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Assessing climate risks and economic impacts on ports: a dual method approach

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ABSTRACT

This study presents a systematic approach to assessing the impacts of climate change on ports. First, it reviews the literature on port climate risk assessments and analyses disaster data from the International Disaster Database (EM-DAT). Second, based on this review, the study proposes the development of the Global Climate Risk Index for Ports (GCRIP), which integrates historical climate disaster data with network-based vulnerability indicators to create a standardised tool for assessing port climate risks. In this study, GCRIP is operationalised for container ports, as they play a critical role in global container supply chains and exhibit high network centrality and operational sensitivity to climate disruptions. While the index framework is conceptually extendable to other port types, its empirical application here focuses solely on container ports. Third, the study investigates the potential future economic impacts of seven specific climate threats: damaging cyclones, sea-level rise, warming trends/extreme temperatures/drought, heavy precipitation, snow/frost cover, and seasonal changes in fog events and wind speed and direction. It is based on container ports and employs a detailed, questionnaire-based approach. The findings provide insights for climate adaptation and mitigation strategies by identifying critical components of container port operations and analysing relevant environmental drivers and climate adaptation considerations.

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Climate risk index; container supply chains; economic impacts; climate threats; adaptation strategies

1. Introduction

Transportation and climate change have a significant mutual influence. While most studies have traditionally focused on the substantial impacts of transportation on climate change, there is a growing trend towards adaptation studies due to the increasing frequency of extreme events disrupting transportation networks (Yang, Lau, and Kanrak 2023; Yang, Lau, and Lei 2024). Assessing the climate risk levels of ports is essential for effective adaptation to climate change (Gu et al. 2025). Ports are critical

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nodes in global transportation networks, sustaining human living standards through economic activities that extend beyond local coastal zones, including energy and food supply. Any disruption or failure may remarkably impede the flow of goods and interrupt supply chains, both internationally and domestically (Mohsendokht et al. 2025). Therefore, evaluating climate risk and adapting to extreme events in ports is necessary for implementing cost-effective adaptation measures (Abbass et al. 2022).

Intergovernmental Panel on Climate Change (IPCC) has defined a few climate-related drivers for climate threats for coastal zone systems and transportation systems, including 'Heatwave/Drought/Wildfires,' 'Flooding,' 'Cold wave/Snow events,' 'Wind gust/ Storminess,' and 'Sea-level rise' (Pachauri et al. 2014). Scholars are working to measure the climate impacts of related extreme events and to analyse the corresponding adaptation solutions (Adshead et al. 2024). However, previous studies reveal significant weaknesses, which have theoretical implications yet are not well addressed in the current literature, including a lack of objective data in modelling, causing subjective bias in port climate risk assessment (e.g. Yang et al. (2018)) and port climate risk analysis following the pattern from a local to global level (e.g. M. C-P. Poo and Yang (2024)).

This paper aims to develop a two-tier methodology for the Global Climate Risk Index for Ports (GCRIP). In the first tier, a Global Climate Risk Index for Port States (GCRIPS) is developed using global climate-disaster data to identify the most significant climate threats and reflect the current state of the climate. In the second tier, port climate vulnerability is incorporated into GCRIPS to obtain the comprehensive GCRIP. Additionally, this study includes a detailed questionnaire-based approach to investigate the potential future economic impacts of various climate threats on ports. This dual approach enables standardised benchmarking of current climate threats across all ports worldwide and provides insights into future adaptation strategies. The paper is organised as follows: Section 2 provides a literature review and identifies research gaps. Section 3 details the two-tier methodology. Section 4 presents the results from the questionnaire-based approach. Section 5 discusses the findings, and Section 6 concludes the paper.

2. Literature review

Climate change and rapid urbanisation increase the risk of compound extreme weather events, presenting challenges for transport infrastructures. However, the current literature argues that there are few possible direct physical impacts of extreme weather events from a transportation perspective (Ji et al. 2022). It therefore calls for evidence-based analysis to identify climate threats and impacts on specific transport infrastructures, such as ports (Verschuur et al. 2023).

2.1. Climate threats and impacts

IPCC has identified the five most influential climate threats affecting transportation systems and port-centric logistics operations (M. C-P. Poo, Yang, Dimitriu, and Qu 2021; M. C-P. Poo, Yang, Dimitriu, Qu, Jin, et al. 2021). 'Heatwave/Drought/ Wildfires' can result in asphalt cracking, liquid asphalt migration and softening rutting, buckled railway, inclined span catenary sag, joint expansion failure, pavement blowups, road closure, more debris, and ground shrinking (Markolf et al. 2019; Meyer and Weigel 2011). 'Flooding' can disrupt the performance of roadways and overload drainage systems in ports and port-related transport networks. Within this context, flooding can wash out the roadways and roads linked to ports (Taylor and Philp 2015; Vajjarapu, Verma, and Allirani 2020). 'Cold wave/Snow events' can severely affect transportation services, increase damage from freeze-thaw cycles, and cause frequent landslides (Chen and Wang 2019; Vajda et al. 2014). 'Wind gust/Storminess' can suspend port operations and logistics services, especially in the port-shipping interfaces. Also, it can blow away the infrastructure, damaging roads and bridges (BEŠINOVIĆ 2020; Wang et al. 2020). Finally, 'Sea-level rise' can cause more frequent and intense flooding and land subsidence in low-lying areas. Road base and bridge support erosions are unavoidable (Brooks, Roberts, and Brooke 2020; Nazarnia et al. 2020).

