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SEA-LEVEL RISE AND EMERGING MARITIME ROUTES: PATHWAYS FOR GLOBAL PORT ADAPTATION

ELEVAÇÃO DO NÍVEL DO MAR E ROTAS MARÍTIMAS EMERGENTES: CAMINHOS PARA A ADAPTAÇÃO GLOBAL DE PORTOS

Rafael Ferraz dos Santos [1], Victor Hugo Souza de Abreu [2], Andréa Souza Santos [3]

[1 2 3] Programa de Engenharia de Transporte, COPPE–UFRJ, Rio de Janeiro, RJ, Brazil.
[1]* rafael.ferraz@pet.coppe.ufrj.br [2] victor@pet.coppe.ufrj.br [3] andrea.santos@pet.coppe.ufrj.br
***Autor Correspondente: Santos, R. F.**

ABSTRACT: In the coming decades, maritime transport will face profound changes driven by climatic and economic factors. Sea-level rise, emphasized by the IPCC Sixth Assessment Report (AR6), poses severe risks to coastal infrastructures, especially seaports, which are critical nodes in global supply chains. Addressing these challenges requires urgent adaptation measures, such as expanding operational areas, retrofitting existing facilities, and planning new resilient infrastructures. The potential emergence of alternative maritime routes, resulting from Arctic melting and shifting trade dynamics, reinforces the importance of adaptive port governance. This article explores the intersection between sea-level rise and global maritime routes, highlighting how port adaptation strategies can sustain trade flows and anticipate geopolitical and logistical shifts. It proposes guidelines for resilient port development, grounded in climate risk assessment and international experiences, while identifying research gaps and institutional barriers. Ultimately, adaptation is framed as both risk reduction and an opportunity for sustainable, efficient, and integrated ports.

KEYWORDS: Port adaptation; Maritime routes; Sea-level rise; Coastal infrastructures; Global trade.

RESUMO: Nas próximas décadas, o transporte marítimo enfrentará profundas mudanças impulsionadas por fatores climáticos e econômicos. A elevação do nível do mar, enfatizada pelo Sexto Relatório de Avaliação (AR6) do IPCC, representa sérios riscos para as infraestruturas costeiras, especialmente os portos marítimos, que são nós críticos nas cadeias de suprimentos globais. Enfrentar esses desafios exige medidas urgentes de adaptação, como a expansão das áreas operacionais, a modernização das instalações existentes e o planejamento de novas infraestruturas resilientes. O potencial surgimento de rotas marítimas alternativas, resultante do degelo do Ártico e da mudança na dinâmica comercial, reforça a importância da governança portuária adaptativa. Este artigo explora a interseção entre a elevação do nível do mar e as rotas marítimas globais, destacando como as estratégias de adaptação portuária podem sustentar os fluxos comerciais e antecipar mudanças geopolíticas e logísticas. Propõe diretrizes para o desenvolvimento portuário resiliente, baseadas na avaliação de riscos climáticos e em experiências internacionais, ao mesmo tempo em que identifica lacunas de pesquisa e barreiras institucionais.

Em última análise, a adaptação é enquadrada como redução de riscos e uma oportunidade para portos sustentáveis, eficientes e integrados.

PALAVRAS CHAVE: Adaptação portuária; Rotas marítimas; Elevação do nível do mar; Infraestruturas costeiras; Comércio global.

1. INTRODUCTION

Port areas have historically played a pivotal role in civilizational development, sustained by the movement of people and the exchange of ideas facilitated by maritime transport. From the earliest trade hubs to the modern global economy, port cities have served as cultural and economic centers that underpinned the consolidation of major nations. The endurance of these infrastructures has always depended on their capacity to foster commercial expansion, reduce transport distances, and establish routes that are both economically viable and logistically efficient (Ghosh, 2022).

In recent decades, the relevance of ports has intensified with the acceleration of global economic integration, the liberalization of trade under the World Trade Organization, and the opening of the Chinese economy. Projections suggest that by 2050 the global container trade could increase by approximately 73 percent, reaching around 2.2 billion units annually. Current capacity, however, will be insufficient to meet growing demand as early as 2030, making the expansion and modernization of port infrastructure indispensable to ensure efficiency in cargo handling. Estimates indicate that the demand for new port areas may reach between 2,510 km² and 5,054 km² by mid-century (Hanson; Nicholls, 2020). This structural pressure is compounded by the challenges of climate change, which amplifies the vulnerability of coastal infrastructure and threatens to trigger systemic crises in essential sectors such as food security, creating shortages and intensifying global trade disruptions (Dos Santos; De Abreu; Santos, 2024).

