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Resilience of Chinese Ports to Tropical Cyclones: Operational Efficiency and Strategic Importance

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Abstract: This study evaluated the resilience of five major Chinese ports—Shanghai, Tsingtao, Shenzhen, Xiamen, and Qinzhou—against the impacts of tropical cyclones. These ports, as integral global maritime supply chain nodes, face rising vulnerabilities from climate-related disruptions such as typhoons, sea-level rise, and extreme temperature fluctuations. Employing a resilience assessment framework, this study integrated climate and operational data to gauge how cyclone-induced events affect port performance, infrastructure, and economic stability. Multi-centrality analysis and the Borda count method were applied to assess each port's strategic importance and operational efficiency under cyclone exposure. The findings highlight variations in resilience across the ports, with Shanghai and Tsingtao showing heightened risk due to their critical roles within international logistics networks. This study suggests strategies like strengthening infrastructure, improving emergency responses, and adopting climate-resilient policies to make China's ports more sustainable and resilient to climate threats. This research offers actionable insights for policymakers and port authorities, contributing to a more climate-resilient maritime logistics framework.

Keywords: climate change; port resilience; Chinese ports; supply chain disruption; adaptation strategies

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1. Introduction

Ports are critical nodes in the global maritime supply chain, facilitating the movement of vast volumes of goods, raw materials, and energy across international borders [1]. Among the world's busiest and most significant ports, China's coastal ports play a central role in global trade, making China a dominant player in international commerce [2]. These ports serve as vital gateways for imports and exports, handling massive volumes of containerised goods, bulk commodities, and energy resources [3]. Their strategic importance is underscored by their location along key shipping routes that connect China with major markets in Europe, North America, and the rest of Asia [4].

However, the increasing severity of climate change presents new challenges to the operations and infrastructure of these essential trade hubs [5]. Rising sea levels [6], more frequent and intense typhoons [7], and escalating temperatures [8] pose significant threats to port functionality, endangering their capacity to sustain the efficient flow of goods. The geographical positioning of these ports along China's eastern and southern coastlines further exacerbates their vulnerability to climate risks, potentially leading to disruptions in both local and global supply chains [9]. Climate-induced disruptions have far-reaching implications, not only for China's economy but also for the global trade network that relies on the smooth operation of these ports [10].

Based on data from the Tropical Cyclone Data Center of the China Meteorological Administration [11], statistical analysis shows that from 1949 to 2023, 661 tropical cyclones made landfall in China, averaging 8.81 tropical cyclones per year. The total number of landfalls reached 893, with an annual average of 11.91, and the number of landfalls with a tropical cyclone intensity of tropical depression (TD) level or above reached 832. Analysis of the statistical charts reveals that the frequency of tropical cyclones making landfall in China has fluctuated significantly in recent years. In 2018, there were 20 landfalls, marking the second-highest number in the past 75 years, while in 2020, there were only 6 landfalls, the lowest in the same period. Additionally, the bar chart shows that after 2000, the frequency of tropical cyclone landfalls in China has frequently reached extreme values. This suggests that under the influence of global climate change, extreme weather events are becoming increasingly unpredictable, with more pronounced fluctuations in trend. Specific data on the number and frequency of tropical cyclone landfalls in China are shown in Figure 1.

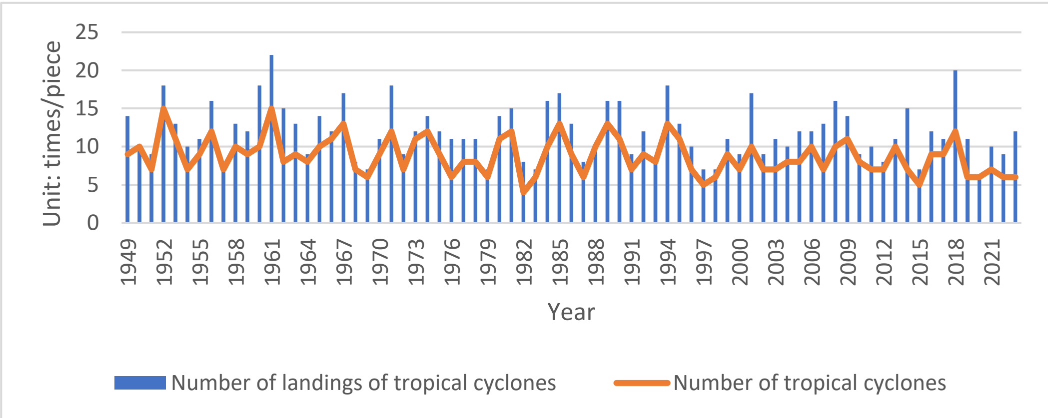

Figure 1. The number and frequency of tropical cyclone landfalls in China.

An analysis of tropical cyclone intensity at landfall reveals 158 instances of TD-level landfalls, accounting for 18.99% of the total. Tropical storm (TS) landfalls occurred 182 times (21.88%), strong tropical storm (STS) landfalls occurred 208 times (25%), and typhoon (TY) level landfalls occurred 223 times (26.8%). Strong typhoon (STY) level landfalls accounted for 48 instances (5.77%), and super typhoon (SuperTY) level landfalls occurred 13 times (1.56%). The data indicate that most tropical cyclones making landfall in China are at the tropical storm (TS), tropical solid storm (STS), or typhoon (TY) levels, which collectively account for over 70% of cases. Notably, over the past 75 years, super typhoons (SuperTY), the most powerful category, made landfall in China 13 times. However, within the short span from 2014 to 2023, super typhoon landfalls reached six instances, with both 2014 and 2016 seeing two super typhoon landfalls each. This trend reflects the increasing frequency and intensity of extreme weather events in recent years, likely influenced by global climate change. Detailed data on the intensity of tropical cyclones making landfall in China is shown in Figure 2.

