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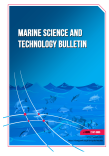

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RESEARCH ARTICLE

Floating ports as support for port relocation measures on sea level rise

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ABSTRACT

Ports are one of the structures where the effects of global warming are most severe and intense in atmospheric, oceanic, and geographical terms. According to the Intergovernmental Panel on Climate Change (IPCC)'s assessment reports, although it is possible to slow down global warming by reducing greenhouse gas (GHG) emissions, it is not foreseen to stop global warming and sea level rise (SLR) in any scenario. The rising sea level, an inevitable consequence of global warming, is a clear threat to conventional port facilities. In summary, SLR triggered by climate change, which is today's hot topic, may cause conventional port infrastructures to be flooded and lose their functionality. To cope with this threat, port facility planning, and design stages must be carried out by referring to the updated threshold values in Shared Socioeconomic Pathway (SSP) scenarios defined by the Working Groups of the IPCC. However, the uncertainty about the scale, timing, and location of SLR makes definitive solution-oriented approaches more prominent. One of these approaches is floating port structures. This study aims to reveal the role of floating port structures in the implementation of the relocation measure emphasized in the IPCC Sixth Assessment Report (AR6) for conventional ports under the threat of SLR. Initially, in this study, regions with higher SLR risk were identified by considering SSP scenarios contributed by Sixth Phase of the Coupled Model Intercomparison Project (CMIP6) data. Afterwards, the dynamic downscaling model was used to determine the regions with higher regional sea level rise (RSLR) risk and the Marine Traffic database was used to determine the ports in these regions. Thus, it is evaluated whether floating ports can be a suitable alternative in the relocation decision of ports under SLR risk. It is expected that maritime transport will be maintained at adequate security and operational levels by revealing the pros and cons of floating ports.

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Introduction

Ports are strategically located to feed supply chains for the sustainability of global trade on coastlines, riverbanks, low-lying areas, and deltas. Asariotis et al. (2018) state that the locations of ports make them vulnerable to a range of hydro-meteorological hazards resulting from climate change, and 72%

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of ports are negatively affected by these hazards. Considering the role of ports in global trade, which is an essential component of maritime transportation that responds to more than 90% of global cargo flows by volume (Sirimanne et al., 2019), disruption of port operations can cause regional and international economic shocks. Therefore, well-targeted response measures are required to reduce climate change impacts on port operations, infrastructure, and assets.

UNCTAD (2011), which provides a platform with an ad hoc expert meeting on climate change subject, is looking for ways to develop policies on how best to improve the understanding of the impacts of climate change on ports and develop effective and appropriate adaptation response measures. Savonis et al. (2008) state that sea level rise (SLR) can cause floods, damaging ports, terminals, intermodal facilities, storage areas, port-connected transportation systems, and, of course, cargo, rendering them unusable, thus disrupting supply chains and transportation. Esteban et al. (2017) underline that the consequences of mean sea level rise (MSLR) will be much more serious if precautions are not taken, especially in regions experiencing rapid subsidence. Reports presented by organizations such as Intergovernmental Panel on Climate Change (IPCC), World Meteorological Organization (WMO), and United Nations Environment Program (UNEP) constantly revise SLR projections upwards (Prestrud, 2007; IPCC, 2023; WMO, 2023). A continuous MSLR, combined with future extreme storm surges, waves, and tides, could result in devastating extreme sea level rise (ESLR) events that pose a serious threat to ports.

The importance of port authorities' contributions to the sustainability of supply chains by taking short-medium-long-term measures against SLR risks is increasing day by day. However, alternative solutions play a critical role as existing long-lasting and strong measures impose high financial burdens on ports. At this point, low-cost floating ports that can support the solution of port relocation where the risk of SLR is absent (maybe valid for a short period) or relatively low should be considered.

Most studies in the field of floating ports have only focused on increasing the capacity or operational flexibility of existing conventional ports (Kim & Morrison, 2012; Baird & Rother, 2013). In other words, the use of floating ports to port relocations to cope with SLR has not been investigated. Therefore, it is still not known whether floating ports can cope with the SLR. Therefore, this paper attempts to show the general technical features of floating ports and analysis the pros and cons of floating port alternatives for SLR that can impact supply chain sustainability.

Sea Level Rise Projection

Studies show that the rate of global SLR since the early 20th century has been sharply above the stable historical course of the previous 2000 years (Church & White, 2006, 2011; Engelhart et al., 2009; Gehrels & Woodworth, 2013; Stocker, 2014). Kemp et al. (2011) showed a consistency between sea level change and global warming using extended semiempirical modeling. In IPCC Sixth Assessment Report AR6, human activities are seen as the main cause of SLR (IPCC, 2023). There has been a dramatic acceleration in the rate of average SLR from the past to the present due to the impact of humans on global warming as is seen in Table 1.