The growing frequency and severity of extreme weather events further heighten the urgency of adaptation. Traditionally designed according to fixed extreme-water-level thresholds, port infrastructures are increasingly exposed to climatic variability beyond their original design standards. The Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) projects a sustained acceleration of sea-level rise during the twenty-first century, even under moderate emission scenarios. The combined effects of ice-sheet and glacier melt, ocean thermal expansion, and other feedback processes could drive a global mean sea-level rise of 0.6 to 1.1 meters by 2100, exceeding the estimates of the Fifth Assessment Report. Relative sea level, influenced by local subsidence, uplift, and climatic oscillations, intensifies the occurrence and magnitude of extreme events (Nicholls *et al*., 2014; Oppenheimer *et al*., 2019; Hanson; Nicholls, 2020; IPCC, 2021). In this context, ports must not only adapt their physical infrastructure to mitigate risks from sea-level rise, but also anticipate the evolving dynamics of global maritime trade (Oliveira; Savio, 2015).

Regional analyses using Shared Socioeconomic Pathway (SSP) scenarios reveal significant differences in how sea-level rise and infrastructure demand will unfold globally. In regions such as Canada and the former Soviet Union, the need for expanded port areas is most pronounced under SSP5-8.5, due to both projected growth in commodity trade and heightened exposure to climate impacts. By contrast, regions such as Central and South America show more stable expansion needs across scenarios (IPCC, 2021). These variations underscore how climate change is directly linked to the reconfiguration of maritime routes, reshaping not only trade flows but also geopolitical dynamics and climate policy.

One of the most striking transformations is the rapid melting of Arctic sea ice, which opens new navigational possibilities. Rising average temperatures of 2°C to 4°C above pre-industrial levels are expected to extend the navigability of passages such as the Northwest Passage and the Northern Sea Route, lengthening their operational seasons and potentially redefining global shipping flows (Mudryk *et al*., 2021). While these shifts offer opportunities for shorter and more cost-effective trade routes, they also pose critical governance and environmental challenges. Geopolitical disputes, such as those between Russia and Canada, highlight the strategic tensions surrounding Arctic navigation (Boylan, 2021). Furthermore, the expansion of traffic in this fragile region demands robust international regulations to mitigate environmental impacts and ensure navigational safety (Chircop, 2007). Climate change thus acts simultaneously as a driver of new maritime opportunities and as a source of heightened risks, requiring integrated governance responses to guarantee long-term viability.

Against this background, the objective of this article is to analyze the implications of climate change for global maritime routes and their repercussions on port infrastructure. Specifically, it seeks to (1) assess the impacts of sea-level rise on existing port infrastructures, (2) examine the opportunities and risks associated with the reconfiguration of maritime routes, with a particular focus on the Arctic and the North Sea, and (3) propose guidelines for governance and sustainability policies that can strengthen port resilience in the face of a changing climate.

2. METHODOLOGY

This study adopts a systematic approach to identify and analyze the scientific literature addressing the relationship between climate change, maritime routes, and port infrastructures. The methodology was designed to ensure transparency, reproducibility, and thematic alignment with the research objectives.

2.1 SEARCH STRATEGY

The Scopus database was selected as the primary source because of its extensive coverage of peer-reviewed journals in transport, environmental, and maritime studies. Search terms were defined in English to capture the most relevant international contributions. Boolean operators were applied to combine climate-related expressions ("climate change", "global warming") with maritime terms ("shipping routes", "maritime routes", "maritime pathways", "maritime transportation").

Table 1. Search strategy

Aspect	Description
Search topic	TITLE-ABS-KEY(("climate change" OR "global warming") AND ("shipping routes" OR "maritime routes" OR "maritime pathways" OR "maritime transportation"))
Database	Scopus
Inclusion criteria	Peer-reviewed publications, thematic relevance, preference for studies published in the last 15 years
Qualification criteria	Scientific quality, methodological consistency, applicability to port infrastructure and maritime trade

Source: Authors' elaboration

The initial search returned 340 documents. A two-stage screening process was conducted. In the first stage, duplicates and documents clearly outside the thematic scope were removed. In the second stage, full-text examination was performed to confirm relevance to maritime routes and climate change. After this process, 336 articles were retained, while 4 were excluded (1.76%). Excluded studies included research on gravel-beach morphodynamics, cyclone tracking methodologies, invasive marine species, and plastic pollution. While environmentally significant, these topics were not directly aligned with the specific focus on maritime transport and port infrastructure under climate change.