An analysis of the geographical locations of tropical cyclone landfalls shows that the eastern coast of China is primarily affected, with southeastern coastal provinces experiencing the highest frequency of landfalls. Guangdong Province recorded the most landfalls over the 75 years, with 277 landfalls, accounting for 30.92% of the total, averaging 3.69 landfalls per year. Hainan Province and Taiwan Province followed with 172 and 153 landfalls, each accounting for over 15% and averaging more than 2 landfalls per year. By contrast, Liaoning Province and Tianjin City recorded the fewest landfalls, with only seven and one occurrences over 75 years, each accounting for less than 1% of the total. These statistics indicate that tropical cyclones primarily make landfall along China's eastern coastal provinces, with a clear trend of increased landfall frequency at lower latitudes. The geographical distribution of tropical cyclone landfalls in China is shown in Figure 3.

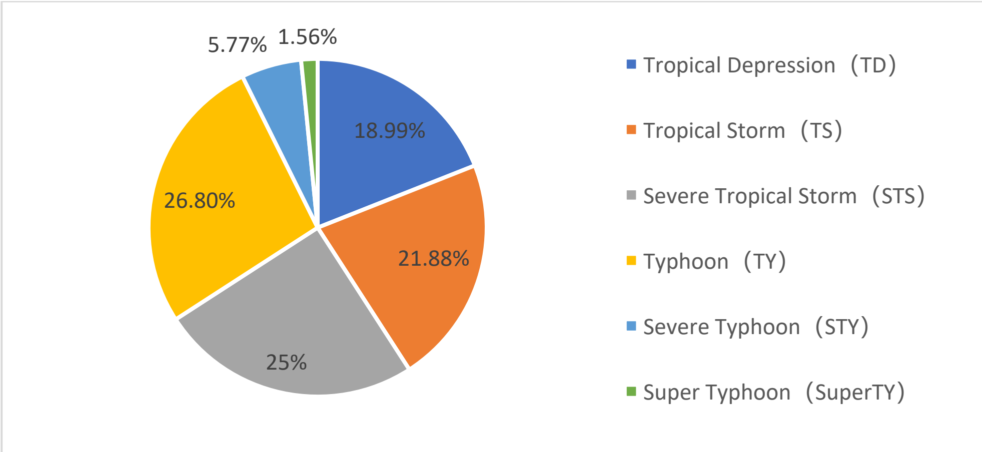

Figure 2. Intensity statistics of tropical cyclones making landfall in China.

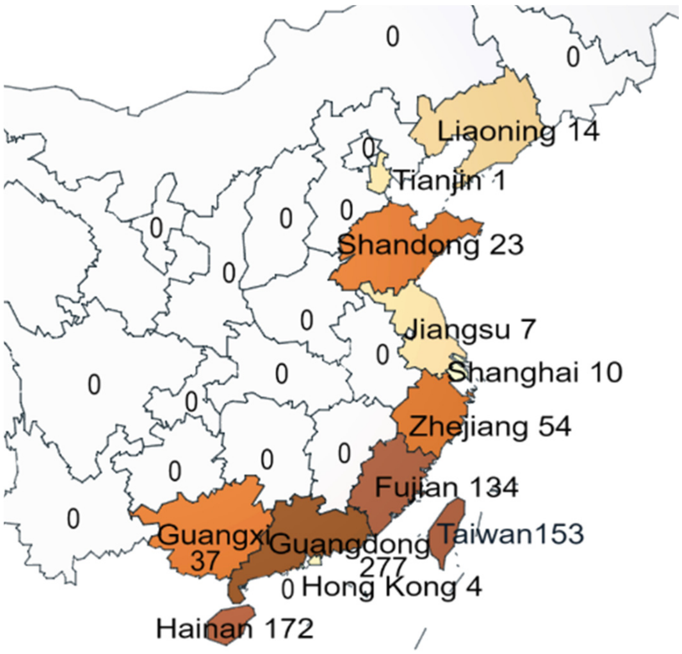

Figure 3. Intensity statistics of tropical cyclones making landfall in China.

The five Chinese ports selected for this study regarding Figure 3 again—Shanghai [12,13], Tsingtao in Shandong [14,15], Shenzhen in Guangdong [16,17], Xiamen in Fujian [18,19], and Qinzhou in Guangxi [20,21]—were chosen based on their trade volume, geographic diversity, and vulnerability to tropical cyclones. They represent critical Shenzhen nodes in China's maritime logistics network. Shanghai, the world's busiest container port at the mouth of the Yangtze River in Shanghai Municipality, is highly susceptible to sea-level rise and typhoons. Tsingtao, located in Shandong Province on the east coast, faces similar risks due to its exposure to coastal storms. Shenzhen, one of the world's busiest container ports and a key hub for electronics and technology exports, is located in Guangdong Province, a highly industrialised zone that is sensitive to rising sea levels and extreme weather events. Xiamen, an essential hub for trade with Taiwan and Southeast Asia, is situated in Fujian Province in a semi-tropical region prone to typhoons and extreme rainfall, threatening its infrastructure. Lastly, Qinzhou, positioned in the Guangxi Zhuang Autonomous Region in the Beibu Gulf Economic Zone, is rapidly growing in container handling and is vulnerable to severe weather due to its proximity to Southeast Asia. These selection criteria ensure that the study covers diverse port types, geographic settings, and climate-related vulnerabilities across China's critical maritime infrastructure.

