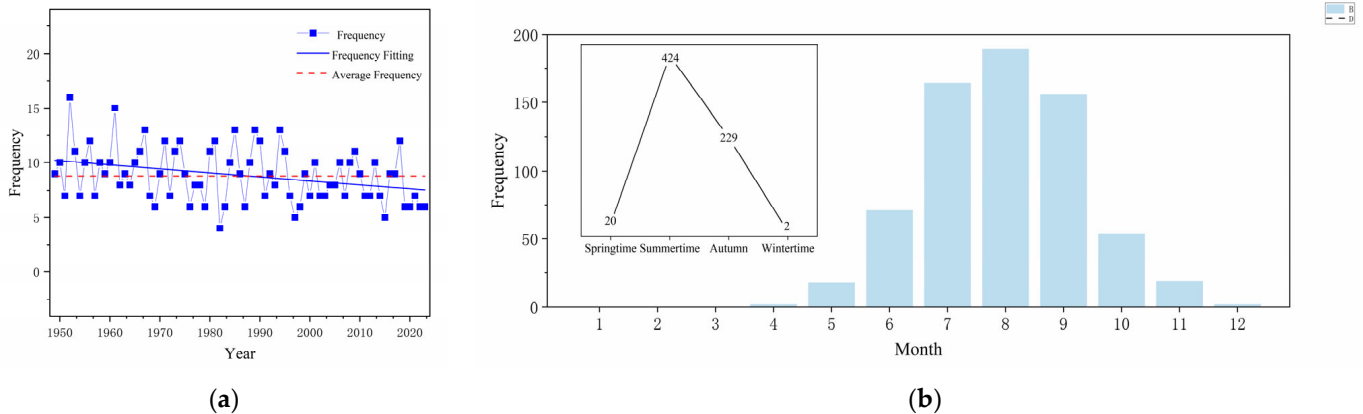


Figure 4. Temporal variation of landfall tropical cyclones in China from 1949 to 2023 (a) Annual Variations. (b) Monthly Variations.

A monthly frequency analysis of tropical cyclone landfalls in China from 1949 to 2023 is shown in Figure 4b. The frequency distribution indicates that landfalls were concentrated between June and October, with August having the highest number of landfalls at 189, representing 28.0% of the total; July follows with 164 landfalls, accounting for approximately 24.2% of the total. Therefore, from a seasonal perspective, there are no tropical cyclone landfalls in China during the winter. Tropical cyclones predominantly make landfall in summer and autumn, which are the peak seasons for tropical cyclone hazards, necessitating enhanced risk prevention measures for such events.

3.1.2. Distribution Characteristics of the Impact Intensity of Landfalling Tropical Cyclones

Statistical analysis of the landfall intensity of tropical cyclones affecting China from 1949 indicated that, as shown in Table 3, over the past 75 years, severe tropical storms and typhoons were the most frequent categories, accounting for 50.6% of the total. The stronger categories, including severe typhoons and super typhoons, made up 10.6% of the total. Although super typhoons occurred only 18 times, each event caused significant damage from formation to dissipation. For example, Typhoon Lekima (No. 1909), which made landfall along the coastal area of Wenling, Zhejiang in 2019, was the strongest tropical cyclone to hit China since the founding of the People's Republic. The maximum wind speed near its center reached 52 m/s (super typhoon), and it remained over land for 44 h, affecting regions including Zhejiang, Fujian, Jiangsu, Shanghai, Anhui, Shandong, Henan, Hebei, Tianjin, and Liaoning, resulting in extensive damage [34].

Table 3. Statistical Count of Tropical Cyclones of Various Intensities Landing in China from 1949 to 2023.

Strength Level	Tropical Depression	Tropical Storm	Severe Tropical Storm	Typhoon	Severe Typhoon	Super Typhoon
Quantity	116	128	158	166	54	18
Proportion/%	18.1	20.0	24.7	25.9	8.4	2.8

Considering the temporal trends of tropical cyclones, although the number of land-falling tropical cyclones has been decreasing, their intensity is increasing. Furthermore, the occurrence of severe typhoons has progressively moved earlier in the year. Specifically, since 1980, the intensity of landfalling tropical cyclones in China has increased by 12.4% to 14.7%, and severe typhoons have shifted from autumn to summer. This shift has led to a higher frequency of summer typhoons, posing a more severe challenge to China's hazard prevention and mitigation capabilities.

