SINERGI Vol. 29, No. 3, October 2025: 573-586
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2025.3.002

Port perspectives in a changing climate: strategies for enduring impact

Astina Tugi[1], Nazirah Mohamad Abdullah[2*], Ami Hassan Md Din[3], Najhan Md Said[4], Badrul Hisham Ismail[5]
[1]Faculty of Civil Engineering and Built Environment, Universiti Tun Hussein Onn Malaysia, Malaysia
[2]Faculty of Applied Science and Technology, Universiti Tun Hussein Onn Malaysia, Malaysia
[3]Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia, Malaysia
[4]National Hydrographic Centre, Malaysia
[5]Port Klang Authority, Malaysia

Abstract
More than 50% of the world's trade happens via seaborne line. The sustainability of the ports is crucial as it boosts economic growth. However, climate change and its effects have disturbed the port's activities. This paper highlighted the possibility of climate change effects threatening some ports worldwide. A systematic literature review has been conducted, utilizing 11 resources have been used to summarize their impact on port activities. The effects of climate change on ports and the adaptation measures taken by their authorities are highlighted. Ports worldwide are considered. As a result, sea level rise (SLR), storm surges, and flooding are among the threats that can impact port activities. Adaptation and mitigation plans can be more successfully implemented with excellent knowledge of the factors leading to increased exposure. From port expansion to creating new port locations, another mitigation and adaptation plan for sustainable ports involves providing accurate topographic maps, effective simulation software, and robust resilience infrastructure and adaptation frameworks. The related ports have suggested and implemented adaptation and mitigation approaches to resolve the problem and sustain their ports and harbour activities. Adaptation and mitigation measures will be taken to respond to the effects of climate change.

Keywords:
Climate change;
Mitigation and adaptation;
Port and harbours;
Sea level rise;

Article History:
Received: July 20, 2024
Revised: November 17, 2024
Accepted: December 31, 2024
Published: September 1, 2025

Corresponding Author:
Nazirah Mohamad Abdullah
Applied Science and Technology
Universiti Tun Hussein Onn Malaysia, Malaysia
Email: nazirah@uthm.edu.my

INTRODUCTION

The sustainability of the maritime sector is crucial, and numerous parties and stakeholders are involved in this sector, as highlighted by [1]. International trade is primarily conducted through maritime channels, accounting for over half of it, while the rest is carried out through land routes [2, 3, 4]. The criticality of the maritime transport environment at ports and harbours is crucial to their operational sustainability [5]. Relative to this, sustaining the port's development could augment its operational cost, efficiency, and recognition. Figure 1 acknowledges the distribution of ports around the world according to the world's largest port in the year 2016 (adapted from [6]). Figure 2 illustrates the world's major container ports volume from 2018 to 2020.

Meanwhile, Table 1 shows the top 20 world ports in million twenty-foot equivalent units (TEU) [7][8]. Almost 50% of the ports listed had growth in the volume of container supply from 2018 to 2020. According to Table 1, most ports experienced an increase in container volume from 2018 to 2020, except for the following ports: Shenzhen, China; Hong Kong, China; Jebel Ali, United Arab Emirates (UAE); Kaohsiung, China; Los Angeles, United States of America (USA); Rotterdam, Netherlands and Hamburg, Germany.

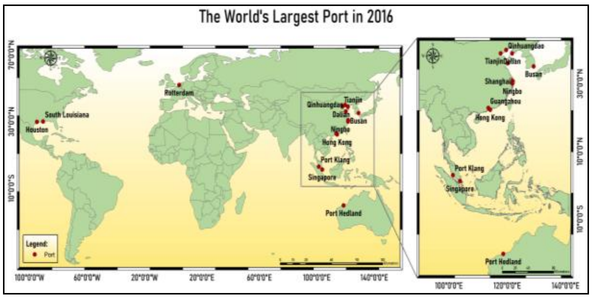

Figure 1. The world's largest ports in 2016 (Adapted from [6])

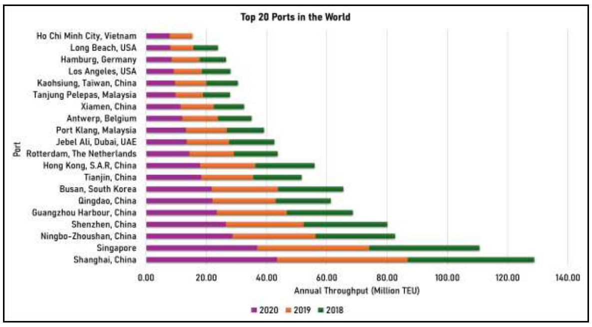

Figure 2. The world's container ports volume (2018 – 2020) (Adapted from [6] and [7])

Table 1. Top 20 World Container Ports (Adapted from [7] and [8]) (Unit: Million TEU)

No.	Port	2020	2019	2018
1.	Shanghai, China	43.50	43.30	42.01
2.	Singapore	36.87	37.19	36.60
3.	Ningbo-Zhoushan, China	28.72	27.53	26.35
4.	Shenzhen, China	26.55	25.77	27.74
5.	Guangzhou Harbour, China	23.50	23.23	21.87
6.	Qingdao, China	22.01	21.01	18.26
7.	Busan, South Korea	21.82	21.99	21.66
8.	Tianjin, China	18.35	17.26	16.00
9.	Hong Kong, China	17.95	18.36	19.60
10.	Rotterdam, Netherlands	14.34	14.81	14.51
11.	Jebel Ali, UAE	13.48	14.11	14.95
12.	Port Klang, Malaysia	13.24	13.58	12.32
13.	Antwerp, Belgium	12.03	11.86	11.10
14.	Xiamen, China	11.41	11.12	10.00
15.	Tanjung Pelepas, Malaysia	9.80	9.10	8.96
16.	Kaohsiung, China	9.62	10.42	10.45
17.	Los Angeles, USA	9.21	9.33	9.46
18.	Hamburg, Germany	8.54	9.27	8.73
19.	Long Beach, USA	8.11	7.63	8.09
20.	Ho Chi Minh City, Vietnam	7.85	7.53	-

Ports and shipping industries are among the key users of maritime space services, and the economy relies on this industry as it is one of the important sectors for commerce and trade, which boosts economic growth [5, 9, 10]. The fact indicates that the maritime trading industry continues to emerge and evolve, and this scenario underscores the significant role played by the port industry. However, several global climate change challenges might have varying effects on port operations [7, 11, 12]. Therefore, adaptation and protection measures against the effects of upcoming climate change, such as sea level rise (SLR), are crucial for the management authorities of ports and harbours, as they play an essential role in global trading and economic growth [12]. [13] interpreted climate change as the changes in climate that can be identified by the changes in their property's variability from statistical test evaluation. The changes would continue as consequences of multiple factors, such as anthropogenic activity or natural occurrences. [9] indicates that natural events such as solar radiation variations and volcanic eruptions also impair the Earth.