2.2 ANALYTICAL APPROACH

The final dataset of 336 articles was examined through bibliometric analysis and qualitative thematic review. Bibliometric indicators included frequency of keywords, temporal distribution of publications, and geographic distribution of authorship. This dual approach made it possible to map quantitative trends while also interpreting qualitative themes emerging in the literature.

Among the retained studies, 302 articles (88.8%) primarily address climate change, often through terms such as "climate change", "global warming", "emissions", and “carbon”. A total of 111 articles (32.6%) focus on maritime routes, with emphasis on the Arctic region and the potential of alternative passages. Meanwhile, 269 articles (79.1%) discuss port infrastructure, resilience, and sustainability, reflecting growing concern with adaptation to sea-level rise, extreme weather events, and environmental regulation.

The overlap among these thematic categories demonstrates that climate change is not an isolated variable but rather a structuring element in the transformations affecting maritime transport and port development. This reinforces the importance of interdisciplinary research that not only advances understanding of these challenges but also supports the development of integrated strategies for resilient and sustainable maritime transport systems.

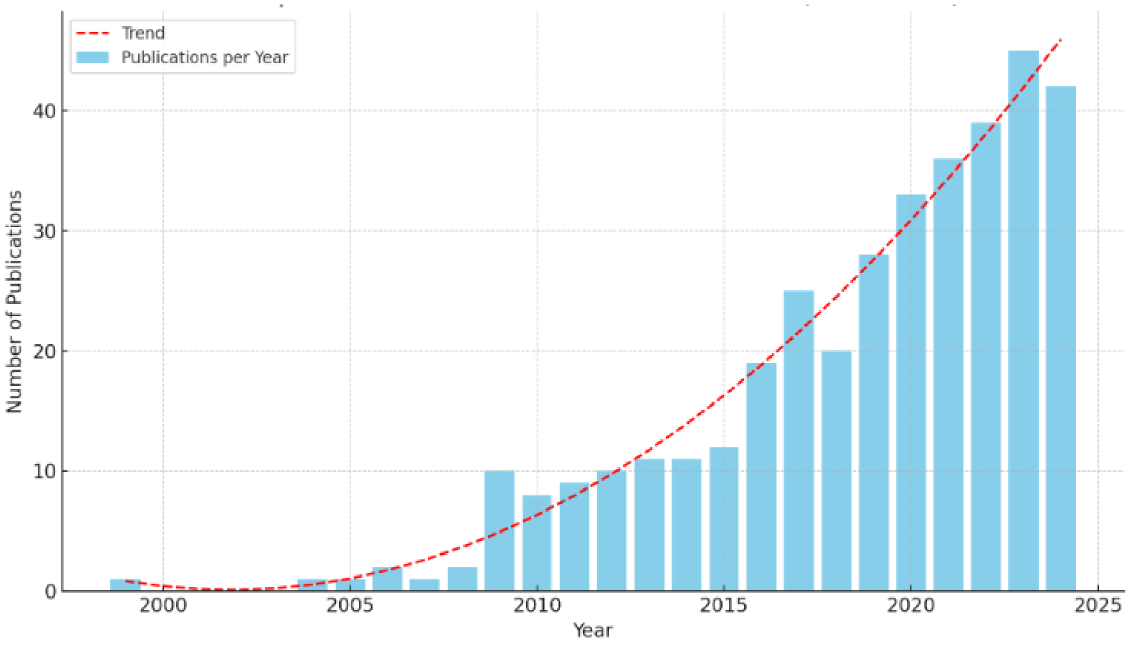
3. RESULTS AND DISCUSSION

The bibliometric results provide a comprehensive overview of the emerging trends and patterns in the scientific literature addressing climate change, maritime routes, and port infrastructure. The compiled database consists of a diverse collection of scientific articles that reflect both the breadth and the depth of contemporary research in these areas.

Figure 1 illustrates the temporal evolution of scientific publications related to the subject over recent decades, highlighting research trends within the field. The temporal distribution of publications, adjusted to the period between 1999 and 2024, reveals a marked increase in the number of works published, particularly from 2016 onwards. This period may be regarded as a turning point, when discussions on climate change, maritime routes, and port infrastructure began to occupy a progressively prominent position in academic literature.

In numerical terms, the year 2010 recorded nine publications, corresponding to 2.65% of the total articles analyzed. By 2020, this number rose to 29 publications, equivalent to 8.53% of the total. Growth continued in 2021 with 35 publications (10.29%) and in 2022 with 38 publications (11.18%). The year 2023 registered the highest number of publications, with 45 articles, representing 13.24% of the total. These figures not only illustrate the maturation and consolidation of the field but also demonstrate the intensification of research and interdisciplinary collaboration in areas that are critical for global sustainability and resilience.