This paper aims to assess the efficiency of the selected ports under the impact of typhoon exposure, using operational data to analyse how such tropical cyclones affect port performance. The motivation for this study stems from the increasing frequency and intensity of tropical cyclones due to climate change, which pose significant threats to the operational efficiency and strategic importance of ports. Given the pivotal role of Chinese ports in global trade and their vulnerability to climate-related disruptions, it is critical to understand how these ports can maintain resilience under extreme weather events. Additionally, this study will conduct a port importance assessment through multi-centrality analysis to understand each port's strategic role within China's maritime logistics network. To compare the status of the five ports comprehensively, this study will integrate a risk matrix with the Borda count method, providing a robust framework for evaluating and ranking their climate resilience. This approach offers valuable insights into port vulnerabilities and resilience strategies, contributing to sustainable maritime logistics and enhancing the adaptability of critical trade infrastructure in the face of climate change.

The paper is structured in several sections. It begins with a literature review that explores global research on the impacts of climate change on port operations, along with resilience in maritime logistics and the economic–environmental intersections caused by climate-induced disruptions. Section 3 outlines a methodological framework for assessing the resilience and operational efficiency of five major Chinese ports facing the impacts of tropical cyclones. Section 3.1 provides a foundation by examining climate data on cyclone frequency and intensity, assessing how these extreme weather events influence operational efficiency and stability within each port. This climate-focused analysis highlights disruptions caused by cyclones, offering an initial perspective on vulnerability. In Section 3.2, the methodology extends to a network analysis of the global shipping network, evaluating the strategic importance of each port within the broader system. This network perspective underscores ports' interconnectedness and the potential cascading effects of disruptions in critical nodes. Finally, Section 3.3 applies a comparative resilience analysis, utilising the Borda count and risk matrix methods. The Borda count ranks the ports based on relative resilience scores, while the risk matrix provides a nuanced view of each port's vulnerability and adaptive capacity. This dual-method approach combines quantitative performance metrics with strategic risk insights, allowing for a comprehensive, layered assessment of resilience in the context of increasing tropical cyclone activity.

The analysis section examines the specific climate vulnerabilities of each port, such as sea-level rise and extreme weather events. A discussion on adaptation and mitigation strategies, including infrastructure improvements, policy recommendations, and technological innovations, follows this. Finally, the debate compares the resilience of the five ports, assesses the economic implications of climate change, and draws lessons for global ports, with the conclusion summarising the essential findings and suggesting future research directions.

2. Literature Review

2.1. Climate Change and Port Operations

The impacts of climate change on port operations have been well documented in global and regional studies. Ports are uniquely vulnerable due to their coastal locations, making them susceptible to sea-level rise, storm surges, extreme weather events, and changing ocean currents. Globally, ports are experiencing the adverse effects of rising sea levels, contributing to increased coastal flooding, damaging port infrastructure, disrupting operations, and creating longer-term threats to port viability. For example, Becker et al. [22] and Ng et al. [23] highlight the need for ports to invest in resilience strategies to mitigate climate change's operational and logistical challenges.

The vulnerabilities are particularly acute in the Asian context, home to some of the world's busiest ports [24]. Research on Asian ports underscores the increased frequency and intensity of typhoons, monsoon variability, and extreme heat events, which disrupt port operations and significantly impact supply chains. China's ports, in particular, are facing growing challenges due to climate change, as indicated by Li et al. [25] Given the country's prominence in global trade, emphasising the importance of adapting China's port infrastructure to withstand climate risks. Shanghai, Ningbo-Zhoushan, Guangzhou, Shenzhen, and Tianjin, which collectively handle a significant portion of the world's maritime trade, are critical nodes requiring comprehensive adaptation measures to ensure long-term operational efficiency.

2.2. Resilience in Maritime Logistics

Resilience in the maritime logistics sector has gained increasing attention in recent years, focusing on how ports can adapt to climate-induced disruptions while maintaining the flow of goods and services [26]. Resilience is the ability to anticipate, prepare for, respond to, and recover from adverse events such as extreme weather or rising sea levels. Various strategies for enhancing port resilience have been proposed, including infrastructure reinforcement, digitalisation, and integration of early-warning systems [27]. Studies by Zhang and Lam [28] and Wang et al. [29] emphasise resilience's critical role in mitigating the economic losses caused by disruptions to port operations.

The escalating effects of climate change have prompted international research initiatives to enhance port resilience through developing sophisticated resilience indices and an in-depth understanding of vulnerabilities faced globally. For instance, León-Mateos et al. [30] introduced the Port Resilience Index (PRI) in the external port of A Coruña, Galicia, Spain, as a proactive tool to address adverse climatic conditions like intensified storm events and rising salinity levels, incorporating stakeholder input to guide resource allocation and adaptation strategies. Similarly, Nursey-Bray et al. [31] investigated Australian ports, highlighting vulnerabilities stemming from low-lying coastal locations exposed to sea-level rise and storm activity. Their study emphasised a dual focus on physical infrastructure and socio-economic frameworks to craft sustainable adaptation strategies. Complementing these efforts, Santos et al. [32] conducted a bibliometric analysis (2012–2023), showcasing contributions from regions like the United States, Spain, and the UK, where indices such as the Coastal Vulnerability Index (CVI) are commonly used. The study advocates for more nuanced indices to address research gaps, enriching the global discourse on port vulnerabilities and resilience.

In the Chinese context, resilience strategies are increasingly incorporated into port management practices [33]. Ports are investing in flood defences, elevating critical infrastructure, and incorporating green technologies to reduce the environmental impact of their operations. Efforts to enhance port resilience also include government-led initiatives to strengthen regional collaboration between ports, as seen in China's Belt and Road Initiative (BRI), which promotes connectivity and joint strategies for sustainable development. While progress has been made, there is still a need for more comprehensive policies that address the full spectrum of climate risks and ensure long-term sustainability.