In addition, anthropogenic activities, such as fossil fuel burning, cause changes to climate conditions due to the release of greenhouse gases (GHG) [14][15]. The release of four types of gases, including carbon dioxide (CO2), nitrous oxide (N2O), methane (CH4), and fluorinated gases (F-gases), contributes to global warming [16]. Global warming increases temperatures and leads to extreme events and catastrophic effects, including human and infrastructure losses [1, 17, 18, 19, 20, 21, 22]. Moreover, global warming will increase evapotranspiration and atmospheric moisture content, therefore altering rainfall patterns [23]. With a high intensity of precipitation, flooding is likely to occur because the water is obstructed by the low level of the bridge girder, which impacts the lack of freeboard height, thereby restricting the flow of river water [24].

According to [25], by 2100, the sea level might increase by up to 2.4 meters, meanwhile, [19] annotated that the SLR might increase up to 5 meters by 2100. SLR will also raise the water depth in and around the harbour. The current wave propagation patterns will alter because of these increasing water depths (shoaling, refraction, and diffraction processes). Additional effects on ports may result from agitation, siltation, or changes in structural stability. The results could be favourable or unfavourable, making the port operability better or worse [26]. Port structures' and facilities' foundations deteriorate due to extreme weather occurrences. Elevated sea levels and storm surges erode buildings, while intense heat and sunlight shorten the lifespans of buildings and other structures, damaging their texture. Climate change mitigation and adaptation measures should be augmented for the maritime industries at ports and harbours, as they concern stakeholders and maritime players due to the significant damages that may affect their facilities and activities under these environmental circumstances [7][27]. The impact of climate-related extremes and trends is affecting port infrastructure [28], port operations [29], navigable water, protection from wind, waves, floods, storm surges, and temperature increases [1, 3, 19, 30, 31, 32, 33].

Conversely, several additional factors might impact maritime operations and trade, such as tidal range and currents, water supply pressures, and health hazards associated with hotter summers. Thus, it might affect navigation, port operations, and land transport [34]. Figure 3 illustrates the proportion of regional populations expected to experience major heatwaves worldwide in 2040 [35]. By some means, climate change has gobbled up some ports due to the rise of sea levels, storm surges, and other environmental factors. Coastal areas are also subject to damage due to the increase in tropical cyclone activity [2]. Figure 4 illustrates the global distribution of tropical storms.

[36] highlighted that to adapt to climate change, a Representative Concentration Pathway has been introduced (RCP). RCP is a novel pathway that includes four conditions created for the climate modelling community to serve as a foundation for both long-term and short-term modelling studies, which are designated as RCP2.6, RCP4.5, RCP6, and RCP8.5. This has been implemented at 43 ports along the Catalan coast. Base level (conditions from the year 1985-2005), RCP4.5 (Base level + 0.47 m), RCP 8.5 (Base level + 0.88 m), and high-end scenario (HES, Base level + 1.80 m) are selected. An investigation into the implications of SLR has been undertaken to apply the projections of RCP8.5 to the Catalan Ports, modelling the consequences of sea level alterations on the coastal region [26]. The coastal area possesses significant economic potential due to its natural resources for fisheries, increasing population, and concentration of tourism activities [37], making the effects of sea level rise a major concern for the near future [38].

Low-latitude regions, such as Indonesia and central eastern Asia, are more vulnerable to climate variations, including extreme temperature and precipitation changes [39]. Moreover, as mentioned by [40], Southeast Asia falls into one of the most susceptible regions of the world to climate change. Southeast Asia is a region comprising ten sovereign states: Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam [41]. Furthermore, these nations have been significant contributors to the global emissions of greenhouse gases (GHG) during the period spanning from 1990 to 2010. Therefore, adaptation and preventive measures are crucial for protecting and mitigating the effects of climate change.

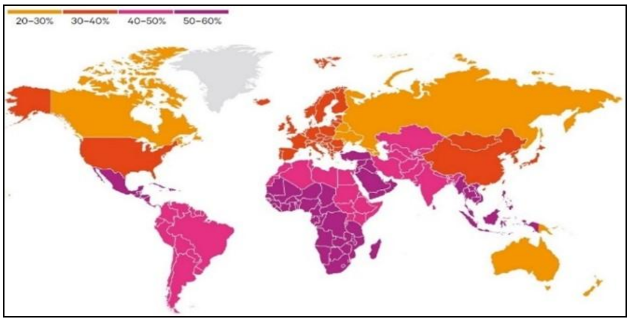

Figure 3. The proportion of regional populations experiencing major heat waves in 2040 worldwide [35]

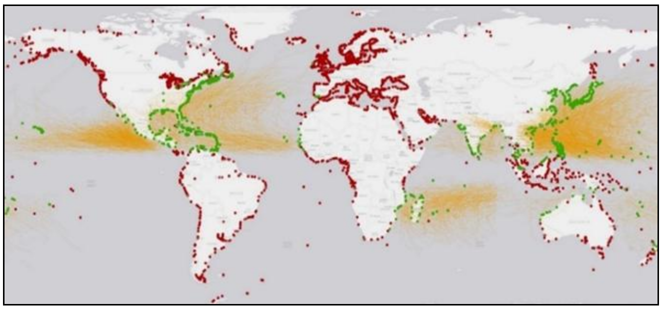

Figure 4. ~1100 ports (green) out of ~3700 total (red) that have come within 50km of a tropical storm from 1960 - 2016. Storm tracks in orange [27]

METHOD

A thorough analysis of the detrimental effects of climate change at ports and harbours is elaborated by adapting the Systematic Literature Review. This technique utilized many kinds of literature, preferably critical materials, and findings interpretation to provide a comprehensive assessment [42]. A systematic literature review is a methodical and evidence-based way to comprehensively search for studies that are relevant to specific research questions. It involves carefully selecting, evaluating, and combining the findings of these studies to provide answers to the research questions. Systematic reviews, in contrast to conventional narrative reviews, often incorporate specific research enquiries, well-defined search methods, criteria for selection, and both qualitative and quantitative summaries [43]. By understanding the idea and the issue, a fair review from multiple sources is executed. The primary flow of the systematic literature review adopted in this study is illustrated in Figure 5.

Research Questions

The research question (RQ) is the key to the systematic literature review. These RQs will guide the focus and direction of the study and narrow it down to its purpose. There are three RQs about the effects of climate change at ports pointed out in the literature review. The RQ are as follows:

a) RQ1: What is the climate change scenario affecting the port area?
b) RQ2: How does the topography of the port correlate with climate change?
c) RQ3: What are the mitigation and adaptation measures taken by the port authority?

Selection of the Study

In parallel with the focus of the research questions, several sources have been selected for review. The selection of articles spans from 2013 to 2023, comprising multiple types of publications, including reports, journal articles, and books. Ten years have been chosen to review the impact of climate change on port industries. Below are the lists of resources for the literature:

a) Google Scholar (https://scholar.google.com/)
b) Science Direct (https://www.sciencedirect.com/)
c) Scopus (https://www.scopus.com/home.uri)
d) Research Gate (https://www.researchgate.net/)

A few keyword strings are used in selecting the relevant academic literature through the website mentioned earlier. The keywords string conveys the appropriate reading resources. A Boolean operation, such as “AND” or “OR” is used to obtain the required sources of information. The literature search encompassed journal articles, conference papers, book chapters, and other published sources. Figure 6 shows the flowchart for conducting a database search using keywords and source filtering. The screening step is conducted once the searching phase has been completed. The articles are being screened using three filtering processes: title filtering, abstract filtering, and content screening. The duplicated article is removed. Final articles are chosen after the screening is done.