Table 1. Historical MSLR rates

Years	SLR range (mm/year)	Average rate of SLR (mm/year)
1901-1971	0.6 to 2.1	1.3
1971-2006	0.8 to 2.9	1.9
2006-2018	3.2 to 4.2	3.7

Note: (Source: Adapted from IPCC (2023))

For years from 1901 to 2018, the average global sea level increased by 15–25 cm, corresponding to an average of 1–2 mm per year (IPCC, 2019, 2023). The apparent reason for SLR is the thermal expansion of seawater and the melting of temperate glaciers (Wouters & van de Wal, 2018). These apparent reasons are triggered by climatic factors such as increase in temperatures, desertification, decrease in precipitation, loss of biodiversity, and degradation of land and forests. If global warming continues in its current form, it has been revealed by the National Research Council (2011) that SLR will accelerate until 2050. After 2050, different SLR rates may be encountered in the light of scenarios produced depending on the amount of emitted greenhouse gas. However, SLR is predicted to occur even in the most optimistic scenario which includes deep emission cuts.

The Intergovernmental Panel on Climate Change's (IPCC) prediction for 2100 was that there will be an MSLR in almost all different emission scenarios (Church et al., 2013). The IPCC's fifth assessment report (AR5) predicted an MSLR of 0.4-0.6 m in the strongly reduced emissions scenario Representative Concentration Pathway (RCP) 2.6 by 2100. According to the high warming scenario (RCP 8.5) of the same report, it was argued that MSL may exceed 1 m and cause more serious consequences. With a comparison between IPCC's AR5 and

AR6, it is seen that MSL is revised upward direction in all defined scenarios due to the expectation of an increase in the frequency of climatic factors such as sharp changes in temperatures, desertification, decrease in precipitation, loss of biodiversity, degradation of land and forests, and retreat of glaciers (IPCC, 2014, 2023). In Table 2, the revised MSLR rates in IPCC AR6 as of 2100 are given so that they can be compared with IPCC AR5.

Unfortunately, research shows that SLR in the future is certain. However, how long and to what extent this increase will occur depends on GHG emissions. Some predictions are made in the scenarios produced (from very low to very high as a five-scale range in IPCC AR6) to understand this projection and be prepared for future SLR risks. Taking 1900 as a reference point, observations, and projections for the years 2100, 2150 and 2300 are given in Figure 1. Kopp et al. (2019) describes the risks of unpreventable SLR as follows: (1) losses to coastal ecosystems and ecosystem services, (2) damage to coastal structures, including ports, and (3) extreme and permanent flooding. In addition, it is expected that more than 1 billion people in the low-lying coastal zone to be affected and extreme sea level events can increase 20-30 times (Hauer et al., 2020; IPCC, 2023). Realization of GHG emissions as in the high scenarios can lead to a larger and faster SLR, requiring earlier and stronger measures to be taken. Protection sets, protection barriers, and planned relocation that can be taken for higher scenarios can be seen as stronger, longer-lasting measures (IPCC, 2023), but on the other hand, these are high-cost.

Table 2. A comparison of the revised MSLR in IPCC AR6 according to IPCC AR5

		Assessment Report 6 (AR6)[1]		**Assessment Report 5 (AR5)**[2]	
Category in WGIII[3]	***Category description***	***GHG emissions scenarios (SSPx-y)***[4] ***in WGI***[5] ***& WGII***[6]	***Global MSLR***[7] ***by 2100***	***RCPy***[8] ***in WGI & WGII***	***Global MSLR by 2100***
C.1	limited warming to 1.5°C (>50%)	Very low (SSP1-1.9)	28-55 cm		
C.2	returned warming to 1.5°C (>50%) after a high overshoot				
C.3	limited warming to 2°C (>67%)	Low (SSP1-2.6)	32-62 cm	RCP2.6	28-61 cm
C.4	limited warming to 2°C (>50%)				
C.5	limited warming to 2.5°C (>50%)				
C.6	limited warming to 3°C (>50%)	Intermediate (SSP2-4.5)	44-76 cm	RCP4.5	36-71 cm
C.7	limited warming to 4°C (>50%)	High (SSP3-7.0)	55-90 cm	RCP6.0	38-73 cm
C.8	warming exceed to 4°C (>50%)	Very high (SSP5-8.5)	63-101 cm	RCP8.5	52-98 cm

Note: ***(***Source: Adapted from (Arias et al., 2021; Church et al., 2013; Field & Barros, 2014; Stocker, 2014; Edenhofer, 2015; Fox-Kemper et al., 2021; IPCC., 2022a, 2022b))

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[1] Intergovernmental Panel on Climate Change's Sixth Assessment Report - The contributions of Working Groups I, II and III were released on 9 August 2021, 28 February, and 4 April 2022 respectively. The Synthesis Report was also released on 20 March 2023.

[2] Intergovernmental Panel on Climate Change's Fifth Assessment Report – The contributions of Working Group I, II and III were released in September, March, and April 2013 respectively. The Synthesis Report was also released in October 2014.

[3] The working group III is about Mitigation of Climate Change.

[4] Shared Socio-economic Pathways

[5] The working group I is about The Physical Science Basis.

[6] The working group II is about Impacts, Adaptation and Vulnerability.