2.3. Economic and Environmental Intersections

The economic and environmental intersections of climate-induced disruptions to port operations are critical areas of concern, particularly for countries like China, where maritime trade plays a significant role in economic development [34]. Ports are crucial economic hubs, facilitating international trade and contributing to local and regional economies [35]. Climate change, however, poses serious risks to the financial stability of port-dependent regions. Disruptions to port operations can lead to supply chain delays, increased shipping costs, and reduced competitiveness in the global market.

Several studies have examined the economic impacts of climate change on ports. For instance, Poo and Yang [24] conducted a study on the resilience of maritime supply chains in the face of climate-related disruptions, focusing on how delays and port closures can ripple through the broader economy, leading to reduced industrial output and trade volumes. In China, where ports are central to the country's role as the largest exporter, the economic impacts of climate change are particularly pronounced. Yang and Ge [36] discussed that disruptions at major Chinese ports such as Shanghai and Guangzhou could have cascading effects on global supply chains, affecting industries far beyond the immediate region.

From an environmental perspective, ports also contribute to climate change, as they are hubs of industrial activity and significant emitters of greenhouse gases (GHGs). Studies by Wang et al. [37] explore how ports can reduce their carbon footprint by adopting renewable energy sources, improving energy efficiency, and integrating more sustainable practices into their operations. As the global shipping industry moves towards decarbonisation, ports must align their sustainability efforts with international environmental goals, balancing economic growth with environmental responsibility.

2.4. Research Gap

Despite extensive research on climate change impacts on port operations, integrated quantitative frameworks still exist that assess and compare port efficiency and resilience, specifically under tropical cyclone exposure. Existing studies rarely address how ports' strategic importance within maritime logistics networks is affected during climate-induced disruptions. This study focuses on developing a comprehensive evaluation framework to bridge this gap. The consolidated research question is how tropical cyclones impact key Chinese ports' operational efficiency and strategic importance and what adaptation strategies can enhance their long-term resilience within the maritime logistics network. This study introduces a novel framework integrating port efficiency metrics, multi-centrality network analysis, and the Borda count method to comprehensively assess the resilience of major Chinese ports to tropical cyclones, offering a nuanced understanding of operational risks and strategic importance. It provides actionable insights for policymakers and port authorities, advancing climate-resilient maritime logistics research while addressing critical gaps in port vulnerability and adaptation strategies.

3. Methodology

Section 3 of this study outlines a methodological framework for assessing the resilience and operational efficiency of five major Chinese ports facing the impacts of tropical cyclones. Moreover, the overall flow is shown in Figure 4.

3.1. Operation Efficiency Assessment

Port efficiency is a critical indicator of a port's capacity to maintain normal operations when facing natural disasters, such as tropical cyclones [38]. This indicator is measured by calculating the port's monthly cargo throughput ratio during tropical-cyclone-affected periods to its total annual throughput. A high-efficiency ratio indicates that the port can sustain a relatively high cargo-handling capacity during disasters, reflecting robust infrastructure and effective emergency management systems that can mitigate the impact of natural disasters. This capability is essential for ensuring supply chain stability and reducing economic risks.

To quantify the efficiency indicator, this section collects data from the past ten years on the monthly cargo throughput, annual total throughput, and the months affected by tropical cyclones for the five sample ports. Firstly, monthly cargo throughput data were gathered from the Ministry of Transport and government websites of the cities where the sample ports are located. Secondly, data on tropical cyclone impacts, including wind and rainfall disruptions, were obtained from official websites such as the Maritime Bureau, Meteorological Bureau, and China Typhoon Network. Finally, the efficiency of each sample port during cyclone-affected periods is assessed, and the efficiency formula and evaluation results are presented as follows.

$$\text{Efficiency} = \frac{\sum C_{month}}{n \times C_{Year}} \tag{1}$$

where C_{month} and C_{year} represents the port's monthly and annual cargo throughput during months affected by tropical cyclones, and n denotes the number of months impacted by tropical cyclones.

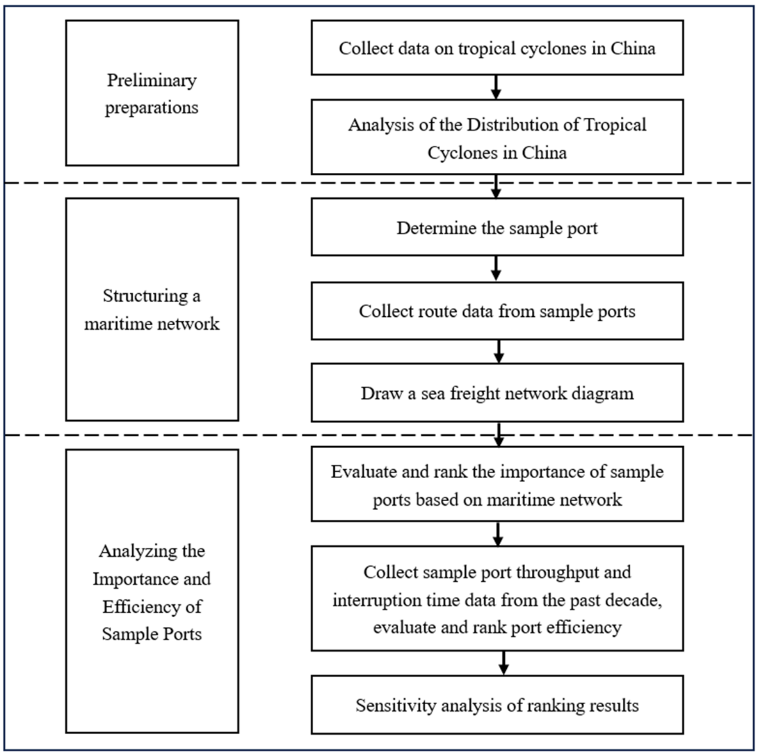

Figure 4. Methodology of the study.