Quality Assessment

The quality assessment for the selected paper is conducted after the desirable sources are selected. The selected papers are chosen based on their context and information through a rigorous review process. The chosen articles were read and examined personally by the researcher, and they must understand the justified RQ. The chosen articles should elaborate and give information to answer the RQ.

An analysis of the RQ relevancy throughout this paper is being undertaken by using a percentage analysis. A weightage has been assigned to each RQ.

Figure 5. The primary steps of the systematic literature review process [44]

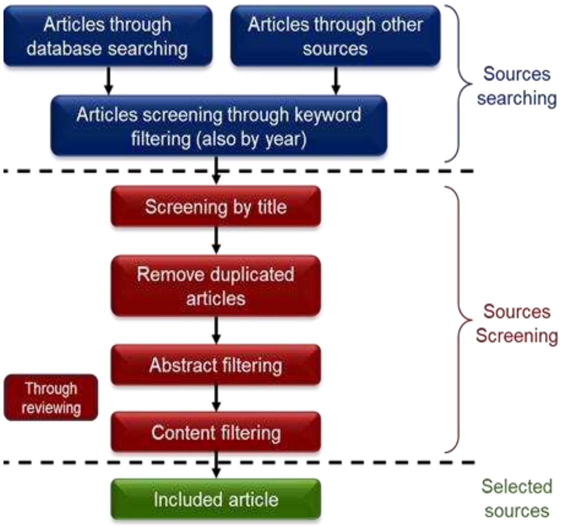

Figure 6. Flowchart of the source's selection (Summarise from [7])

Below is the weightage used in analyzing the research question with the selected reference sources [7]:

a) 0 when the sources do not offer any material relevant to this question.
b) 0.5 for a question that has been partially but thoroughly answered in a paper.
c) 1 for a question that was thoroughly explained in the article.

RESULTS AND DISCUSSION

The combinations of "climate change" AND "port operation", "climate change" AND "port adaptation", "climate change impact" AND "port", and "port and harbours" AND "climate change variabilities" were performed. Figure 7 shows the flowchart for conducting a database search using keywords in pertinent libraries. Figure 7 indicates that a total of 191 items were retrieved using the specified keyword. These articles have been restricted from the year 2013 to 2023. Next, a process of title filtering is carried out, resulting in the removal of 88 papers and the elimination of 6 duplicate articles. In addition, only a total of 70 papers were available for unrestricted access.

The abstracts are then carefully filtered, and 58 papers are shortlisted. Finally, content screening is performed manually, and a total of 11 papers are selected for final assessment. Table 2 enlisted the final selected resources for the analysis, and Table 3 shows the Journal Impact Factor (JIF) score for all the related articles and reports. The selected papers featured a variety of materials, including books, reports, and journal articles. According to Table 3, most of the journal articles are categorized under JIF quartiles 1 and 2 (Q1 & Q2), with six papers. Moreover, two papers are categorized under JIF quartiles 3 and 4 (Q3 & Q4), and the rest are indexed by Scopus (Sc). The papers are divided into years: 2023 (2 papers), 2021 (2 papers), 2020 (2 papers), 2019 (2 papers), 2017 (1 paper), 2016 (1 paper), and 2013 (1 paper).

Table 4 shows the percentage of the relevancy of the literature sources to the research questions, respectively. Additionally, Figure 8, Figure 9, and Figure 10 show the weightage of RQ1, the weightage of RQ2, and the weightage of RQ3, respectively. Moreover, Figure 11 shows the histogram of the RQ weightage percentage. According to Figure 11, from a total of 10 resources, most of the resources have exceeded 50% of weightage percentage. Moreover, it can be seen from Figure 8 and Figure 10 that most of the resources have high relevance to the RQ addressed.

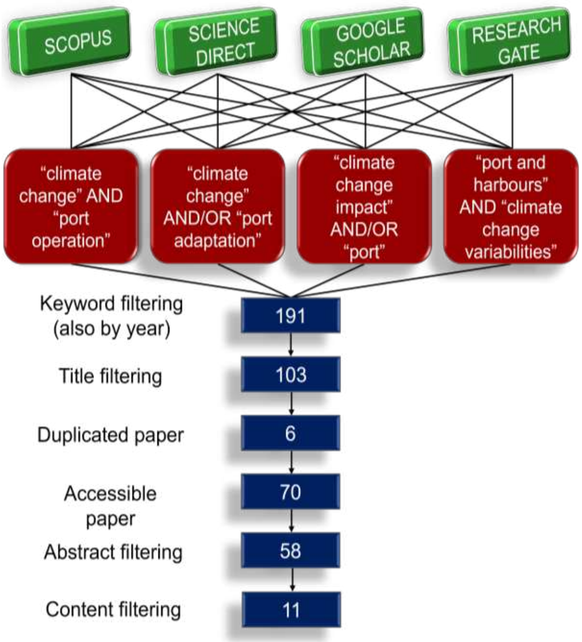

Figure 7. The flowchart for conducting a database search using keywords in pertinent libraries

Table 2. Details of the chosen reading sources

Ref.	Title	Type
[21]	Reporting Climate Change Impacts on Coastal Ports (NW Iberian Peninsula): A Review of Flooding Extent (2023)	Journal article
[19]	The Impact of Climate Change and EU Green Deal on Port Competitiveness (2023)	Book
[45]	A System to Improve Port Navigation Safety and Its Use in Italian Harbours (2021)	Journal article
[7]	Adapting to the impacts of climate change on port operation (2021)	Journal
[29]	Assessing The Impact of Sea Level Rise on Port Operability Using LIDAR-Derived Digital Elevation Models (2019)	Journal article
[46]	Climate change adaptation and mitigation in ports: Advances in Colombia (2020)	Book chapter
[28]	Stakeholder awareness of climate adaptation in the commercial seaport sector: A case study from Ireland (2020)	Journal article
[31]	Sea-Level Rise in Ports: A Wider Focus on Impacts (2019)	Journal article
[27]	Implications of Climate Change for Shipping: Ports and Supply Chains (2017)	Journal article
[47]	Seaport climate change impact assessment using a multi-level methodology (2016)	Journal article
[48]	Climate Change and Sea Level Rise Impacts at Ports and A Consistent Methodology to Evaluate Vulnerability and Risk (2013)	Journal article

Table 3. JIF of the literature resources

Ref.	Journal/Publisher	JIF
[21]	Journal of Marine Science and Engineering	Q1
[19]	Peter Lang GmbH	Sc
[45]	Applied Sciences	Q2
[7]	Australian Journal of Maritime & Ocean Affairs	Sc
[29]	Remote Sensing of Environment	Q1
[46]	Elsevier	Sc
[28]	Marine Policy	Q2
[31]	Maritime Economics and Logistics	Q2
[27]	Wiley Interdisciplinary Reviews: Climate Change	Q1
[47]	Maritime Policy & Management	Q3
[48]	WIT Transactions on Ecology and the Environment	Q4

However, for RQ 2, the topography of the port location is not thoroughly explained, as most ports in the world are typically located in areas such as coastal regions and estuaries. Based on the result of the percentage, the articles that comply with all three research questions are from [21].

