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Climate Change Adaptation in the Port Industry: Evaluating Evidence of Implemented Adaptation Using a National Adaptation Inventory

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Key Points:

- No matter how well adapted ports are to current conditions they must consider new or increased risks within short and long-term planning
- Evaluation of some of the largest commercial ports in the UK highlights they are incrementally adapting to diverse climate-related risks
- More transformational adaptation will require a shift from business-as-usual to consider climate risks and adaptation in longer-term plans

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract

Ports provide critical infrastructure services, supporting global trade, economic growth and development. Owing to their exposed coastal locations, ports are expected to face increasing climate-related risks, such as sea-level rise (SLR) and changes in storminess. However, there is a gap in current literature evaluating how ports are addressing climate-related risks through implementation of adaptation actions. This study explores if, and how, some of the largest commercial ports in the UK are adapting to risk in practice. Evidence of implemented adaptation action is extracted from Adaptation Reporting Power (ARP) reports, as mandated under the UK Climate Change Act 2008. Evidence of incremental adaptation was identified, in response to an increasingly diverse range of perceived climate-related risks. However, uncertainty around future changes in some climate-related risks, and different risk perceptions, meant ports were also coming to different judgments on when and how they should adapt. A discord between short and longer-term planning was also identified. Consequently, there remains the need to shift thinking from business-as-usual toward a more systematic and integrated consideration of short- and longer-term climate risks, adaptation and wider benefits to support decision making. This would align with a more transformational adaptation approach. This could include exploiting the renewal and investment cycle so new port infrastructure is climate-proofed when constructed. The framework presented here, to identify, catalog and evaluate implemented adaptation actions in the UK, could be applied to other regions. This would provide a more comprehensive picture of how ports are implementing adaptation globally.

Plain Language Summary

Ports provide services, support global trade, economic growth and development. Whilst they have historically developed to cope with extreme weather conditions given their exposed coastal locations, climate change means they will be increasingly exposed to events and conditions beyond current experience. To understand how ports are adapting to cope with current and future climate-related risks, the study extracted and evaluated evidence of adaptation actions reported by some of the largest commercial ports in the UK. The analysis highlighted that, at least for larger ports, they are evaluating short- and longer-term climate-related risks and increasingly implementing adaptation actions such as upgrading or investing in new flood protection infrastructure. Most actions identified were implemented in an incremental and ad-hoc fashion. Given risks are likely to increase with continued global warming there remains a need for a longer-term vision which views adaptation, and enhanced resilience, alongside wider port development and investment decision making. This would be a step toward more transformational adaptation, which would establish more flexibility in the sector to longer-term unknown or uncertain climate-related risks. The framework presented could be applied to other ports globally, helping to address the gap in our current understanding of how ports are adapting in practice.

1. Introduction

Ports provide critical infrastructure services. They are essential for maritime transport and global supply chains, supporting economic activity, growth and development (Azarkamand et al., 2020; Izaguirre et al., 2021; Verschuur et al., 2023). It is estimated that over 80% of goods traded globally (by volume) are transported by sea routes (Becker et al., 2013; León-Mateos et al., 2021). Whilst the COVID pandemic led to unprecedented levels of disruption, there is evidence of a robust recovery in trade and the connections between ports (Li et al., 2024). Trade projections indicate that port capacity will almost certainly need to expand further to meet growing demand (Hanson and Nicholls, 2020). For example, the British Ports Association (BPA) reported surging investment of over £1bn in UK ports in 2021 (compared to £600m in 2020) reflecting longer-term growth prospects (BPA, 2021).

Ports are sensitive to weather hazards and climate-related risks due to their strategic positioning along coasts and rivers (Asariotis et al., 2024). Sea level rise (SLR) can change onshore wave propagation, wave induced currents and related morphodynamics. Coastal wave heights will commonly increase even if offshore waves are constant due to diminished nearshore wave dissipation.

Verschuur et al. (2023) highlight that 95% of ports are exposed to more than one natural hazard while 50% are exposed to four or more. Of these hazards storms and flooding pose key risks. Additionally, high temperatures and heatwaves can affect infrastructure and staff productivity; heavy rain and surface water flooding can damage infrastructure and affect power supply; snow and ice can affect transport and mobility around ports; and fog can disrupt operations (Bricheno et al., 2023; Jenkins et al., 2022a). Hazards occurring outside the port area can also disrupt port operations due to interdependencies with external infrastructure outside the control of ports (Glavovic et al., 2022). Disruptions can cause short-term effects, such as operational shutdowns and supply chain delays, as well as longer-term repercussions, including prolonged supply chain bottlenecks and a loss of trade competitiveness and investor confidence. These longer-term repercussions may persist until infrastructure and networks are fully reconstructed (Koks et al., 2019).