2.2. Climate risk analysis

To understand the impact and risk of ports from climate change, scholars have conducted different risk assessments (Lam and Lassa 2017; M. C-P. Poo, Yang, Dimitriu, Qu, Jin, et al. 2021) and resilience analyses (Lam and Su 2015; M.-P. Poo and Yang 2020). The national or regional assessments are based on individual assessments with input from the simulation (Hoshino et al. 2016) and local quantitative and qualitative data collection (Mcintosh and Becker 2019; Yang et al. 2018). The corresponding studies have laid the foundations for enhancing resilience across various areas and ports, based on findings and recommendations for adaptation.

Previous studies often overlook crucial aspects when assessing port climate resilience. These studies often fail to incorporate objective climate-risk data, thereby introducing subjective bias. Moreover, they often neglect to consider both the port state's climate risk level and the vulnerability of ports within the context of global transport networks. An international standard for integrating climate risk and resilience assessments for ports is also lacking. Addressing these gaps would provide valuable insights into port climate resilience. Leveraging tools such as the Global Climate Risk Index could facilitate the analysis of weather-related loss events across countries and regions using evidence-based approaches and big data (Eckstein, Künzel, and Schäfer 2021). Furthermore, utilising extensive climate disaster data, including fatalities and economic losses, could help mitigate the subjective bias inherent in current climate risk analysis methods (Zhang et al. 2025). This approach could establish a routine global climate risk assessment and serve as a benchmark for international port resilience and adaptation to climate change.

2.3. Climate risk indices and data

The Centre for Research on the Epidemiology of Disasters (CRED) sets up the International Disaster Database (EM-DAT) (EM-DAT 2020). Climate change disasters are categorised as meteorological, hydrological, and climatological. Meteorological disasters encompass hazards associated with extreme weather events and short-lived atmospheric conditions that last from minutes to days (e.g. extreme temperatures, fog, and storms). Hydrological disasters are hazards caused by the movement, distribution, and occurrence of surface and subsurface water (e.g. floods, landslides, and wave action). Finally, climatological disasters result from long-term atmospheric changes, ranging from multi-decadal to intra-seasonal climate variations (e.g. Drought, glacial lake outbursts, and Wildfires).

A total of 12,112 related disasters were recorded in EM-DAT from 1972 to 2021, with details of damages, deaths, disaster types, countries, and regions used for further analysis. Some disaster reports provide more detailed information, such as specific locations and aid contributions. Tables 1-4 present the distribution of damages and deaths, along with the timescale and geographical regions (i.e. port states), for visualising the distribution of damages and deaths.

Table 1 shows the constant increase in damages to the meteorological sector. Although there has been a reduction in the hydrological and climatological sectors over the past two decades, the absolute damage values remain extremely high, underscoring the need to develop new approaches to climate risk analysis and prevention.

Table 2 presents the fluctuations in total deaths resulting from climate disasters across the three sectors. There have been different reductions in mortality in recent decades compared with the 70s. In the hydrological sector, the data show a gradual decline since 2011. In the meteorological and climatological sectors, a significant reduction is attributable to the state of global civilisation. Comparing the patterns of total estimated damages with those of total deaths, we observe different trends across the three sectors: as damages

Table 1. Total estimated damages in decades.

	Total estimated damages (in 000'US$ adjusted value)		
Type	Meteorological	Hydrological	Climatological
1971–1980	109176910	41980088	30697459
1981–1990	170051712 (+55.76%)	1.17E+08 (+179.77%)	66756221 (+117.46%)
1991–2000	364005701 (+114.06%)	3.95E+08 (+235.91%)	93116782 (+39.49%)
2001–2010	678391285 (+86.37%)	2.47E+08 (−37.40%)	59716712 (−35.87%)
2011–2020	866763053 (+27.77%)	4.29E+08 (+73.57%)	1.77E+08 (+195.68%)

Source: EM-DAT.

Table 2. Total deaths in decades.

	Total deaths		
Type	Meteorological	Hydrological	Climatological
1971–1980	57165	85489	122086
1981–1990	54220 (−5.15%)	49428 (−42.18%)	554664 (+354.32%)
1991–2000	217176 (+300.55%)	108661 (+119.84%)	4099 (−99.26%)
2001–2010	320176 (+47.43%)	66409 (−38.88%)	21815 (+432.20%)
2011–2020	51301 (−83.98%)	55692 (−16.14%)	950 (−95.65%)

Source: EM-DAT.

Table 3. Total estimated damage rations in regions (from 1971 to 2021).

Data Type	Total estimated damages		
	Meteorological	Hydrological	Climatological
Australia and New Zealand	41.65%	25.62%	32.74%
Caribbean	97.32%	1.13%	0.26%
Central America	82.02%	13.04%	4.71%
Central Asia	31.80%	63.17%	5.04%
Eastern Africa	60.70%	19.64%	19.66%
Eastern Asia	40.15%	52.69%	6.16%
Eastern Europe	11.59%	66.92%	21.49%
Melanesia	83.82%	11.89%	4.30%
Micronesia	99.67%	0.00%	0.33%
Middle Africa	1.19%	82.54%	16.27%
Northern Africa	7.04%	71.86%	21.10%
Northern America	79.90%	8.54%	11.56%
Northern Europe	53.62%	43.74%	2.64%
Polynesia	92.47%	3.58%	3.95%
Russian Federation	0.59%	99.41%	0.00%
South America	6.17%	61.63%	32.20%
South-Eastern Asia	31.86%	50.34%	17.76%
Southern Africa	21.43%	31.80%	46.78%
Southern Asia	25.39%	69.36%	5.19%
Southern Europe	20.22%	46.73%	32.40%
Western Africa	3.24%	51.84%	44.92%
Western Asia	39.05%	52.99%	7.96%
Western Europe	53.20%	45.39%	1.40%

Source: The international disaster database (EM-DAT).