Table 4. The percentage of the relevance of the literature sources to the research questions

Ref.	RQ1	RQ2	RQ3	Total	Per (%)
[21]	1	1	1	3	100
[19]	1	0.5	1	2.5	83.33
[44]	1	1	0.5	2.5	83.33
[7]	1	0	1	2	66.67
[29]	1	0	0.5	1.5	50.00
[45]	0.5	0.5	1	2	66.67
[28]	1	0.5	1	2.5	83.33
[31]	1	1	1	3	100.00
[27]	0.5	0.5	1	2	66.67
[46]	0.5	0	1	1.5	50.00
[47]	0.5	0	1	1.5	50.00

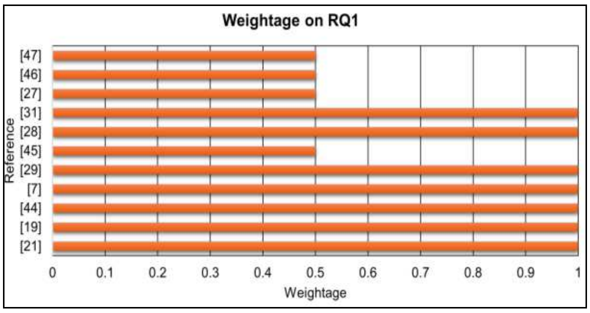

Figure 8. Weightage of RQ1

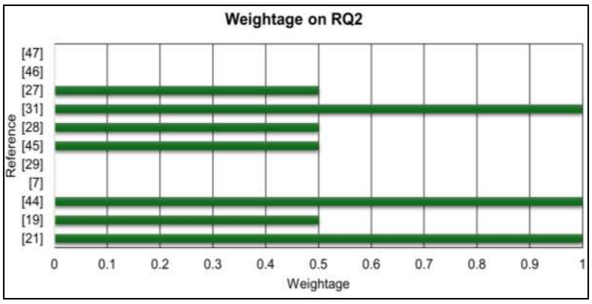

Figure 9. Weightage of RQ2

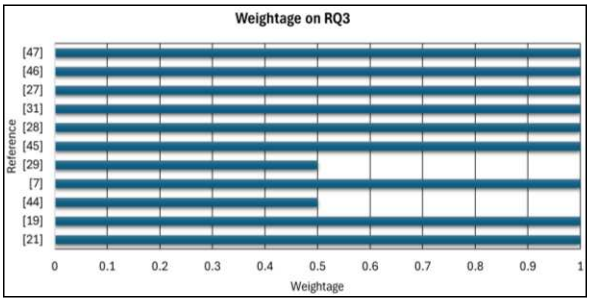

Figure 10. Weightage of RQ3

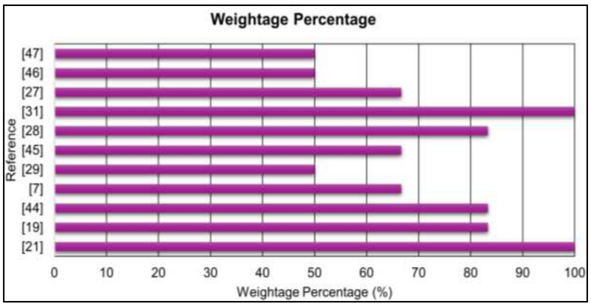

Figure 11. Histogram of the RQ weightage percentage

Discussion

The subsections below provide a brief discussion of the study's results and the literature review. One of the primary repercussions of climate change is SLR, storms, and typhoons. These situations may damage coastal regions and impair various facilities, notably seaports and harbours, whose operations may be jeopardized. The following section discusses climate change scenarios in parallel with their consequences for the ports and harbours area. The geomorphologically driven climate change is also briefly discussed. Continuously, adaptation and mitigation measures are also being discussed. Adaptation involves upgrading existing infrastructure and designing new facilities to endure the primary effects of climate change, such as rising sea levels and floods. On the other hand, mitigation focuses on reducing greenhouse gas emissions to diminish future climate change. Adaptation measures for a specific location should be designed using site-specific assessments that consider local and regional characteristics [31].

Climate Change Effects on Ports and Harbours Activities Around the World

Activities such as shipping and international goods trading occur at the port, thus, maintaining the port's reliability and durability is essential [28]. The major port authorities worldwide rank climate change as one of their top three concerns [19]. Because ports are situated in low-lying areas, such as deltas and coastal regions, they are particularly susceptible to the impacts of climate change [19, 21, 28]. The regional impacts of climate change, such as short-duration, intense storms, may cause urban flood inundation, which has become a concern for the global community [47]. Moreover, SLR, coastal flooding, storm surge, and extreme sea levels [28], [29] threaten the port industry. Strong winds and storm surges were found to be particularly sensitive to the cranes aboard ships, and wave height, wind strength, and heavy precipitation can all restrict crane operations [7]. Additionally, rainfall patterns are expected to shift, resulting in more intense rainfall events and changes in monthly average rainfall [21][46].

The escalation of sea levels and storm surges can inundate transportation infrastructure, resulting in costly damages and the cessation of operations within the sector [46]. When mean sea-level rise and storm intensity increase, forecasting these factors becomes crucial to addressing the impact of climate change on the port industry. It may be vulnerable to flooding due to its location and is influenced by the strength and periodicity of factors such as relative sea level and wave-induced currents. Increased hazard is seen when many of these factors hit their maximum values [21]. Furthermore, SLR will impact port operations by reducing the amount of freeboard available at docks and piers [29]. An example of this impact can be seen in the Port of Vancouver, which is confronting dangers from the floods on the Fraser River. A catastrophic flood event may cost the city of Vancouver billions of dollars in economic damage [27].

Nevertheless, in another review of a range of regions, including the Mediterranean Basin, sea-level fluctuations are predominantly attributable to astronomical tidal phenomena associated with the gravitational interactions among the Earth, the Moon, and the Sun [45]. If we observe the topography of a location, for example, Colombia, a South American country flanked by the Caribbean and Pacific seas, it benefits from natural protection against rising sea levels. Natural ecosystems, comprising coral reefs, mangroves, and coastal beaches, serve as vital protective agents by helping to regulate the climate, manage water resources, and mitigate erosion. However, industrialization in this area has slowly destroyed the environment for this ecosystem. As for Colombian seaports, they suffer from gales, floods, erosion, and sea surges. Studies using the General Equilibrium Model Climate Change Computable (MEG4C) by Colombia's National Planning Department stated that the country's GDP would be 0.49% lower each year than a scenario without climate change [46].