[7] Mean Sea level Rise

[8] Representative Concentration Pathways

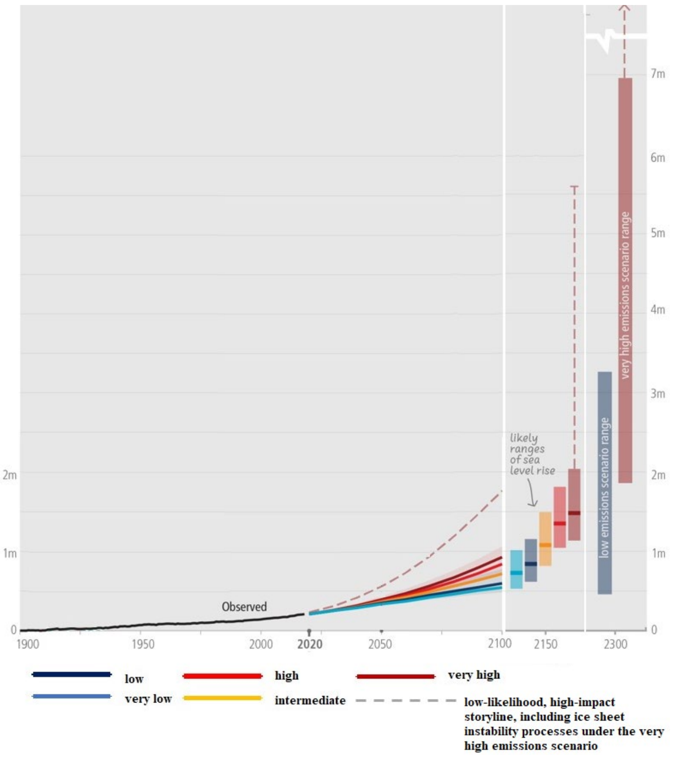

Figure 1. Observed and projected MSL change (Source: Adapted from IPCC, 2023))

Sea Level Rise Risks for Ports and Floating Ports

There is a growing body of literature that is concerned with the potential risk of SLR for ports from different perspectives. Karl et al. (2009) argued that an average sea level rise of 1.2 m would permanently flood more than 70% of existing port facilities on the US Gulf coast, whereas SLR of 5.5 m above the current mean sea level (MSL) to cause temporary flooding of 98% of port facilities. The study conducted on Small Island Developing States (SIDS) reveals that some ports in the Caribbean may be affected even by global warming below 1.5°C (Mycoo, 2018). In the study providing a wider focus on the effects of SLR on ports, Christodoulou et al. (2019) discuss the critical scenario in which approximately 450 ports in Europe may be affected when SLR exceeds 7.5 meters. Hanna et al. (2013) suggest that the change in MSL rise for this worst-case scenario could occur due to a combination of (i) ocean thermal expansion due to increased ocean heat content; (ii) increased ocean water mass due to melting of continental ice sheets, mantles, and glaciers; and (iii) isostatic adjustment, anthropogenic coastal subsidence, and changes in land water storage. Karim & Mimura (2008) argue that SLR leads to higher water levels in rivers and estuaries, increasing the risk of flooding for inland water ports. Pickering et al. (2012) state that the tidal regime affected by SLR may cause some changes in port infrastructure and operational planning. Hallegatte et al. (2011) address SLR risk and storm surge for the port city of Copenhagen, demonstrating a methodology for assessing the climate change's economic impacts at city and port scales and the benefits of adaptation.

Becker et al. (2016) and Radfar et al. (2021) state that ports in sensitive regions where SLR impacts can be seen need high-cost technical interventions. Defense methods against SLR include raising port walls and even relocating the port. Nicholls et al. (2008) claim that the costs of precautions taken by rich port cities against SLR are unaffordable for poor countries. While the cost of building an international port is approximately four billion Euro (Schade et al., 2013), the cost of a kilometer-long embankment that can provide protection for one-meter-high water can vary between one and four million Euros (Hippe et al., 2015). In other words, raising the port wall (which has an upper limit) or relocating the port can be a very burdensome solution.

In addition to its economic and financial dimensions, Thoresen (2010) emphasizes that building a port is a challenging process, starting from the planning stage and extending to the calculation of environmental forces and determining its technical and operational properties. This challenging process also includes an in-depth analysis of possible increases in the severity of ecological forces that ports may face with the impact of global warming. Reducing the margin of error in practical applications depends on more precise analysis by supporting assumptions with real data whenever possible. However, Gallivan et al. (2009) emphasize a major deficiency by stating that the data generally used in the planning phase of ports does not include climate change predictions. Although port planning processes do not have specific features to account for impacts associated with climate change, SLR is one of the more definitive consequences of climate change. Headland et al. (2011) draw attention to the responsibilities of relevant coastal management institutions in new project development permits by addressing SLR. The fact that there are various scenarios about SLR and its uncertainty in terms of scale, timing, and location causes hypothetical prediction thresholds to be considered particularly high. A scheduled maintenance/upgrade/adaptation is suggested by maintaining the desired security and operation standards in scenarios with varying risk levels to prevent seaports from being affected by SLR. On the other hand, alternative port structures that can support SLR measures can be considered as an approach to ensure the sustainability of maritime transport.