Table 4. Total death ratios in regions (from 1971 to 2021).

Data Type	Total deaths		
	Meteorological	Hydrological	Climatological
Australia and New Zealand	21.51%	24.15%	54.34%
Caribbean	31.00%	0.00%	53.94%
Central America	20.71%	0.21%	79.08%
Central Asia	94.27%	0.00%	5.54%
Eastern Africa	2.53%	96.49%	0.98%
Eastern Asia	74.57%	3.66%	21.76%
Eastern Europe	3.51%	0.36%	96.13%
Melanesia	44.33%	4.94%	50.73%
Micronesia	0.00%	0.00%	100.00%
Middle Africa	43.96%	51.69%	1.60%
Northern Africa	3.71%	95.95%	0.34%
Northern America	11.84%	2.06%	86.10%
Northern Europe	3.50%	0.00%	96.50%
Polynesia	23.20%	0.00%	76.80%
Russian Federation	42.65%	0.00%	57.35%
South America	92.63%	0.36%	7.01%
South-Eastern Asia	12.82%	0.75%	86.35%
Southern Africa	63.33%	22.42%	14.25%
Southern Asia	37.10%	0.30%	62.59%
Southern Europe	5.21%	1.12%	93.66%
Western Africa	56.53%	0.21%	6.97%
Western Asia	81.47%	1.79%	16.74%
Western Europe	1.95%	0.07%	97.99%

Source: EM-DAT.

Table 5. Universal disaster severity Classification scheme (UDSCS).

Severity level	Fatality Range
UDSCS 0	F < 1
UDSCS 1	1 ≤ F < 10
UDSCS 2	10 ≤ F < 100
UDSCS 3	100 ≤ F < 1000
UDSCS 4	1000 ≤ F < 10,000
UDSCS 5	10000 ≤ F < 0.1M
UDSCS 6	0.1M ≤ F < 1M
UDSCS 7	1M ≤ F < 10M
UDSCS 8	10M ≤ F < 100M
UDSCS 9	100M ≤ F < 1B
UDSCS 10	1B ≤ F

Source: Caldera and Wirasinghe (2022).

increase, deaths decrease. It can also represent the improvements in disaster management measures over the past few decades, despite the ongoing effects of climate change. It provides a theoretical foundation for stimulating port climate risk analysis studies aimed at preventing climate disasters.

Tables 3 and 4 present the diversity of disaster consequences across regions of the Earth, with respect to economic and fatality impacts, respectively. It provides detailed data support for the proposed GCRIP modelling in Section 3. For example, Micronesia and Polynesia are primarily affected by meteorological disasters, whereas the Russian Federation is mainly affected by hydrological disasters. For death counts, the patterns differ again. Taking Micronesia and Polynesia as comparative examples, they have different splits in death counts in different sectors, even though they have similar damage. It illustrates the importance of addressing the diversity of climate vulnerabilities from two perspectives: climate threats and geographical locations (i.e. port states).

2.4. Research gap

Despite extensive research on climate threats and their impacts on transportation systems, significant gaps remain, particularly concerning ports. One major gap is the lack of a fixed formula or standardised methodology for assessing the economic impacts of various climate threats on port operations. Existing studies often rely on qualitative assessments or region-specific models that do not provide a universally applicable framework for economic impact analysis. This lack of standardisation hampers the ability to effectively compare and benchmark global climate risks across different ports.

Furthermore, studies are scarce that project and assess the levels of various climate threats for future timeframes. Most existing research focuses on historical data and current climate conditions, giving insufficient attention to future climate scenarios and their potential impacts on ports. This oversight limits the ability to develop long-term adaptation strategies and effectively prepare for future climate conditions.

To address these gaps, this study proposes a dual approach to quantify ports' current and future climate risks. First, developing GCRIP will integrate historical data to create a standardised tool for assessing port vulnerabilities. Second, a detailed questionnaire-based approach will investigate the potential future economic impacts of seven specific climate threats: damaging cyclones, sea-level rise, warming trends/extreme temperatures/

drought, heavy precipitation, snow/frost cover, and seasonal changes in fog events and wind speed and direction. By incorporating both historical data and future climate projections, this dual approach aims to provide a comprehensive and objective assessment of climate threats on ports, offering valuable insights for future adaptation strategies and mitigation efforts in global port systems.

3. Global climate risk index for ports

In this section, we outline the comprehensive methodology employed to develop GCRIP. It is designed to quantify ports' vulnerability to various climate threats, providing a standardised tool for assessing and comparing the global climate risks ports face.