On the other hand, the port in New Jersey, United States of America (USA), was closed for more than eight days after Hurricane Sandy in 2012, resulting in significant damage. The ramifications of climate change are exceptionally pronounced in Europe, where more than 60% of port traffic relies on linkages with ports that are significantly susceptible to the phenomenon of SLR [31]. Moreover, one of the world's largest ports, the Port of Rotterdam, is in an extremely vulnerable area where flooding and SLR might occur due to its geographic, deltaic setting. The vulnerability of this European port is increased by the activities and presence of a developing, exposed, and congested populace [28].

Moreover, [21] averred that the Coruna Outer Port and Vigo Port on the Iberian Peninsula might be vulnerable if extreme climate conditions occur, leading to higher wave heights, winds, and currents. According to [31], between 2010 and 2100, approximately 200 million tonnes of cargo are vulnerable to extreme sea levels higher than 4.5 m. This might affect ports located in Norway, Portugal, the United Kingdom, Ireland, and Spain, particularly those vulnerable to extreme sea level conditions exceeding 4.5m. Additionally, most of the European coastline will experience extreme sea level rises of more than 0.5 meters under the high warming scenario. On the other hand, the North Sea, the Western Baltic Sea, and portions of the British and French Atlantic coasts will experience more than a meter rise. Compared to the North Sea, the Black Sea and the Mediterranean are predicted to see noticeably fewer consequences (lower extreme sea levels).

The regional effects on the European hinterland and the European foreland are considered when evaluating the more significant consequences of possible interruptions in port operations, taking into account Europe's linkages to major ports globally [31]. A vulnerability assessment of the impact of climate change conducted by [19] discovered that Puerto Rico is ranked first in the high-risk category among eight ports within the category. The USA and Japan are in the medium-risk category, while the Philippines, Cuba, and Indonesia are in the high-risk group. High-risk ports include those in Jakarta and Santo Domingo. In addition, the Persian Gulf and the Red Sea region (Arabian Peninsula) are predicted to face increased danger in the future due to rising temperatures, while Mediterranean ports are expected to see a shift towards high and extremely high risk. In addition, a study conducted at four Catalan ports —Arenys de Mar, Palamós, Cambrils, and Vilanova i la Geltrú—indicated that if port authorities take no adaptation measures, there will be a general decline in port operability during the 21st century due to SLR [45]. Based on [7][48], the Port of San Diego repeatedly and permanently faces inundation of low-lying regions due to SLR, drought, water scarcity, storm intensification, floods, and temperature rises. These are some of the effects of climate change that might pose hazards to the port. SLR is the primary effect of climate change that will impact the port, depending on its location, operating activities, and planning work. The effects of climate change are particularly severe for the port industry and its location; therefore, adaptation and mitigation measures need to be taken.

Geomorphologically Driven Climate Change

In port construction, it is crucial to consider both the location and geomorphology of the port area. Local climatic conditions, shaped by factors such as topography and land use, determine how climate change impacts are felt in specific areas. The effects of climate change can be location dependent [28]. In addition, the intensity of its repercussions will change over time, depending on natural climatic variability and the level of man-made atmospheric warming [27]. Ports located in low-lying areas are particularly vulnerable to hazards such as sea level rise, hurricanes, and storm surges. Storm surges cause elevated water levels within harbours. These fluctuations, combined with strong winds, lead to significant sea-level increases and heighten the risk of flooding [19]. Additionally, high-energy sea waves and changes in siltation increase the need for seabed dredging in ports. Dredging, which involves deepening the harbour basin, leads to higher expenses for facility improvements [19][27].

[21] examine the impact of climate change on different types of geomorphologies in the Atlantic Ocean, including marine, rias, lagoon, and estuary areas at several ports in the Northwest Iberian Peninsula (NWIP), namely Coruna Outer Port, Vigo Port, Aveiro Port, and Lisbon Port, respectively. Climate drivers included for these areas are the increase in mean sea level, extreme sea levels, waves, and river stream flow. The outcomes indicated that the coastal flooding is susceptible to enclosed areas such as lagoons and estuaries due to the SLR and high river discharge, meanwhile, rias and marine areas are mostly affected by SLR and storm surge combination [21]. Moreover, all coastal areas experience impacts from gales, floods, erosion, and sea surges. An analysis

conducted in 12 coastal regions of Colombia revealed that most of these regions face threats from climate change [46].

On the other hand, [45] highlighted the importance of astronomical tides and meteorological tides in the Mediterranean area in updating sea levels. This is towards establishing and enhancing systems to improve port navigation safety. Similarly, the location of the ports influences the impact of climate change on the port area. According to [31], an extreme sea level (ESL) projection has been conducted to identify ports that are threatened by inundation. The outcome from the projection shows the location of the risky ports with the largest mean sea level (MSL) in the North Sea and Atlantic Coast. Contrarily, the Baltic Sea has the smallest MSL due to the land uplift. Ultimately, the location of a port significantly determines the impacts to which the port is vulnerable, as the effects of climate change vary geomorphologically. Various factors and parameters should be identified to project and counter the upcoming effects on the port.

Adaptation and Mitigation Measures

Understanding the location-dependent effects of climate change is crucial for developing tailored adaptation and mitigation strategies for different regions. A few adaptations and mitigation methods need to be implemented to ensure the sustainability of port activities and to make them financially practical now, while also ensuring simplicity of change in the future. It is essential to choose designs that might readily support future adaptation measures. [28] underlined the adaptive measures in reducing the vulnerability of ports, incorporating the engineering solutions, changes to technical in port operation, and future planning measures. According to the European Green Deal, the aim is to combat climate change by reducing greenhouse gas emissions. Hence, the focus on climate change adaptation, which involves identifying associated risks and enhancing port resilience through proactive measures, is highlighted.

These measures were also agreed by [46][48] that lowering greenhouse gas emissions, a major cause of climate change, can assist in reducing world temperatures. As mentioned, Colombia has set a goal of reducing 20% of greenhouse gas emissions by 2030 in its climate action plan [46]. Moreover, "Cold ironing" technology is one example of minimizing the emissions from docked ships by supplying them with energy from onshore sources, thereby reducing carbon emissions [19]. Moreover, Amsterdam Port and London Port, which are situated in a region especially vulnerable to severe weather events, have already implemented protective strategies against highly intense events [31].

Alternatively, a larger port is thought to be more equipped for advanced approaches to innovation and port policy towards environmental management. Rotterdam Climate Initiative (2013) outlines the development of the Rotterdam Climate Proof Programme. The Port of Rotterdam Authority has facilitated collaborative agreements with diverse stakeholders, encompassing municipal services, governmental bodies such as water boards and Rijkswaterstaat, as well as public and private entities, including housing corporations, project developers, and utility providers. Intending to make Rotterdam 100% climate-proof by 2025, the Rotterdam Climate Proof Adaptation Programme emphasises the development and implementation of techniques for climate-proofing rather than making predictions [28]. Several indicators need to be defined in the context of port operational and infrastructure resilience.