Figure 1. Temporal evolution of scientific publications (1999–2024)

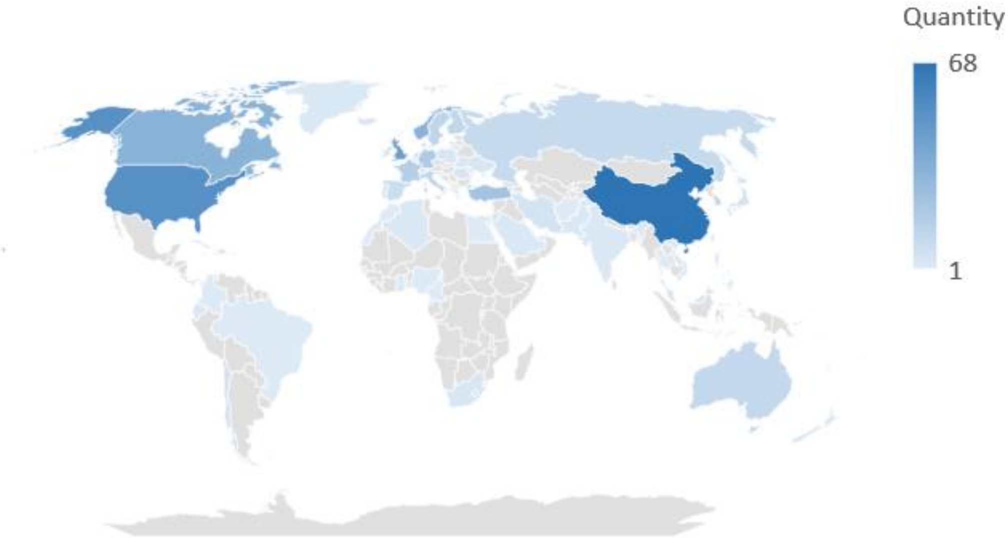


Source: prepared by the authors.

Figure 2 shows the geographical distribution of publications, evidencing a substantial concentration of research on sea-level rise and new maritime routes in Asia, North America, and Europe. China, with 68 publications, leads this scenario, followed by the United States (52) and the United Kingdom (44). This predominance in scientific production not only reflects the role of these countries as global maritime powers but also signals their growing concern with the threats posed by climate change, particularly sea-level rise. The significant presence of these nations in research on sea-level impacts is closely tied to the vulnerability of their densely populated coastal regions, which host essential infrastructures for their economies (IPCC, 2021).

China's case is particularly noteworthy, as many of its major coastal cities, such as Shanghai and Tianjin, face high risks due to their proximity to the sea and the concentration of port activities that are vital to the global economy. Similarly, the United States, with its Atlantic and Pacific coasts as well as economically critical areas such as the Gulf of Mexico, remains highly exposed to the risks of sea-level rise, which could disrupt maritime trade and threaten local populations. The United Kingdom, as an island nation, also has vulnerable coastal zones where the intensification of climate change may directly affect maritime trade routes and transport infrastructure (IPCC, 2021).

Figure 2. Leading countries in number of publications on the subject.



Source: prepared by the authors.

Furthermore, the dominance of these countries in research on new maritime routes is directly associated with the growing interest in exploring trade pathways emerging from Arctic ice melt, such as the Northern Sea Route, which may profoundly alter global transportation and trade dynamics. The study and monitoring of these transformations are essential to anticipate the economic and social consequences of sea-level rise, particularly in regions of vital importance for international trade and for the economies of these maritime powers (Pizzolato *et al*., 2016).

China, for instance, has increasingly expressed interest in Arctic routes, driven by the potential to significantly shorten transit times between Asia and Europe compared to traditional routes through the Suez Canal. This interest is embedded in a broader Chinese strategy to expand its influence in global maritime trade through the Belt and Road Initiative, which seeks to establish new trade corridors and strengthen economic linkages between Asia, Europe, and beyond. The inclusion of Arctic routes within this initiative reflects China's strategic vision of harnessing climate change to reshape the map of global trade, thereby ensuring greater control and participation in emerging maritime routes (Brzezinski; Bartosik, 2019).