3.1. Methodology

The first part of this two-tier GCRIP methodology involves developing GCRIPS at the port state level, which indicates the risk levels of all climate threats affecting ports in the states where they are located. The results at the port state level indicate the overall climate risk for ports, which will then be integrated with the climate vulnerability of all ports in the same country to distinguish their climate risk differences through GCRPI. The GCRIPS at a port state level is developed based on the GCRI (Eckstein, Künzel, and Schäfer 2021) but with significant changes to the methodology to enhance it within the port context. There are various assessments of global climate change, but it is challenging to provide such analysis for different ports due to data availability. The GCRI is calculated by Equation (1), in which Germanwatch has collected EM-DAT data for 20 years and taken the average value for the involved four parameters (i.e. Average losses in US$ (PPP) (AL), average losses per unit GDP in % (AAL), average fatalities (AF), and average fatalities per 100,000 inhabitants (AAF)). For example, in 2021, the data from 2000 to 2019 were collected for 227 countries ($N = 227$) to calculate AL, AAL, AF, and AAF for ranking the GCRI of each country by the Borda count method, with ratios for a country i, where it is an integer from 1 to 227.

$$\mathrm{Rank}_{\mathrm{GCRI}}(\mathrm{i}) = \mathrm{Rank}_{\mathrm{AL}}(\mathrm{i}) \div 6 + \mathrm{Rank}_{\mathrm{AAL}}(\mathrm{i}) \div 3 + \mathrm{Rank}_{\mathrm{AF}}(\mathrm{i}) \div 6 + \mathrm{Rank}_{\mathrm{AAF}}(\mathrm{i}) \div 3 \quad (1)$$

To develop the GCRIP at a port state level, the first difficulty is to classify and standardise the scope of natural disaster impacts, often presented in two forms: injuries and economic damages. Caldera and Wirasinghe (2022) have developed a regression model and described the relationships between fatalities, injuries, and damage by the following equation:

$$\mathrm{Fatalitiies} = \mathrm{Constant} + 0.03 \times \mathrm{Injurues} + 3.06 \times 10^{-8} \times \mathrm{Damage} \quad (2)$$

By Equation (2), the severity level of disasters can be defined by a value between 0 and 10 based on the number of fatalities and developed a Universal Disaster Severity Classification Scheme (UDSCS) as shown in Table 5.

The second difficulty lies in the aggregated risks from major climate threats affecting ports. To expand the GCRI into GCRIPS, data must be imparted to categorise the index ports. Five independent climate threats (i.e. j = 5) have been defined by M. C-P. Poo, Yang, Dimitriu, Qu, Jin, et al. (2021) as 'Heatwave/Drought/Wildfires,' 'Flooding,' 'Cold wave/Snow events,' 'Wind gust/Storminess,' and 'Sea-level rise.' In the aggregation process, it is rational to use the ratio of their (the five climate threats) impacts (Rj), being 'Warming trend/Extreme temperature/Drought/Wildfire' as 22.99% (R1); 'Extreme precipitation/Flooding' as 23.18% (R2); 'Snow cover/Cold wave/Snow events' as 15.13% (R3); 'Storminess/Wind gust' as 15.52% (R4); and 'Sea-level rise' as 23.18% (R5).

The third weakness of the GCRI, when applied to support the development of GCRIPS, is that it focuses on the severity of consequences and overlooks the occurrence frequency of one climate threat in a port state, particularly in terms of the two parameters (i.e. AL and AF). The severity level (UDSCSj) is revised to be combined with the frequency of corresponding disasters from 1972 to 2021 (fj) for each country (i) to better present the climate risk level of the jth climate threat in the ith port state through a new risk matrix (RMj) in Equation (3).

$$RM_{k,j}(i) = \left(UDSCS_{k,j}(i) + 1\right) \times \left(f_{k,j}(i)\right) \tag{3}$$

where k means one of the two parameters in Equation (1) (i.e. AL and AF); i represents a port state; and j is one of the five climate threats. Obviously, $RM_{k,j}(i)$ can be used to obtain $Rank_{k,j}(i)$ by counting their positions in the relevant ranking lists. The addition of the value 1 after UDSCS in Equation (3) is to avoid the negative effect on the accuracy of the result in the situation in which two disasters with two different consequences of less than 1 fatality (meaning UDSCS values are 0) and different frequencies are counted with the same risk level. Therefore, the GCRIPS of a port state can be obtained through Equation (4), in which AF (i.e. fatalities) and AL (i.e. loss) are combined through Equation (3), and their ratios (i.e. 1/6) are combined into a new ratio of 1/3. New Equation (4) has superiority over Equation (1) because compared to AAF and AAL (i.e. average consequence values taking into account frequency), AF and AL in Equation (1) are absolute consequent values, which have been updated into the combined AF in Equation (4) by the new addition of their frequencies in Equation (3). As a result, all three parameters in Equation (4) are based on both consequence severity and occurrence frequency.

$$Rank_{GCRIPS,j}(i) = Rank_{AF,j}(i) \div 3 + Rank_{AAF,j}(i) \div 3 + Rank_{AAL,j}(i) \div 3 \tag{4}$$

The corresponding disasters for these five types are divided and collected. For 'Heatwave/Drought/Wildfires,' total deaths and estimated losses are summarised from three disasters: heatwave, drought, and wildfires. For 'Extreme precipitation/Flooding,' flood, landslide, and mudslide data are summarised. For 'Snow cover/Cold wave/Snow events,' data on cold waves and severe winter conditions are used for representation. For 'Storminess/Wind gust' and 'Sea-level rise,' damaging cyclone, and sea-level rise data are used. Equation (5) summarises the insights from five areas to a single rank by the Borda count method. Therefore, the lower the multi-driver local climate change risk index (X), the greater the climate risk, and vice versa.

$$GCRIPS(i) = \sum Rank_{GCRIPS,j}(i) \times R_j \tag{5}$$

Finally, the obtained GCRIPS(k) represents the local climate vulnerability of the kth port, which quantifies the direct exposure and sensitivity of an individual seaport to climate hazards such as flooding and sea-level rise. This local index is then integrated with Vi,k, the network vulnerability of the kth port, to derive the overall GCRIP(k) in Equation (6). It is essential to note that Vi,k is derived solely from network analysis, also known as a multi-centrality assessment. It reflects the systemic or regional importance of a port within the entire shipping network, rather than its local climatic conditions. The purpose of this integration is to capture how local climate impacts on an individual port (GCRIPS) can propagate through the network depending on that port's structural position (Vi,k). The original Vi,k values for major container ports are obtained from M. C-P. Poo and Yang (2024) and Equations (7)–(21). A lower GCRIP value indicates a higher overall climate risk for the port.