Ports have historically embedded a high level of preparedness into their operations, to cope with adverse weather conditions (Hein and Schubert, 2021; Jenkins et al., 2022a). However, observed impacts of flood and storm induced damages in coastal areas and damage to infrastructure have been increasing across the globe, with risks along coastlines projected to rise rapidly in the mid-to longer-term (IPCC, 2022). For example, the proportion of intense tropical cyclones and their peak wind speeds are projected to increase at the global scale (Seneviratne et al., 2021). Climate risk information and projections will therefore play a vital role in supporting decision making of global port operators. At the regional level Fernandez-Perez, Lara et al., 2024 evaluate effects of climate change on port infrastructure and operations in Northern Spain, accounting for waves, wind, SLR and the interdependencies of infrastructure. Izaguirre et al. (2021) provide a global analysis of risks highlighting that coastal flooding and overtopping due to SLR, as well as implications of increasing temperature for heat stress, will be key areas to plan for. Verschuur et al. (2023) estimates that economic losses to port infrastructure and operations due to multi-hazard events are equivalent to 7.5 billion US$ per year globally. Risk frameworks such as these are key to help communicate the need for action. At the regional and local level they can support planning and investment decisions regarding the implementation of adaptation to enhance port resilience (Becker et al., 2012; Fernandez-Perez, Lara et al., 2024; Zhang et al., 2020).

Port infrastructure and assets will also evolve over time, given the need for port expansion. Satellite measurements show that 65 of the world's top 100 container ports have used land reclamation to expand seaward from 1990 to 2020. This reflects the need to accommodate growth in megaships and increasing capacity of container ports (including mega-hubs). Therefore, any assessment of future risk should consider the implications of dynamic and potentially seaward expansion of ports on future exposure and vulnerability (Sengupta and Lazarus, 2023). Conversely, global alliances in shipping companies may increase operational resilience to disruptions due to the industry's enhanced flexibility in rerouting and rescheduling (Hesse et al., 2018; Yang et al., 2025). Given that high performing ports can attract significant foreign investment and support economic development, there is growing awareness of the reputational role that resilience to climate change could play in enhancing competitiveness (Humphreys, 2024; Xia et al., 2024).

1.1. Climate Change Adaptation in Ports

The Intergovernmental Panel on Climate Change (IPCC) define adaptation as “measures taken to reduce climate risks and vulnerability mostly via adjustments of existing systems” (IPCC, 2023, p. 20). Adaptation can be further categorized as incremental or transformative (Fedele et al., 2019). Incremental adaptation involves making changes or upgrades to existing systems and infrastructure to enhance resilience to the impacts of climate change. Transformative adaptation implies a more fundamental shift than incremental adaptation, typically requiring higher upfront investment but potentially offering greater long-term resilience. It requires changes to the structure or function of systems and approaches to reduce exposure and vulnerability to short- and longer-term risks (O'Neill et al., 2022; Sayers et al., 2015, 2017; Lonsdale et al., 2015). As some climate change is inevitable, but the magnitude is uncertain, the system (e.g., comprising people, infrastructure, institutions, and environments) needs to be flexible and capable of adjusting to longer-term change (Sayers et al., 2017).

Despite there being multiple definitions of transformational adaptation (O'Neill et al., 2022; Sayers et al., 2015, 2017; Lonsdale et al., 2015), moving from a theoretical to practical framing remains difficult. For ports transformational adaptation could be viewed through the lens of anticipatory, as opposed to reactive risk management. This would mean not just responding to and prioritizing short-term risks but longer-term planning and investment in adaptation actions today in preparation for longer-term risks (IPCC, 2022). It could encompass innovative solutions that move away from incremental upgrades or business-as-usual approaches, with decision making informed by long term projections and uncertainty (Lonsdale et al., 2015). Transformational adaptation, which involves system-wide changes, particularly considers multiple and potentially compounding risks due to interdependencies across port infrastructure and operations (Fernandez-Perez, Lara et al., 2024). Likewise transformational adaptation could be designed alongside other environmental and social goals and targets (Becker, 2017), such as wider port sustainability or mitigation plans, to enhance the feasibility of actions.

However, while ports can be dynamic and adaptive in how they cope with changing conditions such as growth in trade, increasing ship size, or shocks such as the COVID pandemic, to date there has been limited evaluation of if and how ports are actually implementing climate change adaptation (León-Mateos et al., 2021; Panahi et al., 2020; Yang et al., 2018). Panahi et al. (2020) evaluated peer-reviewed articles on adaptation in ports in the UK from 2005 to 2019. Whilst the number of articles increased over time the focus was on the development of risk assessments and inception of adaptation rather than the process of implementing action. Similarly, Cabana et al. (2023) reviewed 650 peer-reviewed articles on coastal climate adaptation and found that only 1% of articles related to the implementation phase as opposed to adaptation assessment, planning or monitoring. This highlights a significant research gap regarding evidence of actual adaptation practices in the port sector and coastal adaptation more broadly.

