
Determinants of Climate Change Adaptation in Contemporary Seaports

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Abstract:

Purpose: The aim of this article is to review research on seaport adaptation to climate change and analyze how the approach to this issue has evolved in the literature. The study covers both the identification of port threats and vulnerabilities and the actions taken in response to changing climatic conditions.

Design/Methodology/Approach: The article uses a literature review on seaport adaptation to climate change. The analysis includes studies relating to climate threats and port vulnerability, adaptation planning, investment decisions, and the implementation of adaptation measures.

Findings: The literature shows a shift in the way seaport adaptation is approached. Initially, research focused primarily on climate hazards, exposure, and infrastructure vulnerability. More recent studies have increasingly addressed the planning of adaptation strategies. Adaptive capacity plays an important role in determining whether knowledge of climate risk is translated into concrete adaptation actions.

Practical Implications: Climate risk assessment should be linked to long-term port development planning, and future climate conditions should be taken into account both when modernizing existing facilities and planning new investments.

Originality/Value: This article organizes the development of research on seaport adaptation, focusing on the transition from identifying threats and vulnerabilities to planning and implementing adaptation measures. Adaptive capacity is used as a framework for linking knowledge about climate risk with the port's ability to take action.

Keywords: Adaptive capacity, climate change, port resilience, seaport.

JEL codes: L91, R42, Q54.

Paper type: Literature review.

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1. Introduction

The development of modern seaports is linked to their continuous evolution. This evolution is a key topic in the literature, with authors pointing to the development of ports from a traditional transshipment function towards more complex logistics hubs (Pettit and Beresford, 2009). Salmonowicz (2012) describes this change as a shift from a transshipment point to a distribution, logistics, and information center.

Regionalization and supply chain integration subsequently expanded the functional boundaries of port operations to include inland terminals, transport corridors, and distribution systems (Notteboom and Rodrigue, 2005; Panayides and Song, 2009; Pettit and Beresford, 2009).

Expanding the functional scope of port operations also means greater dependence on changes occurring in their environment. Modern ports operate as complex systems, in which entities with different goals, resources, and competencies operate. This structure means that the port's ability to respond to changes in its environment depends, among other things, on the following factors: on technological, financial and human resources and management methods (Notteboom, 2016).

The scope of changes requiring port adaptation is clearly evolving. In recent years, their operation has been shaped, among other things, by the growth in ship size and requirements for infrastructure availability and navigational support (Notteboom, 2016). In turn, economic and logistical disruptions, such as those related to the COVID-19 pandemic and the financial crisis of 2008/2009, impact cargo flows and the organization of transport networks (Notteboom *et al.*, 2021).

Geopolitical tensions, such as the Red Sea crisis in 2023, are further examples of disruptions affecting the dynamics of shipping and logistics, impacting the operation of modern seaports (Notteboom and Haralambides, 2025). At the same time, ports are subject to technological changes related to digitalization and sustainable development (Belmoukari *et al.*, 2023), pressure to reduce emissions (Fadiga *et al.*, 2024) and decarbonization (Karaś, 2024), the implementation of which requires the cooperation of many stakeholder groups (Alamouch *et al.*, 2024; Grima *et al.*, 2020).

Adaptive pressures are therefore multidimensional and result from both sudden disruptions and long-term changes. Exposure to a threat alone does not determine the manner and scope of a port's response. Ports operating in similar conditions may react differently due to resources, infrastructure, financing options, access to technology, competencies, organization and management, and relationships with external entities.

Literature provides insight into the various types of changes occurring in ports and the ways in which they respond to them, and adaptation also depends on the ability to mobilize resources and undertake and coordinate the actions necessary to

implement change. In the context of port operations, resilience refers to the ability to anticipate, prepare for, respond to, and cope with these uncertainties, threats, and problems (Ekpinar *et al.*, 2023), while the response to disruptions leads to the concept of adaptive capacity (Thalassinos *et al.*, 2015; Thalassinos and Michalopoulos 2005).

This allows for the separation of the pressure itself from the ability to respond to it. This distinction is also important because the issue of port adaptation is addressed in several partially separate research streams. The literature on port resilience analyses the ability of ports to prepare for, respond to, and recover from disruptions, with contemporary approaches encompassing not only infrastructure but also organisational, technological, and environmental aspects (Tsoulfas, 2026).

Climate change is a particular source of pressure. Ports' location at the interface between sea and land makes them directly exposed to sea level rise, floods, storms, and other extreme weather events. The effects of these events impact port infrastructure and facilities, and consequently, the continuity of operations and the stability of supply chains (Grudniewski *et al.*, 2025). Identifying climate threats and the ability to prepare ports for their impacts are becoming increasingly challenging.

The aim of this article is to review and synthesize existing research on seaport adaptation to climate change, with particular emphasis on climate threats, port vulnerability, and the actions and conditions enabling adaptation.