In this study, container ports serve as the analytical unit, as they are a major component of global seaport operations and play a crucial role in international supply chains. Although both seaports and container ports are exposed to similar climate hazards, such as sea-level rise, storm surges, and extreme weather, container ports are particularly vulnerable due to their high network centrality, operational time sensitivity, and reliance on specialized equipment and digital systems (Becker et al. 2018; Ng et al. 2018; M. C-P. Poo and Yang 2024; Yang et al. 2018). Consequently, using container ports allows for a more precise assessment of how local climate vulnerability interacts with network-wide resilience in the global shipping system.

$$\mathrm{GCRIP(i,k)} = \mathrm{GCRIPS(k)} \times \mathrm{V_{i,k}} \tag{6}$$

Then, the importance of the ports in networks needs to be considered. Degree centrality is the first to be invented and calculated by the number of links connecting to a node, as shown in Equations (7) and (8). In-degree ($D(in)$) is the number of connections that point inward at a vertex, and out-degree ($D(out)$) is the number of connections that originate at a vertex and point outward to other vertices. The less the degree value of a port, the less it is connected to or from other ports, and vice versa.

$$D(in)_k = \sum\nolimits_h^P w_{hk} \tag{7}$$

$$D(out)_k = \sum\nolimits_j^P w_{kj} \tag{8}$$

N represents the total ports within an investigated network, w_{hk} represents the weighted link from h to k, and w_{kj} represents the weighted link from k and j. In-closeness ($C(in)$) and out-closeness ($C(out)$) of a port are computed by Equation (9) and Equation (10) by dividing the number of the port in the network, except for k ($P-1$) by the shortest path between k and other ports in the network.

$$C(in)_k = \frac{P-1}{D(in)_k} = \frac{P-1}{\sum_h^P w_{hk}} \tag{9}$$

$$C(out)_k = \frac{P-1}{D(out)_k} = \frac{P-1}{\sum_j^P w_{kj}} \tag{10}$$

Betweenness centrality (B) considers a port in relation to other port pairs, as illustrated in the diagram, showing the role of the port in the network. Since intermediate points control the linkage between these ports, the higher the betweenness of the ports, the more influential the ports are. It can be defined by adopting Equation (6) where $\mathrm{s, t}$ represents a port pair, $\mathrm{w(s, t|k)}$ is the number of times that s and t cross the port k with the shortest interval and $\mathrm{w(s, t)}$ is the total number of shortest paths between s and t.

$$B_k = \sum_{\substack{s, t \in P \\ s, t \neq k}} \frac{w(s, t|k)}{w(s, t)} \tag{11}$$

To measure the full effect and vulnerability of the investigated ports within a shipping network, this study combines all three centrality measures by employing a Borda Count approach. The Borda Count method can aggregate different centrality properties into a single rank while incorporating ease and visibility into the calculation process. The higher values calculated by Equations (7)–(11) result in higher ranks for ports. $R_{D(in)}, R_{D(out)}, R_{C(in)}, R_{C(out)}, R_B$ refer to the ranking position of all ports in the network by Equation (7)–(11), where the ranks for $D(in)_k, D(out)_k, C(in)_k, C(out)_k, B_k$ can be obtained independently. The count score $(S_{D(in)}(k), S_{D(out)}(k), S_{C(in)}(k), S_{C(out)}(k), S_B(k))$ is provided by the ranking order of every centrality for the k^{th} investigated port as shown in Equations (12) to (16).

$$S_{D(in)}(k) = P - R_{D(in)}(k) + 1 \tag{12}$$

$$S_{D(out)}(k) = P - R_{D(out)}(k) + 1 \tag{13}$$

$$S_{C(in)}(k) = P - R_{C(in)}(k) + 1 \tag{14}$$

$$S_{C(out)}(k) = P - R_{C(out)}(k) + 1 \tag{15}$$

$$S_B(k) = P - R_B(k) + 1 \tag{16}$$

The ranks of degree and closeness centrality measures involve two directions together. To ensure a fair contribution by degree, closeness, and betweenness centrality, a one-third count score of each centrality type is used for the result, according to Wu et al. (2019), as shown in Equation (17).

$$S_O(k) = \frac{S_D(k) + S_C(k) + S_B(k)}{3} \tag{17}$$

The new index, GCRIP, is designed to measure climate vulnerability by combining the local vulnerability index - GCRIPS(k) and the regional vulnerability index - $Y(\mathrm{i}, k)$. In addition, GCRIP is developed by jointly connecting GCRIPS(k) and $Y(\mathrm{i}, k)$ in Equation (18). In terms of the three datasets, $Y(\mathrm{i}, k)$ is from the multi-centrality assessment defined by M. C-P. Poo and Yang (2024). $\mathrm{GCRIPS(k)}_a$ is defined as an adaptability score and $X\mathrm{GCRIPS(k)}_v$ is defined as a vulnerability score in this manuscript in Equation (19) with reference to Briguglio (2010). The original local adaptability index $\mathrm{GCRIPS(k)}_o$ is defined by $\mathrm{GCRIPS(k)}_a$ subtracting by $\mathrm{GCRIPS(k)}_\mathrm{v}$ in Equation (19). The lowest local adaptability index $\mathrm{GCRIPS(k)}_{o,min}$ among all seaports under assessment, it is used to adjust all $\mathrm{GCRIPS(k)}_o$ to positive values and transform the data to GCRIPS(k) in Equation (20). The overall rank score $S_o(k)$, defined in Equation (19), is used in Equation (21). The maximum overall rank score among all seaports under assessment is used to normalise the scores into $Y(k)$.