To address this research gap, this study applies a systematic approach to identify and collate evidence of implemented climate change adaptation across a set of the largest commercial ports in the UK. While it is argued that progress in implementing adaptation on the ground has been slow to date (Asariotis et al., 2024), it is also postulated that evidence of implemented adaptation will be more readily identified from gray literature sources such as organisational reports (Jenkins et al., 2022a). As such this study marks a difference in approach to previous studies which focused on academic literature (Cabana et al., 2023). In this study publicly available reports compiled and submitted to the Department for Environment, Food and Rural Affairs (Defra, a UK Ministerial Department responsible for protecting the environment) by commercial ports in the UK are analyzed. This provides new insight into whether UK ports are adapting to current and future climate-related risks. It also provides a new evidence base which can be evaluated to further understanding of the types of adaptation being implemented; any adaptation gaps, barriers or enabling conditions; and contribute to wider discussions on how implemented adaptation aligns with incremental or transformative thinking. Whilst the identification of implemented port adaptation is focused on the UK the transferability of the method to other regions is also discussed.

2. Method

2.1. The UK Case Study

In the UK the consideration of climate change and SLR in the design of sea defences has been evolving since 1989 (MAFF, 1999, 2001). The project appraisal guide for operating authorities related to flood and coastal defense projects highlighted the need to consider both extreme sea levels in combination with surge and wave conditions (assuming extremes would be stationary) and the need for adjustments, accounting for the effects of climate change, due to SLR within longer-term sustainability assessments (assuming a linear rate of global rise in SL of 4.5 mm per year) (MAFF, 2001). Inclusion of SLR has since moved from a lack of recognition (Sayers et al., 1998) to being recognised but not mainstreamed (Besley & Sayers, 2000), and subsequently mainstreamed into longer-term risk assessment and design (e.g., Fernandez-Perez, Losada et al., 2024; Thoresen, 2014).

This is key given observed increases in extreme still-water levels around the UK are predominantly due to rising mean sea levels (Haigh et al., 2022). Furthermore, populations in the UK, and internationally, will face centuries or more of climate-induced SLR due to historical anthropogenic emissions alone, even with stringent mitigation scenarios (Nicholls et al., 2018; Oppenheimer et al., 2019). Even the most optimistic SLR outcomes for the UK

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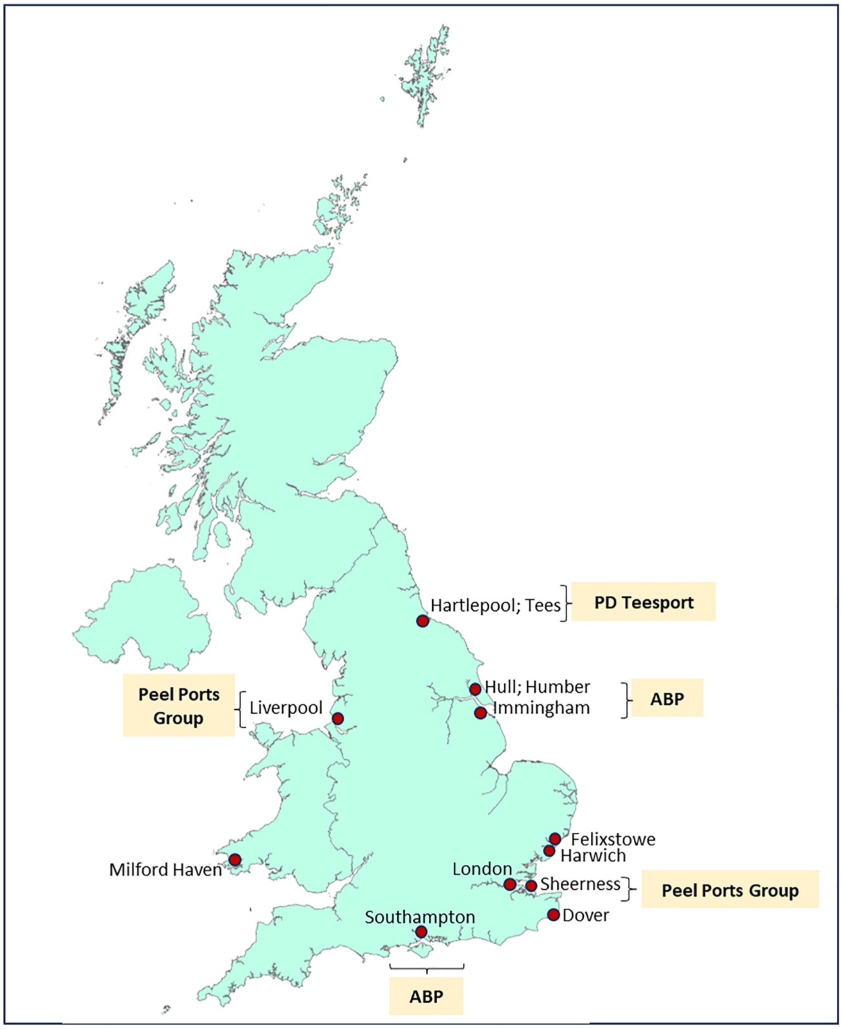

Figure 1. Location map of the ports and reporting port operators (see Table 1). Based on (DfT, 2024).

will require adaptation of up to 1m for large sections of the coastline by 2300, with high-end increases of up to 4.3 m possible for London (Palmer et al., 2024).