The occurrence of flooding events, such as those at the berthing and storage area, vessel delays, and port damages, needs to be comprehended. For example, Coruna Outer Port is equipped with a robust breakwater designed by its port authority to withstand extreme weather, serving as an artificial harbour. A 3360m long breakwater with three alignments is responsible for the berthing area of the ships that can withstand the worst weather [28]. Also, upgrading or expanding infrastructure and raising the crest level were two possible ways to lessen the consequences of climate change. Elevating the port area with seawalls and dikes, or relocating it to a higher elevation for future trade, is also one of the mitigation measures that can be considered by the port authority [21, 27, 48].

Not to be forgotten, assessing the impact of climate change at the port is vital. The adaptation action for port authorities includes technology, engineering, design, maintenance, planning, insurance, and management systems [27]. To identify susceptible locations and modify plans accordingly, adaptation techniques such as Geographic Information Systems (GIS) should be utilized to track changes in terrain or sea level rise in coastal areas [7]. A climate impact assessment has been conducted at the ports of Livorno and Bari in Italy to monitor and analyze their environmental parameters. The system utilizes "virtual traffic lights" to identify hazardous regions for ships navigating through the ports. This assessment helps the port in managing and analyzing the maritime traffic and optimizing the port's activities [45].

As for Aveiro Port, a software package called DELFT3D enables the simulation of outflow and waves in coastal, riverine, and estuarine environments using a multidisciplinary approach. The FLOW and WAVE modules of the DELFT3D package mimic flow and short-wave propagation, respectively. For the Aveiro Port, the accuracy of a model simulation is primarily determined by its inputs, necessitating an evaluation of the physical processes involved, particularly regarding the frequency of flooding, which is greatly influenced by high sea levels and riverine flows [21]. The current situation at the port needs to be analyzed, and defining the problem requires understanding its implications, risks, opportunities, and vulnerabilities [27][29]. This can enhance emergency evacuation plans for climate resilience [27].

This is followed by the projection of maritime traffic growth and an evaluation of the infrastructure and superstructure requirements. Next, alternatives are explored, and a corresponding economic-financial analysis is conducted for each option. The chosen alternative is detailed and includes an assessment of its compatibility with urban planning, an environmental impact study, a public consultation and a discussion phase. The work is phased through tendering and execution over several years [29]. Moreover, the Port of San Diego has initiated a framework for evaluating and making decisions on adaptation to climate change that first considers pertinent historical data and climatic projections to determine physical vulnerabilities, and then considers financial risk data relevant to ports and marine transportation [48].

The assessment of financial risk recognizes the implementation of a comprehensive Net Ecosystem Services Analysis (NESA) valuation as an effective framework for addressing the entire range of pertinent issues when calculating costs and benefits across different land-use types, encompassing social, economic, and environmental aspects. Future research should consider current and anticipated human activities and land uses when evaluating the extent of flooding [21]. Moreover, [47] also conducted an assessment using a multi-level methodology to analyze the impact of climate change on the port area, and the results can benefit the authority in developing adaptation and mitigation strategies. This study employs a high-resolution analysis level, utilizing a probabilistic technique to model outcomes with process-based models and analyze hazard, exposure, and vulnerability data at a precise geographic scale.

Establishing an evaluation task force that includes all stakeholders and professional assessment bodies in addressing climate change issues is crucial. Adopting a sustainability policy that focuses on reducing the risks to its facilities caused by climate change and engaging in collaborative measures with regional stakeholders, the public, and private sectors is crucial in mitigating these risks. By analyzing and identifying the vulnerabilities, adaptation options can be generalized [7][28].

Table 5. Summaries of the selected references on adaptation and mitigation

Ref.	Adaptation and Mitigation
[21]	• The construction of seawalls, dikes, and marine ecosystems to protect from the impact of climate change. • Relocation or elevation to compensate for sea level rise.
[19]	• Reducing carbon emissions to lower the GHG effects. • Efficient use of financial resources for climate change adaptation
[45]	Optimizing port navigation to avoid critical situations.
[7]	Analyzing and identifying the vulnerabilities and climate impact assessment.
[29]	• Assessment of the climate impact to understand the implications, risks, opportunities, and vulnerabilities. • Modelling the simulation for the port area, such as outflow and wave intensity.
[46]	Reducing carbon emissions to lower the GHG effects.
[28]	The construction of a strong breakwater that functions as an artificial harbour was created to withstand the extreme weather
[31]	• Defences against storm surges to protect port infrastructure. • Measures may restrict ship movement during extreme weather.
[27]	• Raise port elevations to combat sea level rise. • Enhance emergency evacuation plans for climate resilience.
[47]	• Evaluation of the effects of climate change on the port area using a multi-level technique • Moving to a higher elevation or raising seawalls and dikes to elevate the port area
[48]	• Reducing carbon emissions to lower the GHG effects. • Evaluating potential adaptation strategies with responsible agencies. • Developing consistent methodologies for risk evaluation and cost-benefit analysis.

However, decision-makers must carefully consider the timing of port adaptation investments or defer them to a later stage, as the efficiency of investments remains uncertain in a competitive environment. The global competitiveness of the port relies on the strategic and effective use of financial resources for climate change adaptation [19][27]. For instance, the Port of Ireland is led by the Environmental Protection Agency (EPA) to develop the National Climate Change Adaptation Framework. On the other hand, the Port Authority of New York and New Jersey has a task force assigned to address several issues, including energy, policy, transportation, communication, water, and waste [28].

Even though the port authority has conducted a projected vulnerability analysis every 30 years (starting in 2020 and continuing until 2080), this analysis proved inadequate once they encountered the impact of Hurricane Sandy. However, this incident has become their benchmark in leveraging their long-term planning of the port adaptation [28]. Moreover, highlighting the significance of mangroves for coastal protection and reforesting degraded areas is a crucial approach to the mitigation effort. Table 5 summarizes the adaptation and mitigation measures highlighted from 11 resources. Several adaptations and mitigation measures are highlighted that can mitigate the impact of climate change on the port. All these measures need to be tackled to address the impact of climate change

CONCLUSION

Around the world, several climate change-related issues may have various impacts on port operations. This investigation contributes to the existing body of knowledge on the implications of climate change for maritime ports by conducting a systematic review of the literature that examines the interplay between port operations and climate change. Several publications covering climate change challenges, their effects on port operations, and potential strategies to address the systematic literature review have found them. The aftermath of climate change on the port industries is numerous and ranges from minor to severe. A systematic literature analysis identified 11 studies focusing on climate change concerns, their impacts on port operations, and proposed strategies to address these challenges.

Extreme weather and SLR are the main consequences of climate change that challenge the port industry. The literature provides several preventive measures to mitigate the consequences of climate change on port activities, offering a means of overcoming them. Since it is a regional and global concern, initiative and cooperation among various groups, including stakeholders and the government, are crucial. To gain a better understanding of this topic, several research initiatives are necessary, as there are currently insufficient studies on the subject, especially in the Southeast Asia region. Moreover, additional references are needed to highlight the importance of port adaptation and the mitigation of climate change effects. The concerns for environmental sustainability and port development should be emphasized in future studies. Collecting all the data in this systematic literature review will be beneficial to practitioners and the academic community, and it may inspire new ideas for future studies on climate change.