Floating ports which are suggested to support port relocation measures for SLR risks are used for various purposes in maritime transport. Kim & Morrison (2012) presented a study that includes the classification of floating ports that provide flexibility for various operational challenges thanks to their technical advantages. Kurt et al. (2021) suggest that larger-capacity floating container port systems can be considered as an alternative to conventional ports and can also be used to increase capacity in ports experiencing land shortages. Pachakis et al. (2017) analyzed the structural and operational implementations of the Venice Offshore-Onshore Port System (VOOPS), proposed by the Venice port authority to both increase the port cargo capacity and reduce the impact of SLR on Venice. The floating ports featured in Ali (2005) and Lau & Ng (2017) studies show that some tailor-made solutions can be developed with both complex and simple designs. Since SLR will increase land scarcity and make it difficult to afford the land needed for new port investments and port relocation, the lack of land purchase costs for floating ports, as stated by Baird & Rother (2013) and Kurt et al. (2015) brings these structures to the fore once again. Waals (2017) states that innovative floating structures proposed as an alternative solution to sea level rise will be more effective than raising dikes and sandblasting.

In the light of the data obtained from the past about SLR, and depending on three drivers (policy, technology, and consumer preferences) that affect how and how much energy will be used, the current situation shows that SLR is one of the consequences of climate change that must be combated in the future. However, studies conducted to date show that floating ports have not been examined to deal with the impacts of SLR on ports. Therefore, examining floating ports and contributing to their development to combat SLR may be a valuable step towards reducing the effects of SLR, if not eliminating it.

Methodology

The analysis focused on identifying ports likely to be affected by SLR in 2050 and 2100, based on global sea level changes according to GHG emission scenarios produced in IPCC AR6. For this analysis, IPCC's SSP emissions scenarios, from SSP1-1.9 to SSP5-8.5 (low confidence), were used to generate SLR projections. The CMIP6 (Coupled Model Intercomparison Project Phase 6) climate models were integrated under some SSP scenarios to project future SLR associated with increasing concentrations of greenhouse gases. The CMIP6 data underpins IPCC AR6, can be accessed through the Program for Climate Model Diagnosis and Intercomparison (PCMDI) (LLNL, 2023). Also, a dynamic downscaling model was applied to reveal regional sea level increases in 2050 and 2100 for ports. In this way, a higher-resolution coastal climate model was obtained. The coastal climate model integrates the effects of the region's atmospheric, oceanic, and geographical features on sea level change.

With this model, predictions of ports' exposure to SLR risk are made by determining SLR projections in port regions around the world. Therefore, a regional sea level rise (RSLR) was defined. RSLR includes geophysical sources that drive long-term changes, such as ice components, oceanic components, and glacier isostatic regulation, but does not account for local subsidence caused by human activities. RSLR is calculated from sea level elevation obtained from global climate models, including ocean, atmosphere, land, and cryosphere components. According to RSLR, major port areas at risk are identified and associated with floating ports that are expected to support the relocation measure emphasized in IPCC AR6. The sequential steps of the methodology are given in Figure 2.

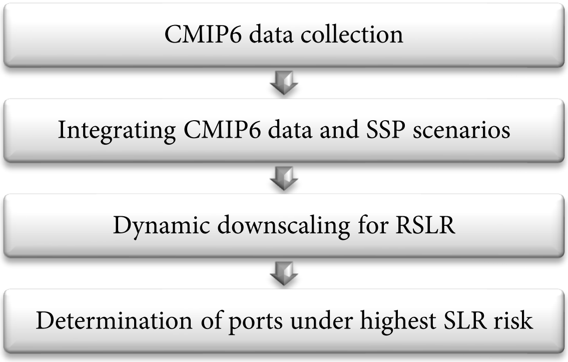

Figure 2. The sequential steps of the methodology

First, coastal areas at risk of SLR were determined by applying the defined model. Afterwards, the existing ports in these regions were determined with the data obtained from the Global Satellite Plan of the Marine Traffic. In the light of the data obtained, regions at risk of SLR were associated with countries and at least one port was defined for each country at risk of SLR. Accordingly, around 150 port areas that are likely to face the SLR threat have been identified. The data received from Marine Traffic includes characteristics of port area, port facilities, and berthing area, but also provides the operational characteristics and capacities of the ports. Thus, if these ports resort to a relocation solution when faced with SLR risk, a projection can be presented regarding the scope and size of the relocation operation.

The second stage is to determine the advantageous and disadvantageous aspects of suitable floating port systems that can provide operational sustainability for port regions whose RSLR was calculated. Thus, it can be discussed whether a floating port can respond to the relocation problem when a conventional port faces SLR risk, and the role of floating ports as a possible alternative port system was revealed. In determining the advantages and disadvantages of floating ports, the features highlighted in floating port projects and the positive and negative aspects mentioned in the existing literature are presented by applying strategic management tools.

Results

Figure 3 provides six sea level projections for 2050 calculated based on IPCC's AR6 generated scenarios (from SSP1(a) to SSP5 (low confidence) (f)).