Alongside SLR the UKs 3rd Climate Change Risk Assessment (CCRA3; Climate Change Committee, 2021) highlighted that the nation will face hotter and drier summers and wetter and warmer winters, amplifying risks of fluvial and pluvial flooding, coastal erosion and extreme summer temperatures. There is limited evidence of any long-term trends in storms and wave heights beyond natural variability, and difficulty in attributing any deviations to climate change (Haigh et al., 2022). However, some studies report an observed increase in storm frequency since the 1990s and increased wave height in the south of the UK (Bricheno et al., 2023) with potential for changes in wind strength and wave height in the future (Climate Change Committee, 2021).

Acknowledging future risks will be key for the port sector in the UK, particularly where there is already potential for present events to exceed historical experiences and surpass current design thresholds. For example, the exceptional winter storms of 2013/14 caused widespread damage to ports (Chatterton et al., 2016; Wadey et al., 2015). Severe flooding was experienced at the ports of Immingham, Hull and Lowestoft, with significant damage and port closures at Immingham and Dover (Adam et al., 2016; see Figure 1 for location map). Immingham was particularly hard hit with 75% of the port area flooded during the event (ABP, 2016). Losses from the winter storms of 2013/14 were estimated to be £10 to £15 million, with the total cost estimated to be over £40 million (Chatterton et al., 2016; Wadey et al., 2015) or closer to £100 million if wider costs to businesses in the port boundary were considered (ABP, 2016). This event also constituted a "near miss" as the flood came close

Table 1
Summary of Reports Evaluated as Published by Port Authorities Under Each of the ARP Rounds

	Port authority	Round 1	Round 2	Round 3
1	Associated British Ports (focused on their Humber, Hull, Immingham and Southampton ports)	Y	Y	Y
2	Port of Dover	Y	Y	Y
3	Port of Felixstowe	Y	Y	N
4	Peel Ports Group (Mersey Docks and Harbor Company Ltd)	Y	N	Y*
5	Milford Haven	Y	Y	N
6	PD Teesport (Teesport and Hartlepool ports)	Y	Y	N
7	Port of London Authority	Y	Y	Y
8	Peel Ports Group (port of Sheerness)	Y	N	Y*
9	Harwich Haven	Y	N	N

Note. Note some, such as Associated British Ports, cover more than one distinct port (* Reported together in single report).

to disrupting national energy supplies (imported biomass fuel). Subsequent reactive investments in adaptation at Immingham have included the replacement of outer lock gates which have a higher standard of protection (ABP, 2016; Chatterton et al., 2016) as well as efforts to improve extreme water level forecasts (French et al., 2017).

2.2. Constructing a Port Adaptation Inventory

The method builds on the approach of Jenkins et al. (2022a) which developed a national UK Adaptation Inventory based upon reported evidence of adaptation action "on the ground" across organizations in key climate-sensitive sectors. Adaptation action "on the ground" was defined based on actions that reflected a tangible and physical change in response, focusing the analysis on the implementation phase, as opposed to building adaptive capacity through planning (UKCIP, 2018). A second benefit of this focus is that it can identify the specific types of adaptation being invested in by ports in response to different risks.

In the initial UK Adaptation Inventory, a key source of evidence was the 2nd round Adaptation Reporting Power (ARP2) reports submitted by climate sensitive sectors. Under the UK Climate Change Act 2008 (UK, 2008), there is a commitment to progress adaptation planning and action (Averchenkova et al., 2021), including a mandate for regular reporting to ensure organizations are identifying climate-related risks and appropriate responses (Committee on Climate Change, 2017). Defra oversees the ARP guidelines, requirements, and reporting process.

This study builds on the existing evidence extracted from the ARP2 (voluntary) reporting round from 2013 to 2016, applying the same method to identify and document evidence from the 1st round (ARP1) (mandatory) (2010–2012) and the 3rd round (ARP3) (voluntary) (2021–2023) of reports submitted by ports. Due to the voluntary nature of reporting in ARP2 and ARP3, compared to the mandatory reporting under ARP1, there are inconsistencies in the coverage of reporting across rounds (Table 1). Whilst results are presented as totals and disaggregated by rounds it is important to note that there are limitations in how temporal trends can be evaluated. Yet, given the limited existing data on implemented adaptation action, it is argued that drawing together information from the combined set of ARPs can provide wider insights into the preparedness and response of the port sector.