Research Questions:

- *RQ1: What threats and impacts of climate change on seaports have been identified in existing research?*
- *RQ2: How does the literature address the transition from climate risk identification to planning and implementing adaptation measures?*

2. Literature Review: Adaptation of Seaports

The need for adaptation arises when a change in the environment disrupts the existing operating conditions of a port or imposes new demands on it. Pressures affecting ports vary in pace and predictability, as some accumulate over years, while others take the form of sudden disruptions with a short response time. The source of change, its scale, pace, and the ability to recognize it in advance are important factors in assessing adaptive capacity.

In the case of seaports, adaptability is additionally linked to the specific nature of their development. Expanding port functions is accompanied by the dispersion of resources and responsibilities among entities participating in the area and surroundings. This means that adaptive capacity should not only refer to a single element, such as infrastructure, but to the broader port system and its ability to

maintain key functions under changing and uncertain conditions. From this perspective, adaptive capacity can be considered one of the mechanisms contributing to port resilience.

The literature on seaport adaptation to climate change is constantly evolving, as knowledge about climate threats and their potential impact on port infrastructure and operations grows. Research encompasses the identification of threats, exposures, and vulnerabilities of infrastructure, as well as ways for ports to adapt to future climate conditions. Numerous scientific publications feature analyses related to adaptive decision-making and the implementation of strategies and actions.

Earlier studies on port preparedness for climate change were conducted by Becker *et al.* (2012), who analyzed the knowledge, perception of potential risks, and planning activities among port managers. In their study, the authors also emphasized the importance of considering future climate conditions in planning long-term port infrastructure and the need for collaboration between the scientific community and practitioners.

The issue of adaptation was further expanded upon by Becker *et al.* (2013), who pointed out that ports' response to climate change can encompass both infrastructure solutions and planning and organizational measures. The authors also emphasized the need for a broader approach to adaptation, encompassing planning, investment, and operations, as well as collaboration between public and private entities.

Ng *et al.* (2013), based on case studies of four Australian ports, analyzed port preparedness for climate change. The results indicated that seaports are aware of the significance of the problem and emphasized the inevitability of climate change impacts in the coming future. The authors noted that adaptation is not limited to actions undertaken within ports but also involves the hinterland.

Subsequent studies increasingly related climate threats to specific infrastructure elements, including Chhetri *et al.* (2015), who developed a 3D model to assess the vulnerability of seaports to sea level rise. The modeling results allowed for the identification of at-risk assets under various climate scenarios, and the authors indicated the possibility of developing adaptation strategies.

Regarding new infrastructure, they also emphasized the need to consider resilience to future climate conditions at the design, specification, and asset purchasing stages. Adaptability therefore depends on both the modernization of existing infrastructure and the decisions made when planning new investments.

The importance of infrastructure planning is also emphasized by Mutombo and Ölçer (2017), who analyzed the exposure of port infrastructure to climate hazards as a starting point for adaptation planning. The authors emphasize the diversity of risks within a port and the need to identify which infrastructure components and the

connections between the sea and land are vulnerable to specific threats. From an adaptive capacity perspective, this means that the ability to adapt infrastructure depends on the port-sea-land location.

In turn, the publication by Touzinsky *et al.* (2018), who studied the behavior of the ports of Charleston, Savannah, and Jacksonville during Hurricane Matthew in 2016 based on AIS data, demonstrated changes in port system performance parameters during subsequent phases of the disruption, from preparation, through the event, to post-storm recovery. These results shift the focus from the mere existence of infrastructure to its ability to maintain basic port functions and restore service after the disruption.

One area of research in the literature concerns barriers that limit the ability to move from threat recognition to adaptive action. McLean and Becker (2021), surveying representatives of North Atlantic ports in the United States, identified seven categories of barriers influencing decision-making regarding adaptation to climate change and extreme weather events. The results indicate that threat recognition is insufficient to implement adaptation measures if decision-makers lack adequate resources.

Panahi *et al.* (2020) summarized the knowledge by reviewing research on port adaptation to climate change based on an analysis of 61 publications published over 15 years. They examined the evolution of research on port adaptation to climate change.

The authors concluded that research remained largely in its early stages of development and emphasized the need to shift it toward action and implementation. They also emphasized the importance of collaboration and the need to bridge the existing gap between problem recognition and adaptation.

Similarly, a study of adaptation strategies for the Port of Kaohsiung identifies infrastructure components vulnerable to the effects of extreme weather events. The most prominent challenge presented in the study, which port authorities faced during natural disasters, was coping with damaged infrastructure, including damaged buildings and quay structures, and siltation and debris blocking key waterways (Yang and Ge, 2020).

In this case, infrastructure adaptability refers to the ability to reduce the vulnerability of specific assets whose damage or loss of functionality disrupts port processes while minimizing losses.

León-Mateos *et al.* (2021) proposed and validated the Port Resilience Index for the port of A Coruña (Galicia). The analysis demonstrated the particular vulnerability of port infrastructure, facilities, and the operating environment to the effects of climate change, including sea level rise, stronger waves, increased salinity, and increased

intensity of extreme weather events. The authors' study shows that the condition and resilience of infrastructure influence the ability to maintain port processes under threat.