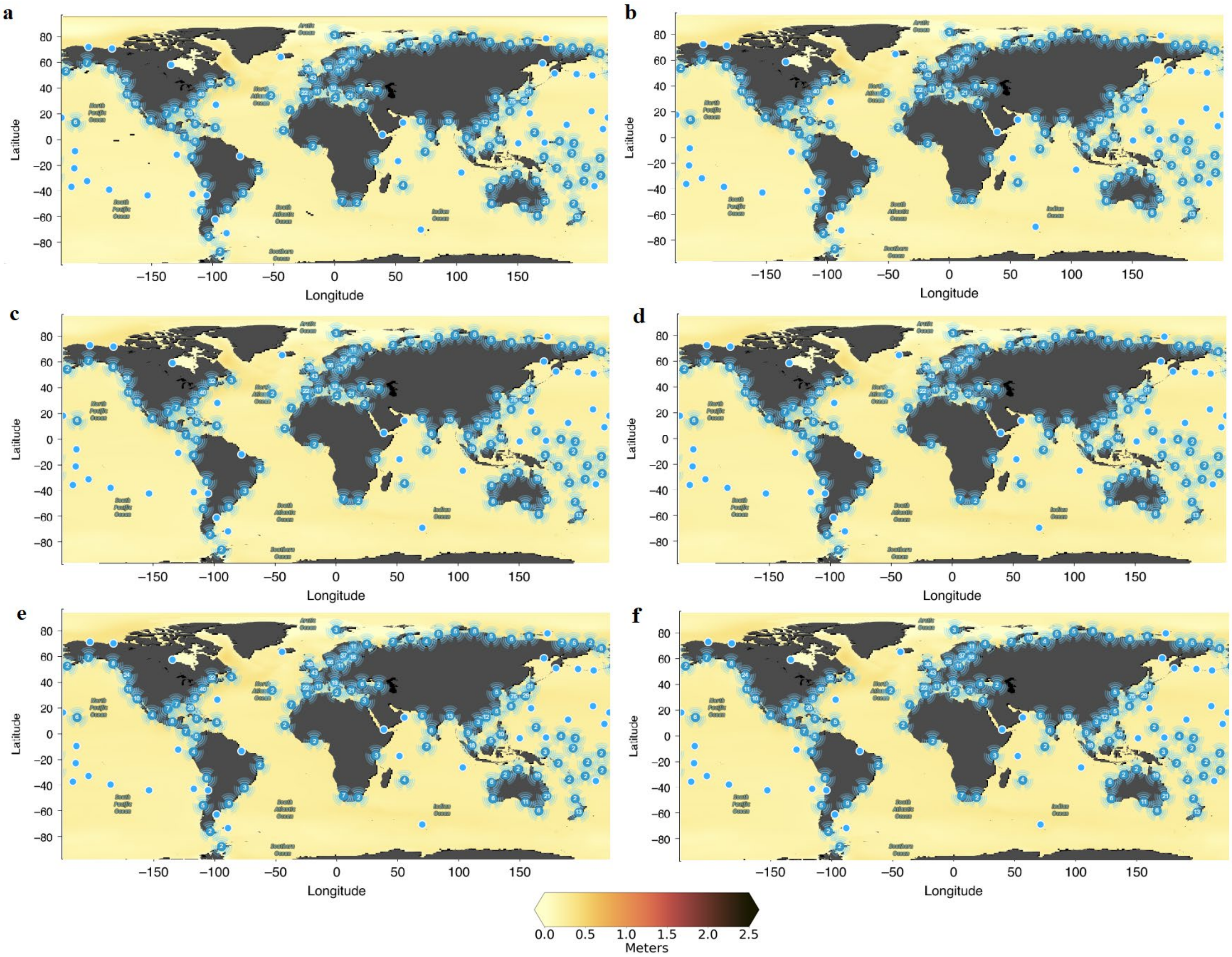

Figure 3. Sea level projections by 2050 according to SSPs based on IPCC AR6.[1]

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[1] These SLR2050 projections are based on the assessment presented in the IPCC Sixth Assessment Report. Sea level projections considering processes for which projections can be made are provided, relative to the period 1995–2014, for five Shared Socioeconomic Pathway (SSP) scenarios. SSP scenarios affecting the six SLR2050 projections are as follows. The maps:

- **a.** Represents the SSP1-1.9 scenario.
- **b.** Represents the SSP1-2.6 scenario.
- **c.** Represents the SSP2-4.5 scenario.
- **d.** Represents the SSP3-7.0 scenario.
- **e.** Represents the SSP5-8.5 scenario.
- **f.** Represents the SSP5-8.5 (low confidence) scenario.