3.2. Port Importance Assessment

Port importance is a multifaceted concept encompassing the port's central role within the shipping network, economic contribution, logistics hub functions, and connectivity with other ports [24,39]. A port of high importance plays a crucial role in international trade and regional economic development. When such a port faces natural disasters, like tropical cyclones, that disrupt operations or reduce efficiency, the impact reverberates deeply throughout the entire shipping network. Specifically, highly important ports often handle large cargo volumes and support busy shipping routes. If these ports are closed or slowed by disasters, it directly affects cargo flow speed and cost, undermining supply chain stability and the operational efficiency of related businesses. Additionally, as these ports may serve as regional or global shipping hubs, their disruption could lead to rerouted shipping routes, cargo backlogs, and increased transportation costs, causing ripple effects in the broader shipping market.

The port importance and efficiency assessment incorporates historical typhoon data for China, sourced from the Tropical Cyclone Data Center of the China Meteorological Administration's tropical cyclone landing records. Typhoon data for each port were retrieved from the official website of the China Meteorological Administration Typhoon Network. The maritime network was constructed based on the Top 100 Liner Operators by Fleet Capacity ranking (as of 7 June 2024) published by the globally renowned shipping consultancy Alphaliner. The analysis focused on the top 12 liner companies, namely MSC, Maersk, CMA CGM, COSCO, Hapag-Lloyd (HPL), Ocean Network Express (ONE), Evergreen (EMC), Hyundai Merchant Marine (HMM), ZIM, Yang Ming (YML), Wan Hai Lines (WHL), and Pacific International Lines (PIL). Shipping route data were collected from the official websites of these companies to build the maritime network. By using these data, the study gathered route information from the top 12 container companies, covering over 1200 routes and 267 ports. With these data, a detailed maritime network was constructed using UCINET software, Version 6.799, to visualise and analyse the importance of the sample ports as shown in Figure 5. The specific marine network map is shown below, and the full port list is shown in Supplementary Document S1.

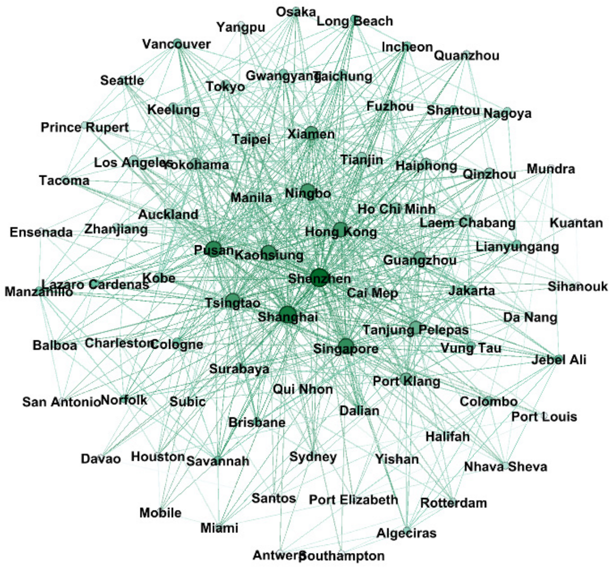

Figure 5. Map of a global shipping network.

To enhance the readability of the maritime network map, this study selectively displays routes and ports by omitting routes not directly associated with the selected sample ports. This approach emphasises critical routes and ports, improving the map's effectiveness in conveying information. Although the visualisation is simplified, the analysis of port importance is still based on complete route and port data, ensuring both clarity in presentation and a comprehensive and accurate assessment of port importance.

The maritime network map reveals that the five sample ports have numerous connecting lines, indicating significant connectivity within the network. To comprehensively evaluate the importance of these sample ports, this study conducts a multidimensional analysis across five metrics: degree centrality, betweenness centrality, closeness centrality, eigenvector centrality, and core–periphery structure.

3.2.1. Degree Centrality

Degree centrality is a metric that measures the importance of a node within a network [24,29,39]. In the context of a port network, if a port has direct shipping routes with many other ports, it holds a central position in the network. The broader the network of connections a port has (i.e., the more neighbouring port nodes it connects to), the higher its centrality, reflecting increased importance within the maritime network. The formula for calculating degree centrality is shown in Equation (2).

$$Degree\ centrality\ \left(R_{Dc_i}\right) = \sum_{j=1}^{n} a_{ij} \tag{2}$$

where a_{ij} represents the number of direct connections between port nodes i and j.

3.2.2. Betweenness Centrality

Betweenness centrality measures the extent to which a node lies on the shortest paths between other nodes in the network [24,29,39]. It reflects the node's control over information flow within the network, highlighting its role as a "bridge" between other nodes. A higher betweenness centrality indicates that the node plays a significant role in connecting different parts of the network, thereby influencing information or resource flow. The formula for calculating betweenness centrality is shown in Equation (3).

$$Betweenness\ centrality\left(R_{Bc_i}\right) = \sum_{j=1}^{n} \frac{\sigma_{st}(j)}{\sigma_{st}} \tag{3}$$

where σ_{st} is the total number of shortest paths between nodes s and t, and $\sigma_{st}(i)$ is the number of those paths that pass through node i.

3.2.3. Closeness Centrality

Closeness centrality measures the total distance from a specific node to all other nodes in the network, assessing how close the node is to the others [24,29,39]. A higher closeness centrality implies shorter average distances to all other nodes, indicating that the node is more advantageous regarding information dissemination and resource access. In a maritime network, a port with high closeness centrality is better connected to other ports, increasing its importance.

$$Closeness\ centrality\left(R_{cc_i}\right) = \frac{n-1}{\sum_{i \neq j} d_{ij}} \tag{4}$$

where d_{ij} is the distance between nodes i and j, and n is the total number of ports in the network.