Globally, port ownership is a diverse landscape, with a mix of private and public entities playing a significant role in global trade and logistics. In the UK, there is a mixture of private, trust and local government ownership. In this analysis, as the primary source is the ARP reports large, private ports are considered. The analysis covers 13 of the largest commercial ports around the UK (Table 1; Figure 1). These ports account for 66% (280 million tonnes) of the 426 million tonnes handled by the 51 major ports in the UK in 2023. The reporting ports are mainly located in England, with one port in Wales. Alongside the 51 major ports, the Department for Transport (DfT) lists 25 minor ports in the UK (DfT, 2024), which are not considered in this analysis.

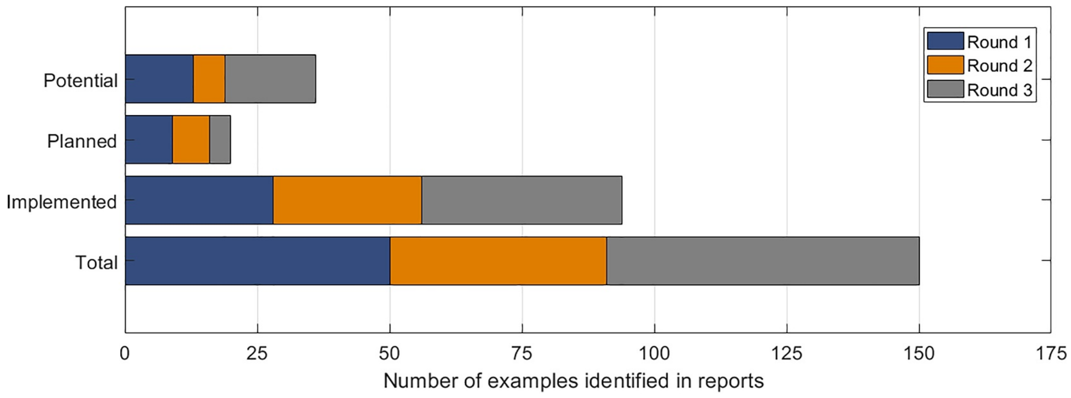

Figure 2. The number of documented examples of adaptation action in total and split by those reported as being *implemented*, *planned* or having *potential*.

The ARP documents were manually screened for evidence of where implemented adaptation was reported and key information collated using the Inventory Framework, to ensure entries for each adaptation example follow pre-defined definitions, categorizations and structure. For example, information on the sector, region, type of adaptation action, expected outcome/benefit and whether the action was reactive or anticipatory (see Table S2 in Supporting Information S1 for full criteria and definitions). The types of adaptation action identified were further categorized into 14 broader groups, based on key terms referenced across the ARP reports. e.g., if they represented operational improvements, habitat restoration or flood protection. Furthermore, adaptation actions are categorized based on the mechanism of the approach as defined by the IPCC (e.g., engineered and built environment or technological approaches; Mimura et al., 2014).

As an extension to the original method, a further column was added to record whether the same adaptation action was reported by the same port in a preceding ARP round report, and if/how that action had progressed over time. The UK Adaptation Inventory is available as a searchable database, where data on ports can be filtered using the sector field, accessible at: nismod.ac.uk/openclim/adaptation_inventory.

3. Results

The number of port operators reporting was nine in ARP1, where reporting was compulsory, declining to six and four in ARP2 and ARP3 respectively (Table 1). Of the 19 ARP reports submitted (covering either a single or multiple ports), 18 documented examples of implemented adaptation with Harwich the exception. The level of detail provided in the reports varied from more generalized descriptions of what adaptation actions had or could be implemented in the short-, medium- and longer-term (e.g., ABP, 2011; Harwich Haven Authority, 2011) to more detailed tables that identified levels of risk, implemented actions, planned or potential actions and barriers (Port of Dover, 2021; Port of London Authority, 2021).

3.1. Evidence on Implemented Adaptation

In total, 150 examples of implemented, planned, or potential adaptation actions were identified in response to 11 different climate related hazards/events or compound events. Of the 150 cases, 63% (94 cases of adaptation action) were reported as already implemented, whilst 13% (20 cases) were planned for implementation and 24% (36 cases) highlighted potential longer-term options (Figure 2).

Focusing on *implemented* actions only, the largest number of adaptation actions documented were reported to be in response to storms, flooding and SLR, reflective of the geographic position and interaction of ports with their coastal environments, and related conditions such as extreme rainfall and increased wind speed (Figure 3). Trends are similar when evaluating all implemented, planned or potential adaptation actions together. The exception is that flooding ranked fifth instead of second, due to fewer examples of future planned and potential actions in ARP2 reports (Figure S1 in Supporting Information S1).