3.2. Hazard Analysis and Assessment of Causative Factors

Based on data from the 1482 meteorological stations in provinces and cities affected by tropical cyclones from 1997 to 2021 during the frequent occurrence period of tropical cyclones (June to October), average daily wind speed, average daily maximum wind speed, and average daily maximum rainfall were recorded over 120 months. The IDW method was applied for spatial interpolation of wind speed data. For average daily rainfall, the ANUSPLIN interpolation method was employed using the latitude and longitude of the data stations as the main variables and terrain as a covariate, enabling the transformation of single-point data for regional analysis. Subsequently, Equation (5) was utilized to standardize the data, converting each indicator into the influence degree for assessment of the tropical cyclone hazard risk. Impact of each hazard causing factor indicator is shown in Figure 5.

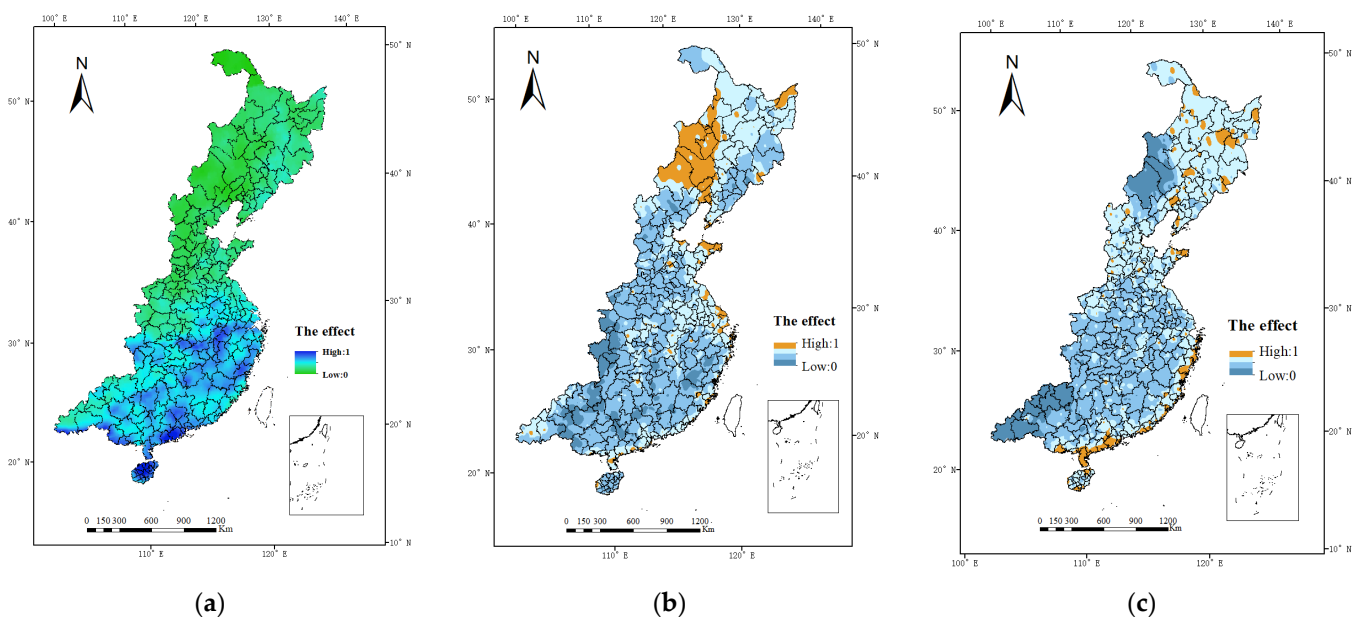


Figure 5. Impact of each hazard causing factor indicator. (a) Average daily rainfall. (b) Average daily wind speed. (c) Average daily maximum wind speed.

The hazard risk of tropical cyclones is the comprehensive result of the combined effects of strong winds and rainfall in the affected areas. Utilizing the standardized values calculated from three indicators (i.e., average daily rainfall, average daily wind speed, and average maximum wind speed) along with their respective weights in the hazard risk assessment of tropical cyclones (as calculated using Equation (7)), hazard scores were obtained. For ease of statistical analysis, the scores were multiplied by 100 for presentation. Subsequently, the hazard levels were classified using the natural breaks method in ArcGIS, as shown in Table 4. Employing graduated colors, the hazard risk of tropical cyclone-induced factors in various regions of China is depicted in Figure 6.