Norway has a long-standing historical and geographical interest in Arctic routes. Its proximity to the Arctic region and deep-rooted maritime tradition make it a natural leader in research on the implications of climate change for these routes. In the United States, research on Arctic passages is motivated by both environmental concerns and strategic interests. The Arctic is becoming a space of growing military and commercial interest for the U.S., which maintains the world's largest fleet of icebreakers and a long Arctic coastline in Alaska. Finally, the United Kingdom, with its robust maritime tradition and strong presence in the scientific field, has directed significant efforts to investigate the implications of climate change on maritime routes, with a particular focus on the Arctic region. The UK's interest in these routes is intrinsically tied to its consolidated position as a global maritime power, as well as its commitment to international leadership in environmental and sustainability issues (Humpert; Raspotnik, 2012).

On the other hand, the uneven distribution of publications between the Global North and the Global South highlights stark disparities in scientific production and access to research resources. In contrast, Global South nations such as Brazil, South Africa, and India display significantly lower levels of contribution. Nevertheless, it is essential to recognize that despite their lower scientific output, these countries are among the most vulnerable to sea-level rise and its subsequent consequences for coastal infrastructures (Moser *et al*., 2012). This reality underscores the urgent need to intensify research in these regions to deepen understanding of their specific challenges and to develop adaptive solutions that are contextually appropriate and effective. This perspective strongly reinforces the relevance of the present study, which seeks to address existing knowledge gaps and contribute to strengthening the resilience of port infrastructures in regions most vulnerable to climate change.

3.1 PORT INFRASTRUCTURE AND GLOBAL MARITIME ROUTES UNDER CLIMATE CHANGE

This chapter presents a systematic and comprehensive review of the challenges and strategies related to port adaptation and expansion in response to sea-level rise, the interplay between infrastructure, geopolitics, and sustainability in the Northern Sea Route, and governance frameworks for enhancing port resilience under climate change. Sea-level rise directly threatens port infrastructure, demanding interventions such as quay elevation, flood barriers, and advanced monitoring technologies. The integration of natural ecosystems and sustainable land-use planning is also fundamental to climate adaptation.

The Northern Sea Route (NSR) has gained prominence due to Arctic ice melt, reducing transit times between Asia and Europe while also generating environmental and geopolitical challenges. The increase in maritime traffic along this passage requires effective regulatory mechanisms and sustainable infrastructure capable of minimizing ecological impacts while ensuring the route's economic viability. At the same time, the resilience of ports to climate change depends on robust governance, with cooperation between governments and the private sector to strengthen infrastructure, mitigate risks, and promote the decarbonization of port operations. These strategies are essential for ensuring both the competitiveness and sustainability of ports in the global maritime system.

3.2 PORT ADAPTATION AND EXPANSION IN THE CONTEXT OF SEA-LEVEL RISE

Port infrastructure plays a central role in the global economy and has undergone significant expansion in recent decades. Projections suggest that the demand for port capacity will continue to grow, requiring not only the expansion of existing areas but also the modernization of facilities to meet the challenges posed by sea-level rise while sustaining operational standards (Dos Santos; De Abreu; Santos, 2025). Estimates indicate that, by 2050, the land area required for port handling may be two to four times larger than in 2010, depending on the scenario considered. Under a high-demand scenario with no effective climate mitigation, the demand may reach 5,054 km², while under a scenario of regionalized production of green energy, the demand could be as low as 2,510 km². Global investments for port adaptation and expansion are projected to range between USD 223 and 768 billion by 2050, with most resources directed to new construction. Adaptation of existing facilities to sea-level rise accounts for at most 6% of these total costs (Hanson; Nicholls, 2020).

Such projections, which vary according to demand growth and mitigation effectiveness, can be summarized in Table 2. The table illustrates the estimated port land requirements and investment costs under different scenarios, highlighting the sharp contrast between expansion needs and the relatively small share of resources dedicated to adapting existing facilities.

Table 2. Projected port land requirements and investment costs under different scenarios (2050)

Scenario	Port land required (compared to 2010)	Estimated demand (km²)	Investment range (USD billion)	Share of costs for adapting existing facilities
High demand, no effective climate mitigation	4x larger	5,054 km²	768	≤ 6%
Regionalized green energy production	2x larger	2,510 km²	223	≤ 6%

Source: Adapted from Hanson and Nicholls (2020); Dos Santos, De Abreu and Santos (2025).

The growth of international trade is directly associated with population expansion and economic activity (Keck *et al.*, 2018). Projections suggest that global freight demand could increase three to sevenfold by 2050 (IMO, 2015), while container throughput is expected to rise by 73% over the same period, reaching 2.2 billion units annually (OECD/ITF, 2017). Current port capacity will be insufficient to accommodate this increase, requiring substantial investments in infrastructure and operational efficiency (ADB, 2010; OECD, 2011; OECD/ITF, 2016). The redistribution of maritime trade and the impacts of sea-level rise add further pressure to port modernization. While the adaptation of existing facilities has been widely discussed (Asariotis *et al.*, 2018), the magnitude of climate impacts calls for more comprehensive strategies. Hanson and

Nicholls (2020) emphasize that expansion costs will likely far exceed adaptation costs for already established facilities. In this context, climate policy will play a decisive role in shaping trade conditions and defining infrastructure requirements.