$$\mathrm{GCRIP_{i,k}} = \mathrm{GCRIPS(k)} \times Y(\mathrm{i}, k) \tag{18}$$

$$\mathrm{GCRIPS(k)_0} = \mathrm{GCRIPS(k)}_a - \mathrm{GCRIPS(k)_v} \tag{19}$$

$$\mathrm{GCRIPS(k)} = 1 - \frac{\mathrm{GCRIPS(k)} - min(\mathrm{GCRIPS(1)}, \mathrm{GCRIPS(2)}, \ldots, \mathrm{GCRIPS(N)})}{2} \tag{20}$$

$$Y(k) = \frac{S_o(k)}{S_o(k)_{max}} \tag{21}$$

After defining GCRIP, Equations (7) to (21) can assess all 134 important seaports in Appendix 2. The ports are selected based on the population, and the entire selection process can be found in M. C-P. Poo and Yang (2024).

3.2. Result of the global climate change risk index for port states (GCRIPS)

The results are presented in Table 6, following the data input and analysis. First, Nepal and Afghanistan face the two highest risks to ports in climate change. It is because they are inland countries, and it can be understood that climate change affects their inland waterway drastically. Then, Bangladesh and Guatemala, commonly known as the victims of climate change, are ranked third and fifth. The complete list can be found in Appendix 1.

Table 6. Countries with the highest ranks in the global climate change risk index for ports states.

Country	GCRIPS	Rank
Afghanistan	43.473	1
Nepal	45.514	2
Bangladesh	48.213	3
Zimbabwe	49.317	4
Bolivia (Plurinational State of)	54.870	5
Guatemala	57.428	6
Somalia	58.175	7
India	60.178	8
Pakistan	61.720	9
Mozambique	63.268	10
United States of America (the)	64.013	11
Romania	64.441	12
Mongolia	64.443	13
Mexico	67.053	14
Paraguay	67.383	15
China	68.237	16
Peru	69.598	17
Chile	70.171	18
Burundi	72.650	19
South Africa	72.804	20

Equation (6) integrates the port climate vulnerability index with GCRIPS to imply the use of GCRIP. The GCRIP index is presented in Appendix 2. Compared to GCRIPS and Vi,k, the new GCRIP improves the index by including more extreme events. The corresponding index is universal and can include all countries worldwide, including those with inland waterway ports.

For instance, previous studies on Vi,k have only concerned two climate threats (i.e. flooding and sea-level rise). As a result, ports in countries such as the United States of America, the Republic of Korea, and Brazil, which encounter various climate risks, including storms, heatwaves, and coldwaves, have significantly raised their GCRIP values in ranking. Those in the states facing severe issues with flooding, such as China and Pakistan, have a drop in GCRIP ranking.

The historical data analysis in Section 3 lays a crucial foundation for understanding the long-term trends and patterns of climate impacts on ports, providing a context for the more forward-looking assessment in Section 4. By examining historical data, we can identify the critical vulnerabilities and risks that have affected ports, providing insights into the effectiveness of past adaptation measures. This retrospective analysis is instrumental in informing the design and focus of the future climate risk questionnaire in Section 4. The questionnaire builds on these insights to project the potential impacts of climate change on ports in 2025, 2030, and 2050. Together, these sections create a comprehensive analysis that combines historical evidence with expert forecasts to provide a holistic view of the evolving climate risks faced by global shipping networks. This integrated approach underscores the need for adaptive strategies informed by historical trends and future projections to ensure robust planning and resilience in the face of climate change.

4. A questionnaire for future climate risk in ports

4.1. Methodology

The primary objective of this questionnaire is to assess the impact of various environmental drivers on container supply chains concerning damage to properties, injuries and loss of lives, environmental damage, and cost of recovery for the years 2025, 2030, and 2050. This assessment aims to assess the potential future risks and challenges posed by climate change to the maritime industry. To achieve the objectives of this study, we employed an online survey method to gather data from a selected group of experts in port operations and container supply chains. An online survey enables efficient data collection from geographically dispersed respondents while ensuring high participant convenience.

The survey targeted 83 experts well-versed in port operations, logistics, and supply chain management. These experts were selected for their experience and expertise in addressing the impacts of environmental change on maritime operations. The questionnaire comprises 12 main questions on economic analyses, each focusing on environmental drivers and their economic impacts. The questions are structured to cover four key areas: damage to properties, injuries and loss of lives, environmental damage, and cost of recovery. Respondents were asked to evaluate the impacts for each area based on predefined scale definitions for 2025, 2030, and 2050. The environmental drivers considered in this survey include damaging cyclones, sea-level rise, warming trends/extreme temperatures/droughts, heavy precipitation, snow cover/frost cover, seasonal changes in fog events, and seasonal changes in wind speed and direction, which are identified as crucial climate threats for ports (M. C-P. Poo, Yang, Dimitriu, Qu, Jin, et al. 2021).