Table 4. Hazard Score Table for Hazard-Causing Factors in the Impact Area of Tropical Cyclones.

Level	Low	Relatively Low	Moderate	Relatively High	High
Scoring range (×100)	$H \leq 16.44$	$16.44 < H \leq 23.95$	$23.95 < H \leq 36.98$	$36.98 < H \leq 53.9$	$53.9 < H$

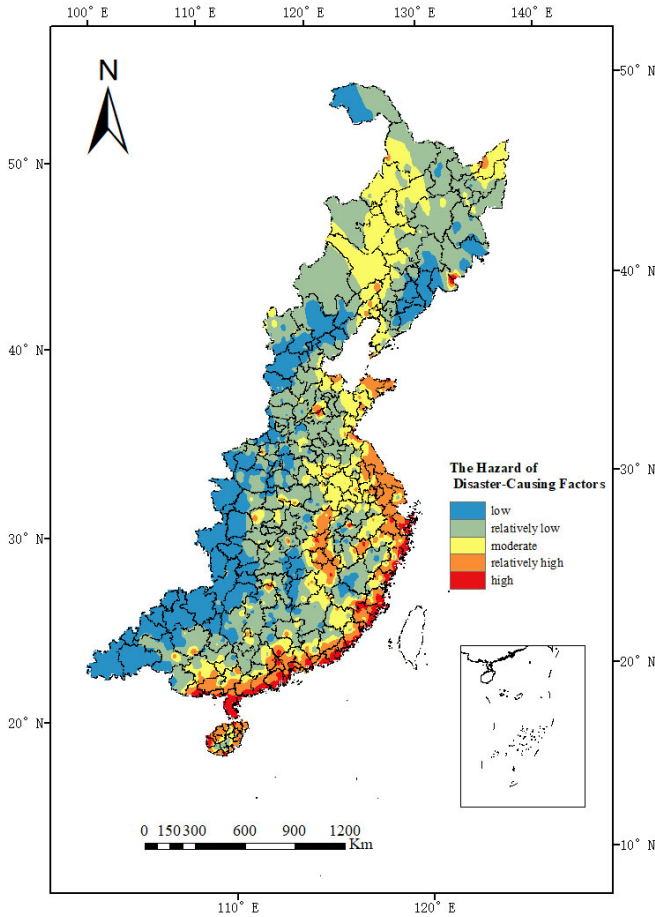


Figure 6. Risk classification of hazard-causing factors.

Based on the evaluation results (Figure 6), there were significant differences in the distribution of hazard risk factors among provinces in China. Cities in the southeastern regions of provinces such as Hainan, Guangdong, Fujian, Guangxi, and Zhejiang—including Haikou, Zhanjiang, Xiamen, Beihai, and Taizhou—were categorized as high-risk areas, with hazard levels rated as high or above. These areas experience frequent occurrences of tropical cyclones with high intensity, resulting in substantial impacts. The northeastern part of Zhejiang Province, the eastern part of Jiangsu Province, the Jiaodong Peninsula region in Shandong Province, and some areas in the northern part of Jiangxi Province exhibit high hazard levels. Most areas in Anhui Province, the eastern part of Shandong Province, and the central part of Liaoning Province, as well as Jilin and western parts of Heilongjiang Province, present moderate hazard levels. The remaining provinces show relatively low or minimal hazard levels. Overall, the hazard risk of tropical cyclone-induced factors in China tends to increase from north to south and from west to east. This trend is attributed to the frequent landfall of tropical cyclones along the southeastern coastal areas and the subsequent weakening of cyclones due to changes in underlying surfaces from ocean to land, as well as variations in terrain elevation and the presence of vegetation and structures. In some areas of Jiangxi Province, abundant precipitation contributes to increased hazard levels; meanwhile, in the central parts of Liaoning Province, Jilin, and the western parts of Heilongjiang Province, the influence of Mongolian cyclones results in persistently high av-

erage daily wind speeds, significantly raising the level of hazard compared to surrounding areas. However, due to environmental changes or the intervention of human factors, the sensor equipment of weather stations may fail or malfunction, resulting in abnormal value distribution of data or other abnormal phenomena and, thus, the assessment of the risk of hazard factors may be partially biased.