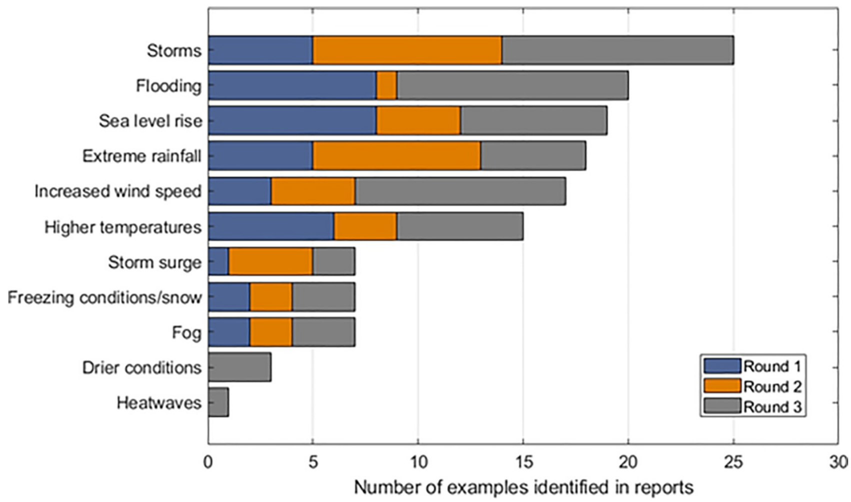

Figure 3. The number of adaptation options *implemented* in response to different climate-related hazards and events (note, terminology used for classifying hazards/events reflects that used within the reports by reporting organizations).

Due to inconsistencies in reporting across the three rounds it is difficult to make wider comparisons over time, although there appears to be a growing awareness of more diverse climate-related hazards e.g. drier conditions and heatwaves in the third round. At the port level, in some cases the transition from planned to implemented adaptation could be identified from the reports. e.g., adaptations related to traffic management at the Port of Dover to cope with extreme weather events were implemented between ARP1 and ARP2 rounds and ARP2 and ARP3 rounds. However, these examples were in the minority, either as the format of subsequent reports did not support tracking of actions, or actions that could be tracked were still not implemented. e.g., the Port of Dover consistently identify larger grit stores and snow clearing services, as well as additional ramp heating, as potential actions to cope with snow and ice in the future. Evidence of timescales for implementing action were also not well documented in the ARP reports. Potential reasons alluded to in some of the ARP reports included that some risks are identified as being longer-term and so a robust business case for short term capital investment and planning can be challenging (e.g., Port of Dover, 2021; PeelPorts, 2021; discussed further in Section 3.3).

A further reflection made in the ARP reports was that uncertainties in projecting some climate variables, including wind speed and direction, lightning, fog and freezing fog, created barriers for understanding risk and informing adaptation decision making. Whilst some ports continually factor in the possibility of low probability high impact sea level ranges in their stress testing, including SLR above 1 m by 2100, approaches vary widely across port operators. This diversity reflects a lack of standardization with different operators reaching their own conclusions on which SLR scenarios should be used in their risk assessment. This is despite the fact they are relying on the same underlying climate science and projections (Table S2 in Supporting Information S1). The range in SLR projections used across ports is highlighted in Figure 4. This also highlights how individual ports may have adjusted projections used over time if they have reported to more than one of the ARP rounds. For example, Dover has used the same SLR projections in ARP1 and ARP2 but switched to using a higher projection for the 2080s in ARP3.

Port operators also made diverse judgments on whether to use climate data generated under medium (e.g., RCP4.5) or high (e.g., RCP6.0 or RCP8.5) greenhouse gas emission scenarios in the evaluation of climate related hazards and events. As with SLR this diversity could reflect that different operators may wish to avoid analyzing more extreme scenarios. For example, if uncertainty tolerance, which refers to the level of uncertainty a user is willing to accept, is high then less emphasis may be placed on evaluating low probability high impact risks (Hinkel et al., 2019) (e.g., as identified in Port of London, ARP1). On the other hand, if there is low uncertainty tolerance more emphasis will be placed on ensuring the risk assessment accounts for unlikely but possible climate extremes (e.g., as identified in Port of Dover, ARP1).