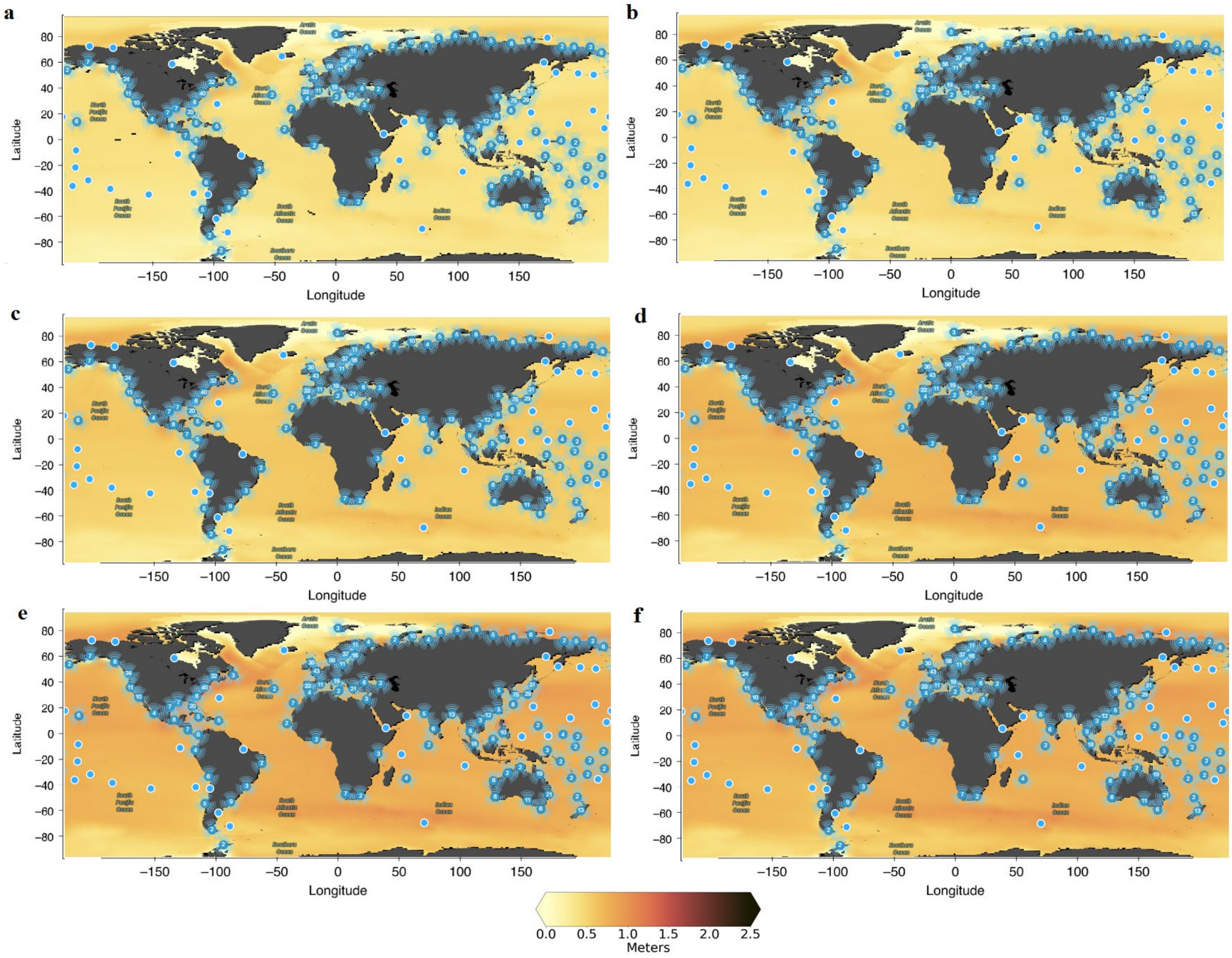

Figure 4. Sea level projections by 2100 according to SSPs based on IPCC AR6.[1]

Figure 4 provides six sea level projections for 2100 calculated based on IPCC's AR6 generated scenarios (from SSP1(a) to SSP5 (low confidence) (f)).

When the described methodological approach is applied, an overlap between SSP scenarios is observed in both 2050 and 2100 projections for most coastal areas. However, while the highest threshold of RCP2.6 calculated in the IPCC AR5 report overlaps with the lowest threshold of RCP8.5, it is seen that the SLR ranges in the SSP1-2.6 scenario do not overlap with those of SSP5-8.5 (see Table 2). Overlap between SSP scenarios is observed in SSP2, SSP3 and SSP5 scenarios. The overlap of SLR ranges in these scenarios explains that the continuum across the scenarios should be considered, especially in the short and medium term, since the future emission trajectory is uncertain. However, while the separation of this continuum spectrum in SSP scenarios, unlike the RCP scenarios, gives an idea that future projections are now more clearly observed, the upward revision of the SLR ranges also shows that the size of the threat has increased.

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[1] These SLR2100 projections are based on the assessment presented in the IPCC Sixth Assessment Report. Sea level projections considering processes for which projections can be made are provided, relative to the period 1995–2014, for five Shared Socioeconomic Pathway (SSP) scenarios. SSP scenarios affecting the six SLR2100 projections are as follows. The maps:

- **a.** Represents the SSP1-1.9 scenario.
- **b.** Represents the SSP1-2.6 scenario.
- **c.** Represents the SSP2-4.5 scenario.
- **d.** Represents the SSP3-7.0 scenario.
- **e.** Represents the SSP5-8.5 scenario.
- **f.** Represents the SSP5-8.5 (low confidence) scenario.