3.3. Sensitivity Analysis and Assessment of Natural Carriers

This study calculated the standard deviation of elevation within adjacent 5×5 grid cells using the spatial analysis tool Domain Analysis in ArcGIS as a quantitative indicator of terrain variation. Subsequently, the impact of elevation changes and vegetation coverage on the sensitivity of natural carriers was assessed using Equation (6), followed by visualization, as depicted in Figure 7.

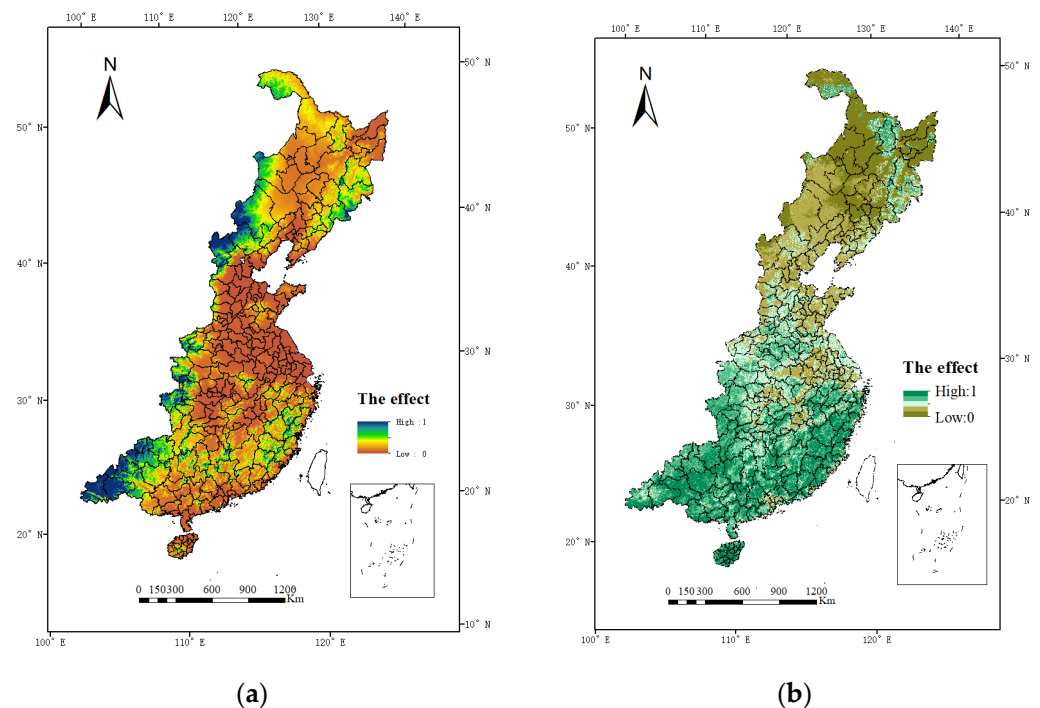


Figure 7. Impact of each index of natural carrier sensitivity. (a) Terrain Elevation (b) Vegetation Coverage.

As the main carriers of natural hazards, China's vast land area and diverse natural environments result in varying degrees of susceptibility to tropical cyclones across different regions. The elevation and vegetation coverage in each province and city contribute to mitigating the impacts of tropical cyclones after landfall, thereby reducing hazard risks. Standard values calculated from elevation and vegetation coverage indicators were used to compute sensitivity scores according to the weights in Equation (9) for natural carriers. To facilitate statistical analysis, the scores were multiplied by 100 for presentation purposes, and sensitivity was classified using the natural breakpoints method in ArcGIS, as shown in Table 5. Subsequently, the sensitivity of natural carriers in various regions of China was visualized using graduated colors, as illustrated in Figure 8.

Table 5. Natural carrier sensitivity scores in the affected areas of tropical cyclones.

Level	Low	Relatively Low	Moderate	Relatively High	High
Scoring range ($\times 100$)	$N \leq 17.54$	$17.54 < N \leq 34.25$	$34.25 < N \leq 51.36$	$51.36 < N \leq 68.79$	$68.79 < N$