Historically, changes in maritime trade have been addressed through modernization of transport methods, such as container standardization, which improved efficiency in cargo handling and optimized the use of port space (Dos Santos; De Abreu; Santos, 2024). These advances underscore the need to integrate technological innovations into port expansion strategies. However, such initiatives must go beyond replication of existing patterns, incorporating solutions tailored to the challenges imposed by climate change (Hanson; Nicholls, 2020). Given the inevitability of sea-level rise, it is essential that port planning integrates updated projections and improved methodologies to mitigate future risks. Studies such as Thoresen (2014) indicate that, while partially adequate, current practices still fail to fully account for the magnitude of climate challenges (PIANC, 2020; Toimil *et al*., 2020). Moreover, the costs associated with advanced handling systems and protective structures remain underestimated, as highlighted by McCarron *et al.* (2018).

In addition, ports must be understood as strategic logistics hubs that connect maritime routes to land-based transportation systems, serving as vital nodes of global supply chains (Obasi *et al*., 2024). Port performance directly influences logistics reliability and costs, while delays, inefficiencies, and bottlenecks undermine competitiveness. To meet these challenges, port planning requires a systemic and long-term approach aligned with national logistics policies, multimodal networks, and urban development strategies (Hanjra *et al*., 2017). The incorporation of environmental sustainability, social responsibility, and corporate governance into port planning further enhances legitimacy and competitiveness under increasingly demanding regulatory environments (Xu, 2017).

3.3 INFRASTRUCTURE, GEOPOLITICS, AND SUSTAINABILITY ALONG THE NORTHERN SEA ROUTE

The steady reduction of Arctic ice coverage has reconfigured maritime navigation, generating both new opportunities and complex challenges for trans-Arctic shipping. The Northern Sea Route (NSR), in particular, emerges as a promising alternative to traditional trade lanes such as the Suez Canal, enabling Asia-Europe connections with up to 40% reductions in travel time (Liu; Kronbak, 2010). This logistical potential has attracted growing interest from nations such as China, South Korea, and Japan, all seeking to reduce costs and geopolitical risks associated with conventional routes (Kirgizov-Barskii, 2021).

The NSR’s accessibility could strengthen European ports in the North Sea, such as Rotterdam, Hamburg, and Antwerp, positioning them as strategic hubs for Asia-

Europe trade. Countries like Norway and the United Kingdom may also consolidate their logistical relevance, leveraging the reconfiguration of shipping flows to attract investment and enhance port infrastructure (Kirgizov-Barskii, 2021). Geopolitically, the NSR reduces Europe's dependence on the Suez Canal, thereby mitigating risks linked to blockades and instabilities in the Middle East (Bayirhan; Gazioğlu, 2021). This shift alters strategic routes traditionally under strong U.S. influence and makes the NSR a geopolitical alternative of growing significance.

Although the NSR lies entirely within Russia's Exclusive Economic Zone (EEZ), its governance is consolidated under strict national control, supported by heavy investment in port infrastructure and icebreaker fleets. By contrast, the Northwest Passage (NWP), located across the Canadian archipelago, remains subject to unresolved legal disputes, as it crosses the EEZ of multiple states including Canada, the United States, and Denmark, hindering the establishment of a unified regulatory framework (Boylan, 2021). Russia currently enforces tariffs and regulations on NSR traffic regardless of international objections, whereas Canada has not fully consolidated authority over the NWP, creating uncertainties for maritime operators and potential investors. This regulatory asymmetry compromises the commercial attractiveness of the NWP, particularly in the absence of international consensus.

To clarify these contrasts, Table 3 presents a comparative overview of the NSR and the NWP, highlighting their opportunities, governance structures, and associated risks.