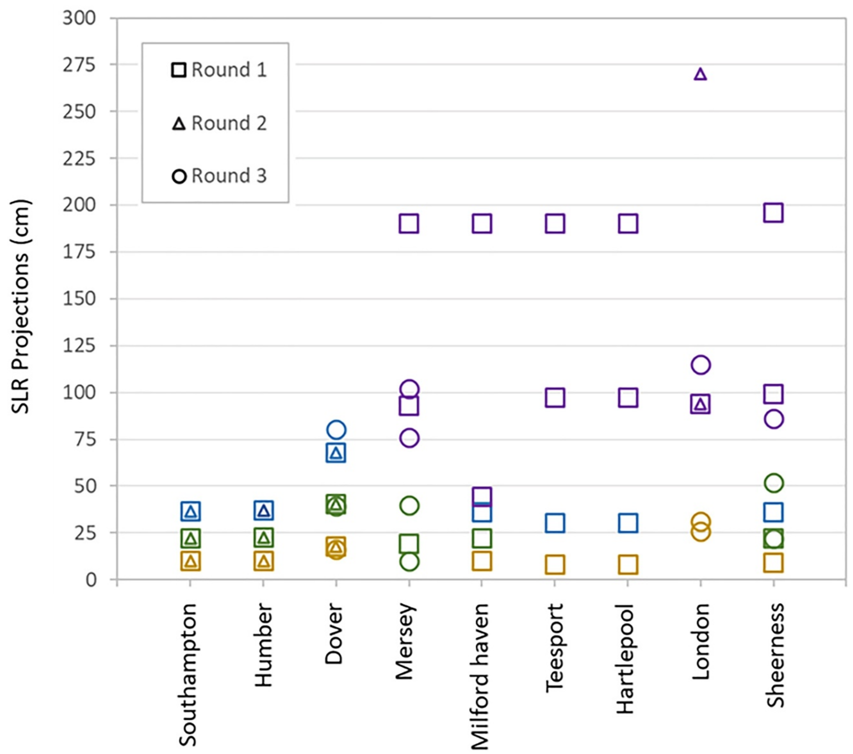

Figure 4. The SLR projections (cm) used to assess risk at different future time periods at different ports around the UK. The shapes signify SLR projections used in the ARP1-3 reports, where referenced and the colors refer to the time period with yellow representing the 2020s; green the 2050s; blue the 2080s and purple 2100.

3.2. Types of Adaptation Action

Out of the 150 individual examples of adaptation identified (implemented, planned, or potential) there were 61 unique adaptation types. This accounts for the fact that the same adaptation type could be reported by different ports and across rounds. To aid the analysis, the 61 unique adaptation types were further categorized and aggregated into 14 groups. Figure 5a highlights that for implemented actions operational improvements (including changes in working practices/times, increased dredging, and new high visibility lights) and flood protection (which encompasses actions such as heightening quay walls and dock gates, pumps and raised infrastructure) are the most common.

Figure 5b shows actions that are reported as being planned (but not yet implemented) or as having potential. Key actions include those related to upgrades/new infrastructure, flood protection and operational improvements. The ARP reports themselves highlight that many assets have a short life span in relation to climate-related risks (e.g., 15 years for fridge/freezer units; 25 years for berths; 30 years for link spans and passenger access ramps) and will be renewed incrementally within annual asset reviews and revision to business plans. The Port of Dover and Port of Felixstowe highlight that some adaptation actions do and will continue to occur autonomously, as part of normal maintenance and infrastructure renewals/upgrades. It should also be noted that quay wall raising, e.g., is something i.e. already included in port design manuals (e.g., Thoresen, 2014). Thus, operational improvements and infrastructure upgrades may be happening more widely without necessarily being recognized and reported by port managers as climate change adaptation in the ARP reports. However, in this analysis, only three examples of existing quay walls being heightened were identified, suggesting limited focus on raising existing quays.

There was limited evidence in the ARP reports detailing if adaptation was reactive or anticipatory. Eight examples, including purchasing flood pumps and back-up generators, were specifically reported as being in response to extreme weather events. For example, ABP highlighted that upgrades were needed to electrical infrastructure, following the extreme storms in winter 2013/2014, to reduce the flood risk of assets such as