The impacts are assessed using a five-point scale ranging from negligible to catastrophic, with specific definitions provided for each category. The scale definitions are tailored to the context of each question to ensure clarity and consistency in responses. For damage to properties, the scales range from catastrophic (damage valued at more than $2.4 million) to negligible (damage valued lower than $120,000). For injuries and loss of lives, the scales range from catastrophic (multiple fatalities) to negligible (less than a minor injury). For environmental damage, the scales range from catastrophic (regional impact with reparative efforts exceeding 10 years) to negligible (no detectable damage). For the cost of recovery, the scales range from catastrophic (cost exceeding $12 million) to negligible (cost less than $12,000). The full details of the questions can be found in Appendix 3.

The collected data will be analysed using statistical methods to observe trends and patterns. Each impact category is assigned a numerical value (Catastrophic = 5, Critical = 4, Major = 3, Minor = 2, Negligible = 1). By quantifying the responses, we can observe the economic impact changes over different time scales (2025, 2030, and 2050). Additionally, we will compare the results of seven climate threats (damaging cyclones, sea-level rise, warming trends/extreme temperatures/drought, heavy precipitation, snow cover/frost cover, seasonal changes in fog events, and seasonal changes in wind speed and direction).

4.2. Result

This subsection presents a detailed analysis of the impacts of seven critical climate threats on ports, focusing on four key areas: damage to properties, injuries and loss of life, environmental damage, and the cost of recovery. This evaluation spans three distinct periods: 2025, 2030, and 2050. The analysis reveals how each climate threat influences these areas over time, utilising data from a comprehensive survey of experts in port operations and logistics. By quantifying the impacts of climate change on a scale from negligible to catastrophic, this section provides insights into the evolving risks and challenges it poses to the maritime industry, facilitating informed decision-making and strategic planning to enhance resilience and adaptation.

In Table 7, the assessment of the impact of climate threats on property damage yields significant insights for the years 2025, 2030, and 2050. In 2025, the average impact score is around 2.82, indicating minor to moderate damage. Snow cover/frost cover poses the highest threat, with an average impact score of 3.05. By 2030, the average impact slightly increases to approximately 2.85, with snow cover and frost cover remaining major

Table 7. Questionaire results of the damage to properties.

Year	Damaging cyclone	Sea-level rise	Warming trend/ Extreme temperature/ Drought	Heavy precipitation	Snow cover/ Frost cover	Seasonal changes in fog events	Seasonal changes in wind speed and direction	Average
2025	2.26	2.79	2.81	2.71	3.05	2.88	3.26	2.82
2030	2.91	2.67	2.74	2.81	3.00	2.76	3.07	2.85
2050	2.79	2.55	2.41	2.83	2.98	2.93	2.93	2.77

concerns. However, by 2050, the average impact will decrease slightly to around 2.77. During this period, seasonal changes in fog events had a greater impact, with an average score of 2.93.

Table 8 shows that the impacts of climate-related threats on injuries and mortality remain relatively stable across the three assessment periods. In 2025, the average impact score is 2.97, indicating predominantly minor injuries with occasional fatalities. This level remains broadly consistent in 2030, with a slightly lower average score of 2.81, suggesting no substantial escalation in human safety risks over the medium term. By 2050, the average score decreases slightly to 2.79, indicating a modest reduction in the severity of injuries and fatalities. Overall, the results suggest that while climate-related hazards continue to pose persistent risks to human safety at ports, their relative impacts are expected to stabilise or slightly decline over time, potentially reflecting improved safety management and adaptation measures.

As shown in Table 9, climate threats are expected to cause minor to moderate environmental damage across all three periods. In 2025, the average impact score is 2.97, reflecting moderate but manageable environmental impacts. This increases slightly to an average score of 3.00 in 2030, indicating a temporary intensification of environmental pressures, particularly from heavy precipitation, fog events, and changes in wind patterns. By 2050, the average score decreases to 2.93, suggesting some degree of environmental improvement or successful adaptation over the longer term. These findings indicate that environmental impacts may peak in the medium term before gradually stabilising, highlighting the importance of sustained environmental protection and adaptation strategies in port operations.

Table 10 presents the estimated cost of recovery associated with climate-related damage. In 2025, the average impact score is 2.82, indicating moderate recovery costs for ports. This value increases slightly to 2.85 in 2030, suggesting rising financial pressures associated with climate adaptation and post-disaster recovery in the medium term. By 2050, the average score declines to 2.80, implying potential improvements in resilience, mitigation effectiveness, or cost efficiency in recovery processes. Overall, the

Table 8. Questionnaire results of the injuries and loss of lives.

Year	Damaging cyclone	Sea-level rise	Warming trend/ Extreme temperature/ Drought	Heavy precipitation	Snow cover/ Frost cover	Seasonal changes in fog events	Seasonal changes in wind speed and direction	Average
2025	2.52	3.05	3.12	2.86	3.00	2.93	3.29	2.97
2030	2.26	2.60	2.88	2.93	2.71	3.05	3.24	2.81
2050	2.57	2.69	2.45	2.83	2.86	3.05	3.10	2.79

Table 9. Questionnaire results of the damage to the environment.