3.2.4. Eigenvector Centrality

Eigenvector centrality considers the quality of a node's connections by considering the number of connections and the importance of the connected nodes [40]. A node's eigenvector centrality increases if it connects to other nodes with high eigenvector centrality values. In a maritime network, a port with high eigenvector centrality indicates it is connected to other strategically important ports, enhancing its likelihood of becoming a key hub in international trade and shipping.

$$Eigenvector\ centrality_i\left(R_{Ec_i}\right) = \frac{1}{\lambda} \sum_{j=1}^{n} A_{j,i} Eigenvector\ centrality_j \tag{5}$$

where λ is a constant, and A represents the adjacency matrix. $A_{j,i}$, a value of 1 indicates a connection between nodes i and j, while a value of 0 indicates no connection between them.

3.2.5. Core–Periphery Analysis

Core–periphery analysis $\left(R_{cd_i}\right)$ is a method in complex networks used to identify core (key) nodes and peripheral (secondary) nodes [41]. Quantifying nodes' connectivity and influence reveals the network's structural characteristics. Core nodes are generally located at the centre of the network, with high centrality and a significant contribution to the overall network operation. By contrast, peripheral nodes are relatively isolated, maintaining close relationships primarily with certain core nodes. These peripheral nodes are sparsely connected with each other, forming a scattered distribution at the network's edges and exerting a minimal influence on the network as a whole.

3.2.6. Entropy Weight Method

This study first uses UCINET software to calculate five key metrics, including degree centrality and betweenness centrality, to evaluate the importance of the sample ports [24,29,39]. Then, the entropy weight method is applied to weigh these five metrics, providing a comprehensive assessment of each port's importance by generating weights by integrating options from 30 experts listed in Supplementary Document S2. Then, Supplementary Document S3 fully explains the detailed calculation steps for the entropy weight method, and the objective weights of the five metrics can be calculated using Python. Finally, Version 3.12.0, a comprehensive scoring formula, determines the overall importance score and ranking for each sample port, as shown in Table 1.

Table 1. Objective weights for port importance indicators.

	Degree Centrality	Betweenness Centrality	Closeness Centrality	Eigenvector Centrality	Core Degree
Objective weight	20.15%	29.98%	18.43%	15.62%	15.83%

3.3. Comparative Resilience Analysis

This subsection applies a comparative resilience analysis to quantify and compare the operational risks the selected Chinese ports face in tropical cyclones. This analysis integrates the findings from the port efficiency and importance assessments to provide a holistic view of each port's resilience by generating operation risk of ports under climate impacts (ROUC).

The comparative resilience analysis utilises a risk framework defined by the product of two primary components: likelihood and impact [42]. This classic framework is captured in Equation (6). It is important to note that we assume all five ports are subjected to the same frequency and intensity of cyclones for the purposes of this assessment. To quantify the resilience of each port, we derive scores using the Borda count method based on their operational efficiency $S_e(i)$ and importance $S_i(i)$, as detailed in Equations (7) and (8) [24,39]. A lower rank indicates higher performance in these equations, allowing us to transform the rankings into resilience scores. ROUC is calculated by combining these scores:

$$Risk = Likelihood \times Impact \tag{6}$$

$$S_e(i) = 6 - Rank_{S_e(i)} \tag{7}$$

$$S_i(i) = 6 - Rank_{S_i(i)} \tag{8}$$

$$Operation\ risk\ of\ ports\ under\ climate\ impacts\ (ROUC) = S_e(i) \times S_i(i) \tag{9}$$

ROUC score serves as a composite metric that reflects both the efficiency of the ports during cyclone-affected periods and their strategic importance within the global shipping network. A higher ROUC score indicates greater vulnerability and operational risk, while a lower score suggests better resilience and adaptability.

4. Result

This section presents the findings from the operational risk assessment of the five major Chinese ports under the impacts of tropical cyclones. The results highlight variations in port efficiency and importance, culminating in the calculation of ROUC.

4.1. Sensitivity Analysis

This study conducted a sensitivity analysis by adjusting the weights of different centrality metrics to evaluate their impact on the final rankings of five ports, as shown in Equations (10)–(14). As the weight of the Betweenness Centrality metric increased, Qinzhou Port's ranking improved and eventually surpassed Xiamen Port, which was consistent with their respective rankings in this metric. The analysis revealed that changes in rankings align closely with the ports' performance in the centrality metrics, as shown in Tables 2–6. Overall, the results highlight the significant influence of metric weights on rankings while maintaining consistency with the inherent characteristics of the centrality metrics, offering valuable insights for optimising weight design in port network studies.

$$S_{Dc} = D_c \times R_{Dc} + B_c + C_c + E_c + C_d \tag{10}$$

$$S_{Bc} = D_c + B_c \times R_{Bc} + C_c + E_c + C_d \tag{11}$$

$$S_{Cc} = D_c + B_c + C_c \times R_{Cc} + E_c + C_d \tag{12}$$

$$S_{Ec} = D_c + B_c + C_c + E_c \times R_{Ec} + C_d \tag{13}$$

$$S_{Cd} = D_c + B_c + C_c + E_c + C_d \times R_{Cd} \tag{14}$$

Table 2. Sensitivity analysis of degree centrality.

Port	R_{Dc}									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Shanghai	1	1	1	1	1	1	1	1	1	1
Shenzhen	2	2	2	2	2	2	2	2	2	2
Tsingtao	3	3	3	3	3	3	3	3	3	3
Xiamen	4	4	4	4	4	4	4	4	4	4
Qinzhou	5	5	5	5	5	5	5	5	5	5

Table 3. Sensitivity analysis of betweenness centrality.