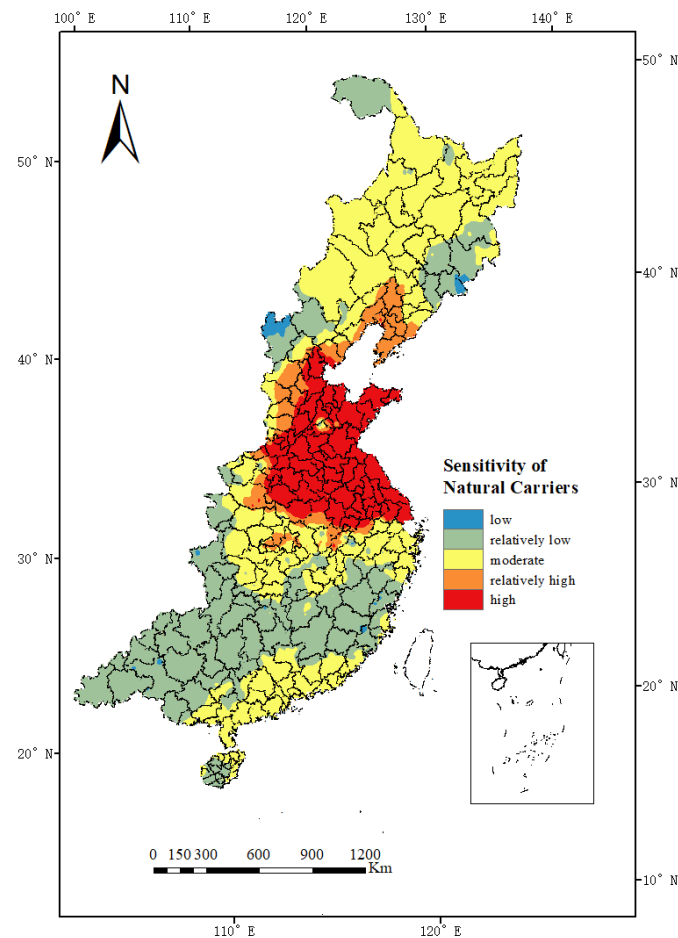


Figure 8. Division of natural carrier sensitivity level.

From the assessment results shown in Figure 8, it can be observed that central Liaoning, Tianjin, the eastern and central-eastern parts of Hebei, Shandong, the eastern parts of Henan, the central-northern parts of Anhui, Jiangsu, and Shanghai exhibited relatively high or higher sensitivity levels. Central Liaoning is situated in the Liaohe Plain, while the central-eastern parts of Hebei and Tianjin are located in the North China Plain. The highly sensitive areas in Henan are situated in the Yellow River Plain, while the northern parts of Anhui lie in the Huaihe River Plain. Shandong, Jiangsu, and Shanghai are predominantly plains, with relatively lower vegetation coverage compared to other regions of China, thus experiencing lesser mitigation effects against tropical cyclones and exhibiting higher sensitivity levels. Conversely, the northern parts of Hubei are separated from Henan by the Funiu Mountains and Qinling Mountains, Zhejiang features a complex terrain of mountains and hills, and the southern parts of Anhui are divided by the Dabie Mountains. The eastern parts of Liaoning are crossed by the Changbai Mountains. Although these areas still have relatively low vegetation coverage, their variable terrain weakens the progress of tropical cyclones after landfall, resulting in moderate sensitivity levels. In the southern part of Guangdong, despite its high vegetation coverage and rough surface, its location in the Pearl River Delta Plain leads to a moderate sensitivity level. Other regions, influenced by the combined effects of terrain elevation and vegetation coverage, exhibit higher resilience against tropical cyclones, hence demonstrating lower sensitivity levels. With the development of China's green economy in recent years, the vegetation coverage of various cities has been increasing annually; however, the latest available vegetation coverage data were obtained for 2019, which may have affected the results regarding the sensitivity of natural carriers.

3.4. Comprehensive Risk Analysis and Assessment of Tropical Cyclone Hazards

Tropical cyclone hazard risk is the result of the combined effects of the hazard susceptibility for various regions and the sensitivity of natural carriers, as well as other factors. Its assessment involves calculating the comprehensive risk score using the influence degree of each indicator and the weighted ranking results, according to the comprehensive risk model (Equation (10)) for tropical cyclone hazards. For ease of statistical analysis, the scoring results were multiplied by 100 and displayed accordingly. Subsequently, the risk levels were classified using a natural break method in ArcGIS, as shown in Table 6. Then, a color gradient scheme was applied to represent the risk levels across different categories for the comprehensive assessment of tropical cyclone hazard risks in various regions of China, as depicted in Figure 9.

Table 6. Comprehensive risk score of tropical cyclone hazard.