ACKNOWLEDGMENT

This research was supported by the Ministry of Higher Education (MOHE) through the Fundamental Research Grant Scheme (FRGS/1/2021/STG08/UTHM/03/2).

REFERENCES

[1] Y. C. Yang and Y. E. Ge, “Adaptation strategies for port infrastructure and facilities under climate change at the Kaohsiung port,” *Transport Policy (Oxf)*, vol. 97, pp. 232–244, Oct. 2020, doi: 10.1016/j.tranpol.2020.06.019.

[2] N. D. Thao, H. Takagi, and M. Esteban, “Economic Growth and Climate Change Challenges to Vietnamese Ports,” *Coastal Disasters and Climate Change in Vietnam: Engineering and Planning Perspectives*, no. June, pp. 339–354, 2014, doi: 10.1016/B978-0-12-800007-6.00016-2.

[3] T. H. Chang and H. Y. Wang, “Analysis and Exploration of the Impact of Average Sea Level Change on Navigational Safety in Ports,” *Water (Switzerland)*, vol. 15, no. 14, Jul. 2023, doi: 10.3390/w15142570.

[4] Y. Zhou, W. Daamen, T. Vellinga, and S. P. Hoogendoorn, “Impacts of wind and current on ship behavior in ports and waterways: A quantitative analysis based on AIS data,” *Ocean Engineering*, vol. 213, Oct. 2020, doi: 10.1016/j.oceaneng.2020.107774.

[5] K. Mutombo, A. I. Olçer, and L. Kuroshi, “A System Inter-dependent Approach in Addressing Climate Change in Ports: A Case Study of the Port of Durban, South Africa,” in *The Palgrave Handbook of Climate Resilient Societies*, Springer International Publishing, pp. 1–66, 2020, doi: 10.1007/978-3-030-32811-5_57-1.

[6] T. Notteboom, A. Pallis, and J.-P. Rodrigue, *Port Economics, Management and Policy*, 1st ed. Oxon: Routledge, 2022.

[7] L. Devendran, M. Menhat, R. Md Hanafiah, N. I. Yatim, N. Ali, and I. M. Mohd Zaideen, “Adapting to the impacts of climate change on port operation,” *Australian Journal of Maritime and Ocean Affairs*, vol. 0, no. 0, pp. 1–20, 2021, doi: 10.1080/18366503.2021.2007615.

[8] Linton Nightingale, “Lloyd’s List’s One Hundred Ports,” UK, 2021. [Online]. Available: www.lloydslist.com/topports21

[9] M. R. Othman, N. A. Noralam, J. Jeevan, M. S. I. Saadon, and T. O. Kowang, “The Sustainability Stimulus of Malaysian Seaport Cluster toward Competitive Vigilance: The Total Quality Management (TQM) Approach,” 2021. [Online]. Available: http://rmk11.epu.gov.my/pdf/strategy-paper/Strategy%20Paper%2014.pdf.

[10] K. V. Gupta and G. Prakash, “Assessment of environmental sustainability issues for South-Asian maritime ports,” *Australian Journal of Maritime and Ocean Affairs*, 2022, doi: 10.1080/18366503.2022.2038903.

[11] C. Izaguirre, I. J. Losada, P. Camus, J. L. Vigh, and V. Stenek, “Climate change risk to global port operations,” *Nature Climate Change*, vol. 11, no. 1, pp. 14–20, Jan. 2021, doi: 10.1038/s41558-020-00937-z.

[12] W. Xia and R. Lindsey, “Port adaptation to climate change and capacity investments under uncertainty,” *Transportation Research Part B: Methodological*, vol. 152, pp. 180–204, Oct. 2021, doi: 10.1016/j.trb.2021.08.009.

[13] H. A. Rahman, “Climate Change Scenarios in Malaysia: Engaging the Public,” *International Journal of Malay-Nusantara Studies*, vol. 1, no. 2, pp. 55–77, 2018.

[14] A. E. Husin, Kristiyanto, and B. D. Kussumardianadewi, “Blockchain-BIM: reducing cost in green retrofitting for sustainable construction development,” *Sinergi (Indonesia)*, vol. 28, no. 3, pp. 521–534, 2024, doi: 10.22441/sinergi.2024.3.009.

[15] I. Hassan, R. M. Kalin, J. A. Aladejana, and C. J. White, “Potential impacts of climate change on extreme weather events in the Niger Delta part of Nigeria,” *Hydrology*, vol. 7, no. 1, 2020, doi: 10.3390/hydrology7010019.

[16] E. J. Arif and A. E. Husin, “Implementation of green river retrofitting concept using Blockchain-BIM for cost performance,” *Sinergi (Indonesia)*, vol. 28, no. 3, pp. 557–566, 2024, doi: 10.22441/sinergi.2024.3.012.

[17] IPCC, “Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change” [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press. Cambridge University Press, Cambridge, UK and New York, NY, USA, 3056 pp., 2022, doi:10.1017/9781009325844.

[18] N. P. Juan, V. N. Valdecantos, and J. M. del Campo, “Review of the Impacts of Climate Change on Ports and Harbours and Their Adaptation in Spain,” *Sustainability (Switzerland)*, vol. 14, no. 12, 2022, doi: 10.3390/su14127507.

[19] K. Elif, “The Impact of Climate Change and EU Green Deal on Port Competitiveness,” in *Service Sectors Role for Economic Development at Local and National Level*, Ç. Basarir and Ö. Yilmaz, Eds., Berlin: Peter Lang GmbH, ch. 13, pp. 1–278, 2023, doi: 10.3726/b20399.

[20] I. Onyekwelu, E. L. Ndulue, J. E. Abon, and R. Singh, “Trends and comparison of climate extreme indices in coastal locations under similar Köppen–Geiger classification using linear modelling approach,” *Journal of Earth System Science*, vol. 132, no. 3, Sep. 2023, doi: 10.1007/s12040-023-02144-8.

[21] A. S. Ribeiro, C. L. Lopes, M. C. Sousa, M. Gómez-Gesteira, N. Vaz, and J. M. Dias, “Reporting Climate Change Impacts on Coastal Ports (NW Iberian Peninsula): A Review of Flooding Extent,” *Journal of Marine Science and Engineering*, vol. 11, no. 3, Mar. 2023, doi: 10.3390/jmse11030477.

[22] M. Keintjem, R. Suwondo, M. Suangga, Juliastuti, and M. Anda, “Quantifying environmental impact: carbon emissions analysis of cut and fill work in construction,” *Sinergi (Indonesia)*, vol. 28, no. 3, pp. 497–504, 2024, doi: 10.22441/sinergi.2024.3.006.

[23] I. G. A. P. Eryani, M. W. Jayantari, and S. Ramli, “Determination of flood vulnerability level based on different numbers of indicators using AHP-GIS,” *Sinergi (Indonesia)*, vol. 28, no. 1, pp. 13–22, 2024, doi: 10.22441/sinergi.2024.1.002.