According to the first evaluation of the RSLR, the highest value is obtained under the SSP5-8.5 scenario. Ports where SLR due to the SSP5-8.5 scenario is further deteriorated by land subsidence will have the highest RSLR values in 2050 (see Table 3 (a)). In the RSLR evaluation conducted for the year 2100, while the land subsidence factor loses its impact, the highest values are observed in ports where the effect of large ocean currents is observed (see Table 3 (b)).

In Table 3 (a), port areas where the RSLR effect will be most intense are required to take positions according to the RSLR of at least 0.5 m or more by 2050. In this scenario, more serious measures should be sought for port areas that are likely to be exposed to 0.92 m RSLR in 2050. For this reason, the authorities of the ports at the top in the maximum RSLR list should operate their decision mechanisms based on 0.5-0.92-meter RSLR in their plans targeting 2050.

For the year 2100, all world ports must plan to be prepared for an RSLR of at least 0.28 m, even in the very low scenario SSP1-1.9. Looking at Table 3 (b), the situation is likely to become inextricable for major ports that may be exposed to RSLR of 1.5 m and above. Although the quay wall elevation is higher than the maximum RSLR, eliminating freeboard requirements for port operability pushes port authorities to take some measures (Gracia et al., 2019; Wijayanti et al., 2023). The findings suggest that it would be more beneficial and economically feasible for port authorities to plan according to the maximum RSLR in the medium and long term, rather than resorting to a series of SLR measures. According to the very high scenario, significant changes were seen in the port area rankings in the period from 2050 to 2100 in Table 3, as the impact of land subsidence in 2100 decreased on the port areas at the highest RSRL and the impact of ocean currents intensified. This global distribution is expected to change from Northern Europe, North Sea, and Black Sea regions to the Eastern American coasts, as shown in Figure 5 and Figure 6.

The lower and upper limit SLR calculated based on the emission scenarios produced by IPCC, RSLR projections including atmospheric, oceanic, and geographical characteristics of the regions and their changes over time determine the flexibility range for new port planning and adaptation of existing ports.

The findings show that floating port systems, which are proposed with a mission to support the relocation measure for existing ports to cope with the effects of RSLR, stand out as a more flexible measure compared to sets and barriers that protect existing ports against RSLR.

Table 3. Top ports with high RSRL in SSP5-8.5 scenario – 2050 (a) and 2100 (b) projections

(a) Maximum RSLR (SSP5-8.5) in 2050		**(b) Maximum RSLR (SSP5-8.5) in 2100**	
Port Region	***(m)***	***Port Region***	***(m)***
Calcutta (India)	0.92	Calcutta (India)	2.28
New Orleans (USA)	0.65	New Orleans (USA)	1.71
Alexandria, Port Said, Damietta (Egypt)	0.63	Mobile (USA)	1.69
Mobile (USA)	0.63	Toyohashi, Honshu (Japan)	1.69
Novorossiysk (Russia)	0.63	Alexandria, Damietta (Egypt)	1.66
Samsun (Turkey)	0.61	Port Said (Egypt)	1.65
Odesa, Illichivsk, Sevastopol (Ukraine)	0.60	Tianjin (China)	1.63
Haydarpasa, Istanbul (Turkey)	0.60	Hampton Roads, Norfolk (USA)	1.57
Varna (Bulgaria)	0.60	Brooklyn, New York (USA)	1.54
Gdansk, Gdynia (Poland)	0.56	Halifax (Canada)	1.54
Toyohashi, Honshu (Japan)	0.56	Baltimore (USA)	1.54
Rotterdam, Amsterdam (Netherlands)	0.54	Chester (USA)	1.53
London (UK)	0.54	Philadelphia (USA)	1.53
Tianjin (China)	0.53	Shanghai (China)	1.52
Immingham (UK)	0.51	Boston (USA)	1.51

Figure 5. Global distribution of top ports with the highest RSRLs based on SSP5-8.5 by 2050

Figure 6. Global distribution of top ports with the highest RSRLs based on SSP5-8.5 by 2100

In regions where some functions or port facilities may become completely dysfunctional due to the SLR effect, the floating port concept is being evaluated to serve especially larger ships and sectors seeking flexibility through transfer, supply, and logistics solutions. It is not possible to mention a uniform floating port design, as there may be a tailored-made design approach according to the location, operational, and technical needs of the ports in the regions shown in Figure 6. For example, the offshore port concept defined in the Portunus Project focuses on safer, greener, and more efficient transportation (Martin, 2021). In some examples, the functionality, flexibility, and economy of floating ports are highlighted by emphasizing land scarcity (BFSA, 2024; SeaTech, 2024). This functionality and flexibility are supported by modular designs whose arrangement can change according to the specific requirements of the port structure (Waals, 2017; National Ports, 2024). Additionally, floating ports can be moved to more protected areas by tugboats or their propulsion system, thanks to a design feature that allows short-distance relocations. Floating breakwaters to protect ships calling at the port from mild sea conditions (Dai et al., 2018) and modular port solutions that allow capacity increase will add dynamism to the structure (RINA, 2024). However, some concerns about the use of floating ports act as a barrier to implementation. Concerns about floating ports in general and possible floating port features in response to these concerns are given in Table 4.