Table 3. Comparative overview of Arctic maritime routes (NSR vs. NWP)

Aspect	Northern Sea Route (NSR)	Northwest Passage (NWP)
Geographic location	Russian Arctic coast, within Russia's EEZ	Canadian Arctic archipelago, overlapping multiple EEZs
Travel time reduction	Up to 40% Asia–Europe	Shorter than Panama/Suez for some routes, but less consistent
Governance	Strictly controlled by Russia; tariffs and regulations imposed	Unresolved legal disputes; Canada claims control, but contested by U.S. and Denmark
Infrastructure	Significant Russian investment in ports and icebreaker fleets	Limited infrastructure; underdeveloped support facilities
Geopolitical role	Strengthens Russia–China strategic cooperation; reduces dependence on Suez	Potential U.S.–Canada axis; politically sensitive sovereignty disputes
Commercial viability	Growing but dependent on geopolitical stability and climate variability	Weakened by lack of legal clarity and infrastructure
Environmental risks	Oil spills, ecosystem disruption, GHG emissions; increasing traffic pressure	Similar ecological vulnerability, compounded by fragile ecosystems and legal disputes

Source: Authors' elaboration based on Liu and Kronbak (2010); Boylan (2021); Bayirhan and Gazioğlu (2021).

In recent years, the Arctic's geopolitical relevance has also drawn renewed U.S. interest. The Trump administration publicly expressed strategic ambitions toward both Canada and Greenland, the latter an autonomous territory under Danish sovereignty, given their potential roles in shaping new maritime routes and expanding U.S. influence in the region. This geopolitical realignment reflects the Arctic's increasing value not only as a space for trade and shipping but also as an arena for power projection and resource control.

Despite potential economic benefits, full utilization of the NSR faces considerable challenges. Arctic and North Sea port infrastructure is not yet prepared to accommodate a major increase in maritime traffic, and the required investments remain uncertain, largely due to geopolitical tensions (Vicentiy, 2021). While the governance of the NSR is relatively stable under Russian authority, the NWP's governance depends on multilateral cooperation, making its future viability more uncertain (Boylan, 2021).

Growing traffic in the Arctic also raises environmental concerns, as increased vessel activity heightens risks of oil spills, disruption of marine ecosystems, and greenhouse gas emissions, thereby threatening Arctic biodiversity (SHARAPOV, 2023). Extreme weather conditions and ice variability further impose operational risks, necessitating specialized vessels and raising logistical costs (Babin; Lasserre; Pic, 2019). Ultimately, the future of these Arctic routes will depend on balancing infrastructure investment, international regulatory agreements, and the adoption of sustainable practices to minimize environmental risks.

The dynamics of the Northern Sea Route are also connected to broader global maritime strategies, particularly China's Belt and Road Initiative (BRI). The BRI integrates strategic ports such as Gwadar, Hambantota, Piraeus, Mombasa, Doraleh, and Chancay into global trade networks, reinforcing China's leadership in maritime connectivity (Hussain; Sargana, 2023; Li; Chen; Grydehøj, 2020). These ports are not only logistical hubs but also instruments of geopolitical influence, often supported by long-term concessions and financial mechanisms. However, they share a common feature: heightened vulnerability to climate change, including sea-level rise and intensifying storms (UNCTAD, 2020). This suggests that adaptation in the BRI is not a local concern but a strategic dimension of global port governance, offering lessons for Arctic governance as well (Moramudali, 2020; Papadopoulos, 2023).

3.4 GOVERNANCE AND SUSTAINABILITY FOR PORT RESILIENCE UNDER CLIMATE CHANGE

Climate change imposes growing challenges on port infrastructures, requiring not only physical adaptation but also new governance approaches (De Abreu *et al.*, 2024). The International Maritime Organization (IMO) plays a pivotal role in this process, particularly through the Polar Code, which establishes safety and environmental risk mitigation standards for navigation in polar waters. In addition to IMO regulations, governance efforts are shaped by the Arctic Council, a forum that brings together the eight Arctic nations and Indigenous peoples' representatives to promote cooperation on maritime safety, scientific research, and environmental regulation. With rising economic and geopolitical competition, however, doubts persist regarding the Council's capacity to ensure effective governance, particularly in light of Russia's unilateral actions in the NSR and the absence of international consensus over the NWP (Boylan, 2021).

The complexity of these governance arrangements can be better understood through a comparative overview. Table 4 highlights the main international frameworks, their objectives, and their current limitations in addressing the dual challenges of climate change and maritime competition.

Table 4. Governance frameworks and challenges for port resilience under climate change

Framework / Actor	Main Objectives	Geographic Focus	Current Limitations
International Maritime Organization (IMO) – Polar Code	Safety and environmental standards for polar waters	Arctic and Antarctic navigation	Limited enforcement capacity; not designed for large-scale commercial expansion
Arctic Council	Cooperation on safety, research, environmental protection; Indigenous participation	Arctic governance	Consensus-based; weakened by geopolitical tensions and unilateral actions
National authorities (Russia, Canada, U.S., EU states)	Control of Arctic passages (NSR, NWP); infrastructure development; security	Exclusive Economic Zones (EEZs) and territorial waters	Conflicting claims; tariffs and regulations often contested; lack of harmonization
Port master plans and national logistics policies	Forecasting demand, guiding investment, ensuring multimodal integration	National and regional port systems	Highly uneven across countries; implementation gaps in the Global South
Global South cooperation and climate justice initiatives	Capacity building, financing, South-South exchange	Vulnerable regions (e.g., Brazil, South Africa, India)	Scarcity of resources; reliance on external funding; limited global visibility

Source: Authors' elaboration based on IMO (2017), Boylan (2021), Xu (2017), Moser *et al.* (2012).