[24] A. Hidayat, R. D. Praptoyo, M. Isradi, and S. Suprapti, “Analysis of floodwater: A Case Study of the Tukad Buluk Poh River,” *Sinergi (Indonesia)*, vol. 28, no. 2, pp. 435–442, 2024, doi: 10.22441/sinergi.2024.2.022.

[25] J. L. Bamber, M. Oppenheimer, R. E. Kopp, W. P. Aspinall, and R. M. Cooke, “Ice sheet contributions to future sea-level rise from structured expert judgment,” *Proceedings of the National Academy of Sciences of the United States of America*, vol. 166, no. 23, pp. 11195–11200, 2019, doi: 10.1073/pnas.1817205116.

[26] J. P. Sierra, I. Casanovas, C. Mösso, M. Mestres, and A. Sánchez-Arcilla, “Vulnerability of Catalan (NW Mediterranean) ports to wave overtopping due to different scenarios of sea level rise,” *Regional Environmental Change*, vol. 16, no. 5, pp. 1457–1468, 2016, doi: 10.1007/s10113-015-0879-x.

[27] A. Becker, A. K. Y. Ng, D. McEvoy, and J. Mullett, “Implications of climate change for shipping: Ports and supply chains,” Mar. 01, 2017, *Wiley-Blackwell*. doi: 10.1002/wcc.508.

[28] J. M. O’Keeffe, V. Cummins, R. J. N. Devoy, D. Lyons, and J. Gault, “Stakeholder awareness of climate adaptation in the commercial seaport sector: A case study from Ireland,” *Marine Policy*, vol. 111, Jan. 2020, doi: 10.1016/j.marpol.2016.04.044.

[29] V. Gracia *et al.*, “Assessing the impact of sea level rise on port operability using LiDAR-derived digital elevation models,” *Remote Sensing of Environment (RSE)*, no. July, 2019, doi: 10.1016/j.rse.2019.111318.

[30] K. Y. N. Adolf, B. Austin, C. Stephen, C. Shu-Ling, E. Paul, and Y. Zaili, *Climate Change and Adaptation Planning for Ports*, 1st ed. New York: Routledge, 2016.

[31] A. Christodoulou, P. Christidis, and H. Demirel, “Sea-level rise in ports: a wider focus on impacts,” *Maritime Economics and Logistics*, vol. 21, no. 4, pp. 482–496, Dec. 2019, doi: 10.1057/s41278-018-0114-z.

[32] S. E. Hanson and R. J. Nicholls, “Demand for Ports to 2050: Climate Policy, Growing Trade and the Impacts of Sea-Level Rise,” *Earths Future*, vol. 8, no. 8, Aug. 2020, doi: 10.1029/2020EF001543.

[33] G. Van Houtven, M. Gallaher, J. Woollacott, and E. Decker, “Act Now or Pay Later : The Costs of Climate Inaction for Ports and Shipping Act Now or,” no. March, pp. 1–36, 2022, [Online]. Available: https://www.edf.org/sites/default/files/press-releases/RTI-EDF Act Now or Pay Later Climate Impact Shipping.pdf

[34] HR Wallingford, “*Climate change and Ports Impacts and adaptation strategies*,” 2021.

[35] D. Quiggin, K. De Meyer, L. Hubble-Rose, and A. Froggatt, “*Climate change risk assessment 2021*,” 2021. [Online]. Available: https://www.chathamhouse.org/2021/09/climate-change-risk-assessment-2021

[36] D. P. van Vuuren *et al.*, “The representative concentration pathways: An overview,” *Climate Change*, vol. 109, no. 1, pp. 5–31, Nov. 2011, doi: 10.1007/s10584-011-0148-z.

[37] M. Amin, I. S. D. Sebayang, and C. M. Sitompul, “Coastal Vulnerability Index Analysis in the Anyer Beach Serang District, Banten,” *Sinergi*, vol. 23, no. 1, p. 17, Feb. 2019, doi: 10.22441/sinergi.2019.1.003.

[38] N. M. Yazid et al., “Optimized gravity anomaly fields from along-track multi-mission satellite altimeter over Malaysian seas,” *Terrestrial, Atmospheric and Oceanic Sciences*, vol. 33, no. 1, Feb. 2022, doi: 10.1007/S44195-022-00003-5.

[39] M. Turco, E. Palazzi, J. Von Hardenberg, and A. Provenzale, “Observed climate change hotspots,” *Geophysical Research Letters*, vol. 42, no. 9, pp. 3521–3528, May 2015, doi: 10.1002/2015GL063891.

[40] D. A. Raitzer, F. Bosello, M. Tavoni, C. Orecchia, G. Marangoni, and J. N. G. Samson, “*Southeast Asia and The Economics of Global Climate Stabilization*,” Manilla, 2015. [Online]. Available: https://openaccess.adb.org.

[41] S. Seah, H. T. Ha, M. Martinus, and P. T. P. Thao, “*The State of Southeast Asia: 2021 Survey Report*,” Singapore, 2021. [Online]. Available: www.iseas.edu.sg

[42] T. Styliadis, J. Angelopoulos, P. Leonardou, and P. Pallis, “Promoting Sustainability through Assessment and Measurement of Port Externalities: A Systematic Literature Review and Future Research Paths,” *Sustainability (Switzerland)*, vol. 14, no. 14, 2022, doi: 10.3390/su14148403.

[43] W. Septiani, N. Rahmawati, D. M. Safitri, and M. Luis, “Usability evaluation for mobile health application: Systematic Literature Review,” *Sinergi (Indonesia)*, vol. 28, no. 2, pp. 287–304, 2024, doi: 10.22441/sinergi.2024.2.009.

[44] M. Ilyas, W. Ahmad, H. Khan, S. Yousaf, K. Khan, and S. Nazir, “Plastic waste as a significant threat to environment - A

systematic literature review," Dec. 19, 2018, *De Gruyter*. doi: 10.1515/reveh-2017-0035.

[45] M. Soldani and O. Faggioni, "A system to improve port navigation safety and its use in italian harbours," *Applied Sciences (Switzerland)*, vol. 11, no. 21, 2021, doi: 10.3390/app112110265.

[46] G. Wilmsmeier, "Climate change adaptation and mitigation in ports: Advances in Colombia," in *Maritime Transport and Regional Sustainability*, Elsevier, 2020, pp. 133–150. doi: 10.1016/B978-0-12-819134-7.00008-3.

[47] C. Izaguirre, I. J. Losada, P. Camus, P. González-Lamuño, and V. Stenek, "*Seaport climate change impact assessment using a multi-level methodology*," 2016, [Online]. Available: https://orcid.org/0000-0002-1730-0400

[48] S. Messner, L. Moran, G. Reub, and J. Campbell, "Climate change and sea level rise impacts at ports and a consistent methodology to evaluate vulnerability and risk," in *Coastal Processes III*, vol. 169, G. R. Rodriguez and C. A. Brebbia, Eds., Great Britain: Lightning Source UK, 2013, pp. 141–153. doi: 10.2495/13CP0131.