Level	Low	Relatively Low	Moderate	Relatively High	High
Scoring range (×100)	$CRTY \leq 17.24$	$17.24 < CRTY \leq 34.65$	$34.65 < CRTY \leq 51.28$	$51.28 < CRTY \leq 68.17$	$68.17 < CRTY$

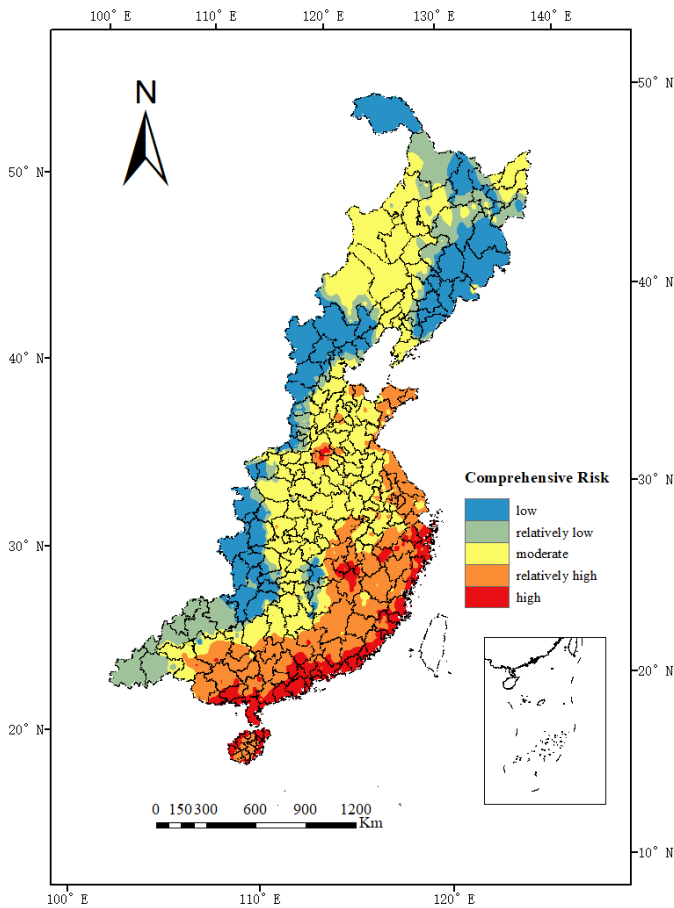


Figure 9. Integrated risk classification of tropical cyclone hazard.

Based on the evaluation results shown in Figure 9 and the weights of various indicators in Table 2, it can be observed that the comprehensive risk assessment of tropical cyclone hazards was based on the hazard susceptibility, given its significant impact weight. Coastal cities such as Haikou, Zhanjiang, Xiamen, Beihai, and Taizhou in provinces like Hainan, Guangdong, Guangxi, Fujian, and Zhejiang exhibited the highest level of comprehensive risk for tropical cyclones. In addition, areas beyond the coastal cities in Fujian, Guangdong, and Zhejiang, as well as central-eastern Hainan, southeastern Guangxi, central-eastern Jiangxi, eastern Jiangsu, and the Jiaodong Peninsula in Shandong, presented a high risk

under the combined effects of hazard susceptibility and sensitivity. The majority of these areas, being situated on plains with relatively low vegetation coverage, experience elevated risks. Regions such as western Jilin and western Heilongjiang, central Liaoning, eastern Hubei, central-eastern Henan, western Shandong, Cangzhou in Hebei, and parts of Tianjin demonstrated moderate risk levels. Although the northeastern provinces of China are less affected by tropical cyclones, they experience frequent strong winds due to the strong influence of the East Asian monsoon and the Mongolian cyclone [35]. Therefore, they fall into the moderate risk category.

In terms of risk distribution characteristics, the results of the comprehensive risk assessment for tropical cyclone hazards demonstrated a decreasing trend from south to north and from east to west. On a large scale, the southeastern regions of China remain at high risk for tropical cyclone occurrences, necessitating a continued focus on hazard prevention efforts in key provinces and cities. While the central regions of China are at a lower risk of tropical cyclone impact, the analysis of tropical cyclone paths indicated a gradual northward and northeastward shift since 1980, leading to an increase in the number of tropical cyclones affecting eastern and southeastern China [36]. For instance, the impacts of Typhoon “Fengshen” in Jiaonan, Shandong in 2002, and Typhoon “Lekima” crossing the Shandong Peninsula in 2019 have intensified. The influence of tropical cyclones on northern and inland cities of China has been gradually increasing, primarily manifested during the weakening and dissipation phases of tropical cyclones, resulting in intense rainfall hazards. For example, the extraordinary rainfall hazard in Zhenzhou, Henan on July 20, 2022, was caused by the combined effects of Typhoon “Yan Hua” and Typhoon “Chapaka” interacting with the subtropical high in the western Pacific Ocean and the unique local terrain [37]. Therefore, in addition to enhancing hazard prevention measures in high-risk areas, it is essential to formulate corresponding prevention and control measures based on the hazard situation in inland cities.