Port	R_{Bc}									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Shanghai	1	1	1	1	1	1	1	1	1	1
Shenzhen	2	2	2	2	2	2	2	2	2	2
Tsingtao	3	3	3	3	3	3	3	3	3	3
Xiamen	4	4	4	4	4	4	5	5	5	5
Qinzhou	5	5	5	5	5	5	4	4	4	4

Table 4. Sensitivity analysis of closeness centrality.

Port	R_{Dc}									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Shanghai	1	1	1	1	1	1	1	1	1	1
Shenzhen	2	2	2	2	2	2	2	2	2	2
Tsingtao	3	3	3	3	3	3	3	3	3	3
Xiamen	4	4	4	4	4	4	4	4	4	4
Qinzhou	5	5	5	5	5	5	5	5	5	5

Table 5. Sensitivity analysis of eigenvector centrality.

Port	R_{Ec}									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Shanghai	1	1	1	1	1	1	1	1	1	1
Shenzhen	2	2	2	2	2	2	2	2	2	2
Tsingtao	3	3	3	3	3	3	3	3	3	3
Xiamen	4	4	4	4	4	4	4	4	4	4
Qinzhou	5	5	5	5	5	5	5	5	5	5

Table 6. Sensitivity analysis of core degree centrality.

Port	R_{Cd}									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Shanghai	1	1	1	1	1	1	1	1	1	1
Shenzhen	2	2	2	2	2	2	2	2	2	2
Tsingtao	3	3	3	3	3	3	3	3	3	3
Xiamen	4	4	4	4	4	4	4	4	4	4
Qinzhou	5	5	5	5	5	5	5	5	5	5

4.2. Port Efficiency and Importance

The comprehensive port importance evaluation results by centrality measures and core–periphery analysis are attached in Supplementary Document S4. By integrating such results with Table 1, $S_i(i)$ can be obtained. Table 7 then summarises the port efficiency ratios, rankings for port efficiency $S_e(i)$, port importance $S_i(i)$, and the resulting ROUC scores for each port. Notably, the efficiency ratios during cyclone-affected periods reveal that all ports maintained a relatively stable throughput, although some exhibited greater resilience than others.

Table 7. Rank of ports of operation risk of ports under climate impacts.

Port	Port Efficiency	$Rank_{S_e(i)}$	$S_e(i)$	Port Importance	$Rank_{S_i(i)}$	$S_i(i)$	ROUC
Shanghai	8.50%	3	3	1.0001	1	5	15
Shenzhen	8.63%	5	1	0.8553	2	4	4
Tsingtao	8.44%	1	5	0.4177	3	3	15
Xiamen	8.53%	4	2	0.2969	4	2	4
Qinzhou	8.45%	2	4	0.0436	5	1	4

4.3. Analysis of ROUC

ROUC scores reflect the combined effects of port efficiency and importance, highlighting the vulnerability of the ports to operational risks due to tropical cyclones.

Shanghai and Tsingtao emerged as the ports with the highest ROUC scores (15), indicating significant operational risks for the resilience of the Chinese port system. Despite having relatively high efficiency during cyclone-affected periods, their importance within the global shipping network exacerbates the potential impact of disruptions. As key nodes in international trade, their closure or inefficiency can lead to extensive ripple effects throughout the shipping network.

Conversely, Shenzhen, Xiamen, and Qinzhou exhibit lower ROUC scores (4), suggesting that while they are also important ports, they maintain better resilience and adaptive capacity when faced with cyclonic disturbances. These ports have demonstrated a more favourable balance between operational efficiency and their role in the shipping network, making them less susceptible to cascading disruptions.

5. Discussion

5.1. Discussion of the Results

This study's resilience assessment of five major Chinese ports—Shanghai, Tsingtao, Shenzhen, Xiamen, and Qinzhou—provides critical insights into these ports' vulnerabilities and adaptive capacities under tropical cyclone exposure. While each port exhibits substantial throughput capacity, resilience levels vary significantly due to differences in geographic exposure, strategic roles in global shipping networks, and operational efficiency during extreme weather events.

Shanghai and Tsingtao have emerged as the most vulnerable ports with high ROUC scores, mainly due to their pivotal positions within the global maritime network. Disruptions at these ports could cause extensive ripple effects, affecting domestic trade and international supply chains. The high dependency of these ports on continuous operational efficiency underscores the necessity for targeted investments in resilient infrastructure and enhanced emergency response protocols to withstand cyclone-induced disruptions. Potential strategies to mitigate these risks include fortifying structural defences, implementing advanced early-warning systems, and diversifying transport routes to lessen the dependency on these high-risk hubs.

By contrast, Shenzhen, Xiamen, and Qinzhou demonstrated lower ROUC scores, reflecting their greater resilience under cyclone impact. These ports balance operational stability with strategic importance, reducing their susceptibility to cascading disruptions. Their resilience appears to result from efficient emergency management frameworks and strategic infrastructure positioning, providing a model of adaptive capacity that could serve as a benchmark for other ports facing similar climate threats. By investing in climate-resilient infrastructure and adaptive operational practices, these ports illustrate the benefits of resilience in extreme weather.

This study's multi-criteria approach, utilising network centrality measures and the Borda count method, highlights the importance of integrating operational efficiency and strategic significance when assessing port resilience. This dual-perspective framework is valuable for prioritising resilience efforts and identifying ports that require immediate fortification to maintain stable trade flows and minimise economic losses from climate-related disruptions.