Year	Damaging cyclone	Sea-level rise	Warming trend/ Extreme temperature/ Drought	Heavy precipitation	Snow cover/ Frost cover	Seasonal changes in fog events	Seasonal changes in wind speed and direction	Average
2025	2.79	2.62	2.62	3.07	3.21	3.17	3.29	2.97
2030	2.45	3.12	2.95	2.93	3.00	3.12	3.43	3.00
2050	2.45	2.95	2.88	2.86	3.00	3.02	3.31	2.93

Table 10. Questionnaire results of the cost of recovery.

Year	Damaging cyclone	Sea-level rise	Warming trend/ Extreme temperature/ Drought	Heavy precipitation	Snow cover/ Frost cover	Seasonal changes in fog events	Seasonal changes in wind speed and direction	Average
2025	2.48	2.55	2.81	2.81	2.98	3.00	3.14	2.82
2030	2.81	2.38	2.64	3.12	3.00	2.91	3.12	2.85
2050	2.81	2.31	2.45	2.88	3.10	3.02	3.00	2.80

results suggest that while recovery costs are expected to increase in the near to medium term, long-term investments in resilience may help moderate financial burdens in the long term.

Tables 6–10 identify seven critical climate threats and evaluate their impact on four key areas: damage to properties, injuries and loss of lives, environmental damage, and cost of recovery. They encounter three periods: 2025, 2030, and 2050. The impacts of damaging cyclones remain relatively consistent across the three assessment periods, with average scores indicating minor to moderate effects on property damage, injuries and loss of life, environmental damage, and recovery costs. Sea-level rise continues to represent a persistent concern, exhibiting moderate impacts across all four assessed dimensions throughout the study period. Warming trends, extreme temperatures, and droughts also show moderate impacts, with a slight reduction in perceived severity by 2050. Heavy precipitation displays a stable impact profile over time, with consistently moderate effects across all categories. Snow cover and frost cover are identified as major contributors to property damage, particularly in 2025 and 2030, although their impacts decline marginally by 2050. In contrast, the impacts of seasonal changes in fog events increase over time, especially in relation to property damage and environmental harm. Seasonal changes in wind speed and direction exhibit moderate impacts across all assessed areas, with a small reduction in severity by 2050.

5. Discussion

The findings from this study highlight the significant impacts that various climate threats have on ports and container supply chains. This research comprehensively assesses current and future climate risks by utilising a dual approach, comprising the development of GCRIP and a detailed questionnaire-based analysis.

The GCRIP methodology incorporates historical disaster data from EM-DAT and integrates it into a standardised tool for assessing port vulnerabilities at the port state level. This index is designed to capture the multifaceted nature of climate risks by combining the severity and frequency of climate-related disasters. However, interpretation of the results requires caution. For instance, countries such as Nepal and Afghanistan, both landlocked and with minimal or no port infrastructure, appear to rank among the highest in terms of port-related climate risk. Nepal lacks major inland ports, and Afghanistan has only a small, limited-use river port facility. These results may reflect broader national climate vulnerability rather than actual risks to port infrastructure. Similarly, while countries such as Bangladesh and Guatemala are well known for their vulnerability to climate change and have port systems exposed to natural hazards, the inclusion of inland countries suggests a need to refine the index. Future assessments should distinguish between seaports, river ports, and dry ports to ensure that climate risk evaluations are context-specific and infrastructure-relevant.

The second tier of the dual approach provides a forward-looking assessment of the potential economic impacts of seven climate threats on ports for the years 2025, 2030, and 2050, based on expert judgement from port operations and logistics specialists. The results indicate that snow cover and frost cover are expected to generate the highest levels of property damage in the near to medium term (2025 and 2030), followed by a modest reduction by 2050. Seasonal changes in fog events are projected to become increasingly influential over time. Impacts on injuries and loss of life remain relatively stable across all periods, with average scores indicating predominantly minor injuries and occasional fatalities, alongside a slight decline in severity by 2050. Environmental damage is assessed as moderate and persistent, with a temporary intensification in 2030, followed by improvement by 2050. Recovery costs are projected to increase marginally by 2030 and then decrease by 2050, suggesting potential gains from improved resilience, mitigation measures, and adaptive capacity in port systems.

This dual approach, which combines historical data with expert assessments, provides a robust framework for understanding the current state and future projections of climate risks to ports. It underscores the need to address immediate threats while planning for long-term adaptation and resilience. Integrating GCRIP with the questionnaire-based analysis offers a comprehensive view of climate risks. The GCRIP provides a baseline understanding of current vulnerabilities, while the questionnaire-based analysis projects future economic impacts, enabling a dynamic assessment that evolves with changing climate conditions. This integrated approach ensures that ports develop targeted and effective adaptation strategies that balance immediate needs with future resilience planning.

6. Conclusion

This study presents a dual approach to assessing climate risks on ports, combining the GCRIP with a detailed questionnaire-based analysis. The GCRIP offers a standardised tool for evaluating current container port vulnerabilities, while the questionnaire provides insights into the potential future economic impacts of various climate threats. The findings underscore the significant and evolving risks of climate change, highlighting the need for robust adaptation strategies.

Future research should focus on refining the GCRIP methodology to incorporate more granular, container-port-specific data and on exploring the effectiveness of various adaptation measures. Monitoring climate threats and their impacts on container port operations will be essential for updating risk assessments and ensuring effective adaptation over time.

In summary, this study provides valuable insights into the climate risks facing global container ports and offers a comprehensive framework for assessing and mitigating these risks. By identifying critical climate threats and assessing their potential economic impacts, the research lays the groundwork for developing robust adaptation strategies that enhance the resilience of global port systems, thereby ensuring their continued operation and contribution to the global economy amid increasing climate uncertainty.

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