Table 4. Concerns for floating ports and the given response

Floating Port Systems	
Motivation to Propose Floating Port Systems	
Floating port systems provides flexibility against sea level rise thanks to their floating feature.	
Concerns	**Responses for Concerns**
It may be more affected by extreme weather due to its offshore location.	It offers the opportunity to relocate to a region where the weather is more stable, thanks to its floating feature.
As the capacity of the floating port increases, the floating flexibility for relocation may decrease or even disappear.	The capacity can be limited so as not to lose its ability to relocate by floating. Modular feature can be provided to increase portability.
It may require complex machinery and navigation equipment for portability.	Portability can be achieved without internal machinery power or by supporting existing machinery and propulsion equipment via tugboats.
Cargoes will need extra handling to reach the hinterland.	Thanks to the extra handling, cargoes can be transferred to the hinterland from locations where the SLR effect is less observed, with marine vehicles designed for different coastal characteristics (such as coastline, inland water).

Table 5. Main pros and cons of floating port systems

Floating Port Systems	
Pros	**Cons**
No dredging required for water draft	Storage yard is restricted
Bridges on navigation route are not a constraint	Personnel facilities are limited
Canals on navigation route are not a constraint	Energy supply should be provided from shore or need extra investment for self-service
Land is not required for port facility	A stability system can be required
Provides higher operation and cargo safety due to not directly contact with land	Require higher equipment technology so needs costly equipment investment
Construction cost is lower	Require higher personnel qualification so more salary budget
Shorter payback period	
Higher internal return rate	

Floating ports, which promise a systematic approach to the relocation measure offered for SLR, also have the potential to attract attention with their short payback period. Floating ports, with their low investment cost, high return rate, and other techno-physical advantages compared to conventional ports, can be considered as an alternative against the SLR threat (Kim & Morrison, 2012; Baird & Rother, 2013; Kurt et al., 2015, 2021, 2023). Creating a sheltered area for a floating port may require the construction of a breakwater, which can cause a significant increase in cost and may negatively affect the economic feasibility of floating ports. However, Zhao et al. (2019) highlighted the advantages of floating breakwaters, such as relatively low construction costs, less dependence on marine geological conditions, low environmental impact, and flexibility. A system in which floating breakwaters and floating ports are integrated can stand out in terms of operational flexibility and economic benefit. In addition, positioning floating ports in sheltered areas against harsh sea conditions or moving them to a sheltered area by tugboats or their propulsion system can increase operational and economic benefits. The advantages and disadvantages of floating ports can be compiled with the aspects discussed in this study as in Table 5.

It can be said that the advantages of floating ports, compared to their concerns and disadvantages, bring these structures to the fore. Floating port structures can be considered not only to reduce the risk of SLR but also to support the sustainability of the maritime transport sector, which is constantly growing and technically exceeds the limits of conventional ports (Kurt et al., 2023). In addition, the fact that the ports in Table 3 are in densely populated locations makes floating port systems an important alternative in case of relocation of conventional ports, as they are not affected by land scarcity and land costs (Waals, 2017). Apart from these, while the modular and portable features of floating ports provide operational functionality and flexibility, at the same time it is possible to escape from atmospheric and oceanic challenging situations to more sheltered sea areas (Kim & Morrison, 2012; Baird & Rother, 2013; Pachakis et al., 2017; Waals, 2017).

Conclusion

According to the scenarios put forward by the IPCC in AR6, all ports in the world are expected to be affected by SLR. However, it has been observed that this effect may vary with atmospheric, oceanic, and geographical components with regional analysis of SLR. This study examines the possibilities of ports facing SLR by considering the effects of RSLR on port areas with 2050 and 2100 projections. As a result of this examination, two ways are recommended to deal with SLR in IPCC AR6: mitigation and adaptation.

Reducing SLR effects is possible by reducing emission values. However, SLR is an inevitable outcome in all scenarios produced by the IPCC. That is, even if the lowest scenario is realized with strict emission reduction measures, adaptation, upgrading, or reconstruction are methods that should be considered as other options for ports to reduce the potential impacts of SLR. In scenarios where emission reduction measures are implemented more strictly, it is preferred to provide port structure protection with sets and barriers. However, if emission reduction cannot be achieved, ports will have to resort to relocation measures by acting according to the high tolerance limit due to the increase in the RSLR.

The floating port option, which offers a systematic approach to relocation measures, is evaluated in this study. The reason why floating port structures are proposed as a systematic approach for relocation measures is that the ability to physically float makes floating structures more flexible in adapting to SLR. The fact that the floating port system can respond to the concerns in physical and technical aspects reveals the flexibility of floating structures. However, the fact that existing conventional ports have not yet faced a serious SLR threat and that floating port systems have not been proposed before to cope with the SLR threat can be defined as the limit of this study. Therefore, performing static and dynamic analyses of a high capacity floating port and determining tailored floating port structures considering regional atmospheric, oceanic, geographical, and operational factors can be recommended for future works.

Compliance With Ethical Standards

Conflict of Interest

The author declares that there is no conflict of interest.

Ethical Approval

For this type of study, formal consent is not required.

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Data Availability Statement

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

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