Given their vulnerabilities, the results highlight an urgent need for strengthened resilience planning and tailored infrastructure improvements for China's ports, particularly Shanghai and Tsingtao. Monitoring cyclone trends and operational impacts will be essential for effective resilience building to adapt to changing climate-related risks. Furthermore, resilience planning should focus on expanding data collection efforts on port operations and planning, including real-time operational metrics, adaptive planning protocols, and port capacity metrics. Additional data on port workforce readiness, equipment maintenance schedules, and supply chain logistics coordination will provide a more detailed understanding of resilience strengths and gaps.

5.2. Strategic Adaptation and Technological Integration

In response to escalating risks from climate threats, ports require robust adaptation strategies that synergise strategic alliances, governmental interventions, and advanced technological integrations. This comprehensive framework synthesises insights from port alliances under stochastic evolutionary game conditions with the innovative Sixth Generation Ports (6GP) model, which emphasises digitalisation, sustainability, and strategic governance [43]. Becker et al. [44] underscores the necessity of integrating these models with empirical climate impact assessments, ensuring that adaptation strategies are grounded in realistic climate variability and sea-level rise scenarios. This combination enhances the resilience framework's applicability and effectiveness, enabling proactive measures and long-term planning. Governmental support and smart technology implementation are pivotal, facilitating efficient responses to environmental challenges while fostering sustainable development within the port sector [45].

Addressing resilience enhancement necessitates substantial investments in physical infrastructure and operational capabilities. Tailored investments are crucial, focusing on both immediate technological upgrades and long-term infrastructural resilience to address a broader range of climatic impacts. Key improvements include strengthening dockyard equipment and storage facilities to handle increased weather variability and integrating real-time climate data into port operations [46]. Adopting advanced information systems is vital for dynamic decision making, aligning operational responses with the unpredictable nature of climate threats [43].

The 6GP model emphasises integrating intelligent technologies such as Artificial Intelligence, the Internet of Things, and blockchain to improve operational efficiency and resilience [45]. These technologies facilitate data sharing and predictive analytics, allowing ports to anticipate and respond proactively to cyclone threats. Case studies from Gulfport, Mississippi, and Providence, Rhode Island, highlight the importance of implementing these technologies with well-defined governance structures, ensuring efficient operation and maintenance. This fact underscores the need to align technological upgrades with robust policy frameworks to enhance resilience across diverse geographic contexts [46].

Sustainability forms a cornerstone of the 6GP model and associated strategic alliance frameworks. Ports are encouraged to adopt green technologies such as electrifying cargo-handling equipment and solar-powered operations, reducing dependency on fossil fuels and aligning with global environmental targets [45]. Becker and Caldwell [46] provide valuable case studies where renewable energy initiatives and waste reduction programmes have effectively minimised operational costs and carbon footprints. These sustainable practices strengthen resilience and ensure compliance with evolving environmental regulations, contributing to broader ecological goals.

Effective governance and collaborative policies are integral to the success of adaptation strategies. The frameworks advocate for governance structures that promote resource sharing and collective resilience planning among port authorities, local governments, and industry stakeholders [43]. Governmental interventions are pivotal in facilitating these collaborations by providing subsidies and support for resource optimisation, ensuring operational continuity during disruptions.

Financing comprehensive adaptation measures requires innovative approaches, including public–private partnerships and green bonds, complemented by government subsidies [45]. These mechanisms address the substantial costs associated with infrastructure improvements and technological advancements. Stakeholder engagement, through transparent communication and participatory decision making, ensures broad support for adaptation measures, fostering an inclusive approach to resilience building.

The long-term success of resilience strategies hinges on robust monitoring and evaluation systems. Establishing key performance indicators, such as recovery times and economic impacts from climate threats, is essential for measuring intelligent technologies' effectiveness and sustainability initiatives' effectiveness. Continuous learning, supported by regular audits and stakeholder feedback, allows for the development of strategies to address evolving climate risks. This iterative process ensures the adaptability and relevance of resilience measures, reinforcing their alignment with operational realities [43,45].

6. Conclusions

This study has developed a comprehensive resilience framework to evaluate the vulnerability of five major Chinese ports—Shanghai, Tsingtao, Shenzhen, Xiamen, and Qinzhou—to tropical cyclones. The framework identifies critical operational risks and resilience gaps by integrating port efficiency metrics, multi-centrality network analysis, and the Borda count method. The findings highlight variations in adaptive capacities, with ports like Shenzhen and Xiamen demonstrating robust resilience, while Shanghai and Tsingtao face higher vulnerabilities due to their strategic roles within the global shipping network.

This study has several limitations. First, it focuses on tropical cyclone impacts, leaving other climate hazards, such as prolonged heatwaves and rising sea levels, for future exploration. Second, the geographic scope is limited to five Chinese ports, which may not capture the full diversity of climate resilience challenges across different regions. Additionally, while this study employs quantitative methods, incorporating real-time climate data and predictive technologies could enhance the framework's applicability and accuracy.

The targeted groups for this research include port authorities, policymakers, and stakeholders within the maritime logistics sector. This study provides actionable insights to guide infrastructure investments, policy development, and route diversification strategies by identifying specific vulnerabilities and resilience strategies. Practical implications include the necessity for ports like Shanghai and Tsingtao to prioritise adaptive measures to mitigate the cascading effects of climate disruptions on global trade.

Future research should broaden the framework to include additional climate hazards, expand the geographical focus, and incorporate innovative technologies like IoT-based monitoring systems and predictive modelling for early warning capabilities. Strengthening port resilience is essential for maintaining robust supply chains, securing economic stability and supporting the long-term sustainability of global maritime trade in the face of escalating climate risks.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/cli12120214/s1, Supplementary Document S1: List of shipping network ports; Supplementary Document S2: Information of survey respondents; Supplementary Document S3: Entropy weight method; Supplementary Document S4: Comprehensive port importance evaluation results by centrality measures and core–periphery analysis.

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