If Arctic routes become widely used alternatives to the Suez and Panama Canals, a new dynamic of geopolitical competition could intensify, with Russia and China promoting the NSR on one side and the United States and Canada defending the NWP on the other (Boylan, 2021). Such a scenario could undermine multilateral agreements and increase the challenges of achieving sustainable governance in the Arctic.

Beyond the Arctic, the debate on governance and sustainability in ports requires a systemic approach. Ports must be planned not only as physical infrastructures but also as institutions embedded in national logistics policies, multimodal networks, and urban development processes (Hanjra *et al*., 2017). Strategic tools such as port master plans enable demand forecasting, investment guidance, and coordination across different levels of government and logistics actors. Integrating sustainability principles, social responsibility, and corporate governance ensures legitimacy and provides competitive advantages under increasingly demanding markets (Xu, 2017). This broader framework expands the scope of governance discussions beyond technical adaptation, aligning them with societal expectations and global sustainability goals.

Equally important, governance must address global asymmetries in scientific production and adaptive capacity. While Global North countries dominate research and innovation in port adaptation, Global South nations such as Brazil, South Africa, and India remain highly vulnerable to climate risks despite their lower scientific output. Addressing these imbalances requires not only financial and technical support but also recognition of South-South cooperation as a legitimate pathway for advancing port resilience (Moser *et al*., 2012). This perspective aligns with the broader principle of climate justice, emphasizing that the burden of adaptation should not reinforce existing inequalities but instead foster equitable and inclusive solutions.

4. FINAL CONSIDERATIONS

The transformations imposed by sea-level rise and the reconfiguration of maritime routes represent one of the most pressing challenges for the twenty-first century. Ports, as strategic nodes of global trade, stand at the intersection of climate risk and geopolitical realignment, requiring not only technical adaptation but also integrated governance capable of anticipating systemic changes. The evidence examined in this study confirms that sea-level rise, projected by the IPCC AR6 to accelerate throughout the century, directly threatens port infrastructure through inundation, erosion, and recurrent extreme events. Simultaneously, the emergence of Arctic passages, particularly the Northern Sea Route, points to a possible reshaping of global shipping flows, with profound implications for trade costs, transit times, and geopolitical influence.

The bibliometric review highlighted the consolidation of this theme in international literature, particularly in countries of the Global North, where research and innovation advance at a faster pace. However, it also revealed persistent asymmetries, with Global South nations contributing less despite being among the most vulnerable. This gap reinforces the urgency of strengthening research agendas, technical cooperation, and

South-South initiatives to build locally appropriate solutions that recognize the principles of climate justice.

From a strategic perspective, adaptation should not be understood solely as a reactive response to risks but also as an opportunity to design ports that are more resilient, efficient, and sustainable. Guidelines for adaptation must combine structural measures—such as quay elevation, protective barriers, and monitoring technologies—with systemic strategies that integrate ports into multimodal logistics, national development plans, and international regulatory frameworks. Equally, governance must move beyond isolated port management and embrace cooperative mechanisms that engage governments, private operators, and civil society, ensuring legitimacy and long-term effectiveness.

By framing adaptation within the dynamics of emerging maritime routes, this study demonstrates that ports are not passive victims of climate change but rather active agents in shaping the geography of future trade. The capacity to anticipate risks, invest in resilient infrastructure, and participate in global governance debates will determine which ports consolidate their strategic role in the new maritime order. The findings also point to critical research gaps: the need for refined economic assessments of adaptation costs, the development of climate-resilient financing models, and the strengthening of regulatory instruments that address both environmental and geopolitical risks.

Ultimately, adaptation in ports should be seen as a pathway to reconfigure the very foundations of global trade in line with sustainability and equity. Ports that embrace resilience not only safeguard their operational continuity but also contribute to a broader transformation in which maritime transport becomes a driver of sustainable development. The integration of climate science, infrastructure planning, and international cooperation is therefore indispensable to ensure that global trade routes of the future are not only more efficient, but also more just and sustainable.

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