The issue of adaptation also applies to investment decisions. Xia and Lindsey (2021) indicate that ports operating under uncertainty face threats related to climate change, but also investments in port capacity. The study indicates that adaptation decisions are linked to the development of the port and its future operation.

Zheng *et al.* (2022) analyzes the importance of adaptation decisions. Using a model of two competing ports, the first being the initiator and the second the follower, the authors answer questions about ports' decisions regarding adaptation investments and which strategy – confidentiality or public disclosure of information about damage caused by natural disasters is more beneficial.

In their study, Fernandez-Perez, Losada, and Lara (2024) propose a framework for adapting port infrastructure to climate change, combining risk assessment with the identification of adaptation needs and possible actions. The research was conducted as part of a case study of the port of Llanes on the northern coast of Spain, where the main climate risk threats were identified, indicating adaptation measures such as the construction of breakwater fortifications or the addition of a protective layer.

Xia *et al.* (2024) expands on the economic dimension of adaptation, pointing out that climate disasters are increasingly causing damage to seaports, necessitating investment in adaptation to increase resilience. Their study is based on a game-theoretic model that encompasses two seaports and analyzes ports' strategic decisions regarding capacity investment, adaptation, and port fee setting, taking into account competitiveness and uncertainty related to climate change.

Recent research increasingly focuses on actual implemented actions, while Jenkins *et al.* (2025) analyzes the adaptation actions of UK ports, pointing to growing climate-related threats. In their study, the authors analyzed 150 examples of implemented, planned, and potential adaptation actions in response to 11 identified climate-related threats, such as storms, floods, and sea level rise. Of the identified actions, 94 have already been implemented, with the results indicating that larger UK ports are adapting primarily through incremental actions.

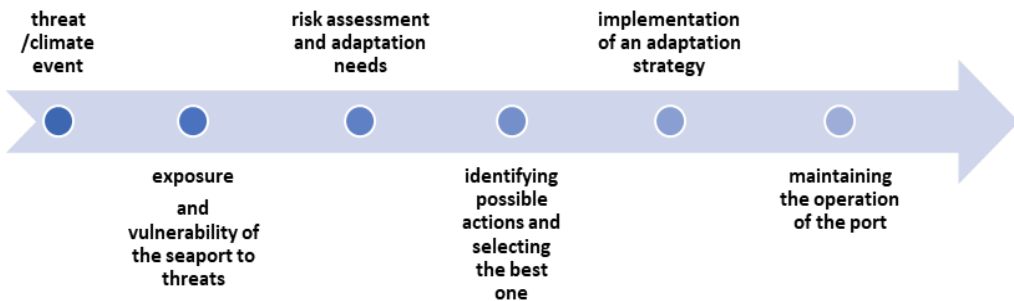
3. Discussion

A literature review indicates a gradual expansion of research on seaport adaptation to climate change. This issue is no longer considered solely through the lens of infrastructure exposure to specific climate threats, and increasing importance is being attached to knowledge about threats and vulnerabilities, which should be used to inform mitigation strategies.

Port adaptation encompasses infrastructure-related dimensions, as well as spatial and location-related, investment-related, organizational, and decision-making aspects.

Based on this review, the relationship between climate risk identification and the implementation of an adaptive response can be illustrated.

Figure 1. *Climate threats and seaport adaptation.*



Source: *Based on a literature review.*

The presented diagram does not constitute a model of the adaptation process, but rather highlights the relationships resulting from the analyzed literature. Knowledge about the threat becomes important when it allows us to determine which infrastructure elements and port functions may be disrupted and what risks such disruption poses.

The next challenge is identifying potential actions and implementing an appropriate strategy – including resources, knowledge, and competencies.

4. Conclusions

This approach is consistent with the adaptation planning framework in line with the PIANC guidelines for port and waterway adaptation planning. The guidelines cover defining the context, utilizing climate information and scenarios, assessing vulnerability, and identifying and evaluating possible adaptation options (PIANC, 2020).

From a management perspective, the challenge is therefore to leverage the results of such an assessment in actual decisions regarding port maintenance, modernization, and development. However, the latest PIANC guidelines highlight the business case for adaptation investments and the uncertainty surrounding future climate conditions as barriers to action.

A central concept in contemporary research is adaptive capacity. In the context of seaports, it can be understood as the ability to translate identified climate risks into the preparation and implementation of adaptation measures.

The literature also indicates that adaptive capacity involves not only responding to the observed impacts of extreme climate events, but also taking future climate conditions into account when designing, modernising and developing ports.

Adaptive capacity should be regarded as one of the mechanisms for building resilience, while adaptation refers to the actions through which this capacity is used in response to changing climate conditions.

When interpreting the review results, it is important to consider the significant variation in the conditions in which modern seaports operate. Exposure to climate hazards, the nature and vulnerability of infrastructure, the scale of operations, and economic and institutional conditions vary among ports, so adaptive solutions that are effective in one case may not be applicable in another.

This limits the possibility of formulating universal adaptation strategies and highlights the importance of the spatial and geographical context in selecting responses to climate risk.

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