Specific suggestions and countermeasures can be put forward according to the risk degree of each region. For the southeastern coastal cities at high risk, it is necessary to strengthen the national government’s investment in hazard prevention and control, establish and perfect the hazard forecasting and early warning mechanism, and take high-standard engineering measures for the construction of river and sea DAMS. For medium-risk areas, as the risk is reduced to some extent, land planning should be strengthened and tropical cyclone protection forests should be established. Inland cities with low risk should mainly focus on the investment of special funds for tropical cyclone hazard prevention and control, and cultivate public awareness of hazard prevention.

4. Conclusions

Based on an analysis of historical tropical cyclone landfall data, this study identified the regions of the study area most affected by tropical cyclones, and summarized the temporal distribution and intensity characteristics of landfalling tropical cyclones. Guided by the theory of tropical cyclone hazards, a set of evaluation indicators based on natural factors was constructed, integrating hazard susceptibility and the sensitivity of the natural environment. Through the Analytic Hierarchy Process and ArcGIS spatial analysis, standardization and weighted overlay calculations were conducted using various indicator data. This process allowed for evaluation of the typhoon hazard risk in mainland China and Hainan, resulting in the formation of a comprehensive risk zoning map and analysis results. The main conclusions are as follows:

1. Between 1949 and 2023, the overall number of tropical cyclone landfalls showed a fluctuating downward trend, with landfall frequency staying below the mean after 1986. In terms of intensity, strong tropical storms and typhoons accounted for the highest proportion, at 50.6% of the total, over the past 75 years. After 1980, the intensity of tropical cyclones making landfall in China increased by 12.4% to 14.7%. Landfalls primarily occurred from June to October each year, with August being the peak month. The occurrence of strong typhoons has gradually shifted from autumn

to late summer, leading to more frequent typhoon events in the summer. Therefore, prevention efforts against tropical cyclone hazards should be intensified, particularly in summer and autumn.

2. Along the eastern coastal areas of China, the hazard susceptibility due to the direct impacts of typhoons is highest, then gradually decreases inland. Some areas in Jiangxi Province experience abundant precipitation, while central Liaoning, Jilin, and western Heilongjiang are influenced by Mongolian cyclones, resulting in persistently high average daily wind speeds and significantly higher hazard levels, when compared to surrounding areas.
3. The sensitivity of the natural environment is concentrated mainly in central Liaoning, Tianjin, eastern Hebei, Shandong, eastern Henan, central-northern Anhui, Jiangsu, and Shanghai, where flat terrain and low vegetation coverage are predominant.
4. The risk distribution characteristics present a decreasing trend from south to north and from east to west. On a larger scale, the southeastern regions of China remain high-risk areas for tropical cyclones, necessitating continued emphasis on hazard prevention efforts in key provinces and cities. However, while enhancing prevention measures in high-risk areas, corresponding measures should also be tailored based on the specific hazard situation in inland cities.

Author Contributions: Conceptualization, J.X. and X.X.; Methodology, J.X., X.X. and B.Y.; Software, J.X., X.X. and B.Y.; Validation, J.X.; Formal analysis, J.X. and W.W. (Wen Wang); Resources, J.X., B.Y. and X.X.; Data curation, J.X., X.X., B.Y. and W.W. (Wen Wang); Writing—original draft, J.X.; Writing—review & editing, J.X., X.X., B.Y., W.W. (Wen Wang) and X.J.; Visualization, J.X.; Supervision, W.W. (Wenxiang Wu) and X.J.; Project administration, J.X.; Funding acquisition, W.W. (Wenxiang Wu). All authors have read and agreed to the published version of the manuscript.

Funding: The investigation was supported by the Innovation Research Team Project of Natural Science Foundation of Hainan Province (Grant Nos.422CXTD515) and the National Natural Science Foundation of China (No.31570708).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Conflicts of Interest: The authors declare no conflicts of interest.

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