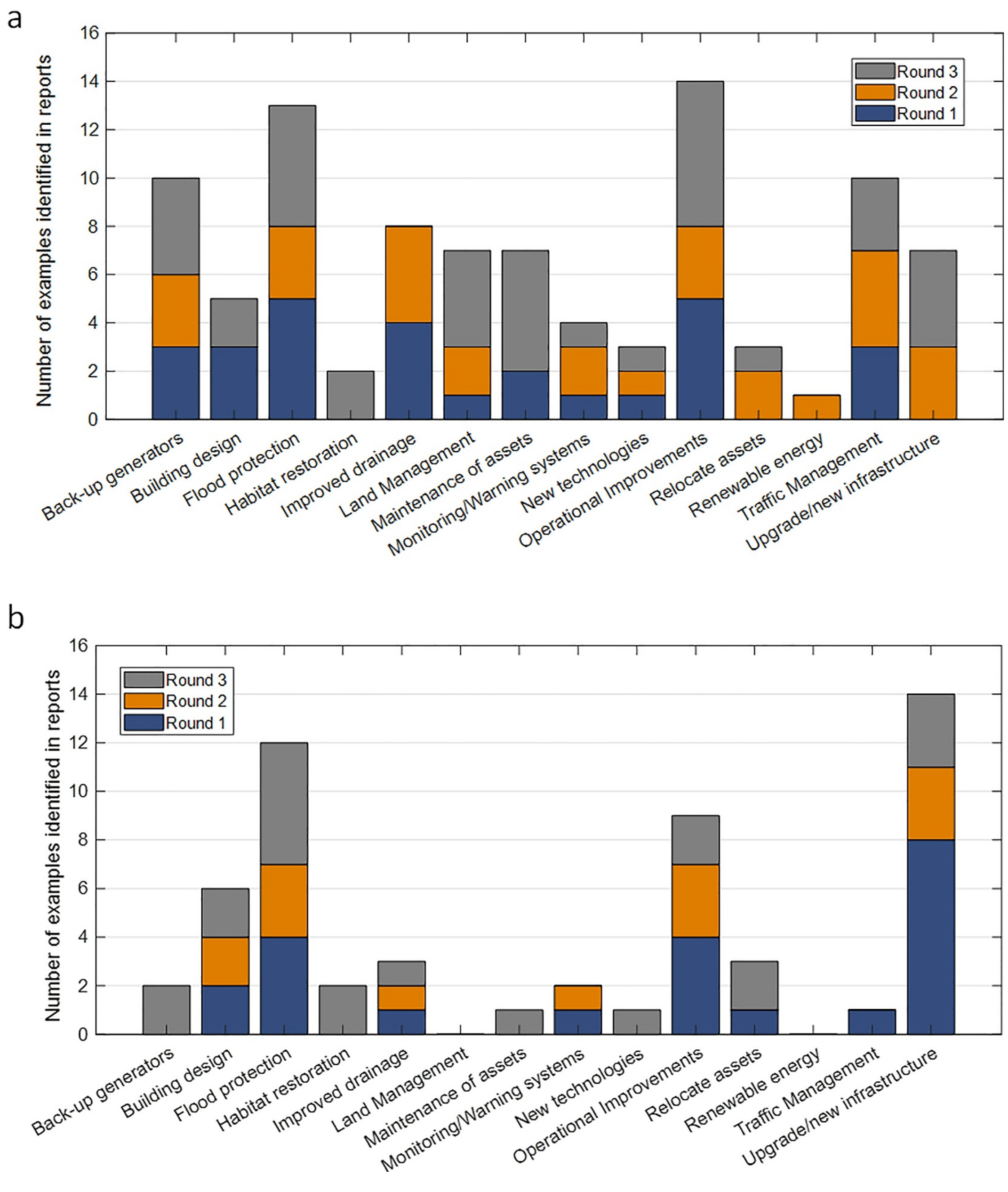

Figure 5. (a) The number of documented examples of implemented adaptation action by ports aggregated by adaptation category type; (b) The number of documented examples reported as Planned and Potential.

electrical substations. Additional investments of £0.5 m and £4.7 m were made to support flood resilience work and install new lock gates (ABP, 2016).

Implemented adaptation actions were also classified based on the mechanism of the approach. All the examples were classed as structural/physical actions, with 52% defined as technological in approach and 33% defined as engineered or built environment approaches. This aligns with broader information and statements made in the ARP reports, whereby ports see advances in technology aligning with their needs for better provision of information and modeling on the coastal environment (ABP), and the assumption that some climate-related risks will autonomously decline as operations are increasingly mechanised or equipment becomes more robust (Port of Felixstowe). Of the remaining implemented adaptation actions 9% were defined as services and 6% as ecosystem-based, reflecting actions that embrace more nature-based solutions to risk reduction or potentially reporting requirements for habitat compensation as adaptation.

3.3. Identified Barriers and Challenges to Adaptation

Information provided by organizations in terms of challenges and barriers to adaptation was flagged as a gap in subsequent reviews of the ARP2 reports (Climate Change Committee, 2017; Jenkins et al., 2022a). Here, information on barriers and challenges has been sought for each of the 150 examples of adaptation identified across the ARP reports. Issues of limited reporting remain clear with only 23% of actions reported detailing barriers and/or challenges. Where information was provided cost was the most common barrier mentioned (58%). Social barriers were the next biggest challenge (17%), reflecting the need for enhanced awareness of staff to manage their environment (such as cooling and heating of buildings) as well as the increased demands that certain actions, including increased maintenance duties or changing work patterns, could place on employees.

Barriers and challenges were also identified that relate more broadly to implementing adaptation actions in an incremental fashion. For example, it was acknowledged in some cases that a more managed adaptive strategy could help reduce costs of actions such as improved drainage, if plans factored in the longer-term risks of climate change. Likewise, it was noted that costs of adaptation could be reduced if actions were integrated into the normal upgrade programs as infrastructure or technology reaches the end of its lifespan. Evidence was also identified in the reports that highlighted the potential for current actions to become less effective in the future. Examples included the need for enhanced capacity to cope with longer power outages than presently seen; future requirements for enhanced cooling needs; and longer-term risks from SLR.

A further barrier identified was how port authorities embed uncertainty and account for longer-term planning horizons when evaluating risk. Based on historical experience infrastructure could well be different in 30–40 years and so potential risks to this future infrastructure are uncertain but still need to be considered. However, the Port of London note it is hard to evaluate costs and benefits of actions more than 10 years in the future due to uncertainties, making the business case for longer-term adaptation investment challenging. This highlights a discord between current incremental adaptation and the longer-term thinking of transformational adaptation, given longer-term adaptation decision-making is often incompatible with shorter-term port investment timescales. Supporting this, Felixstowe port highlighted that normal business risks are often regarded as more urgent than longer-term risks from climate change, making short-term investments a priority. It is therefore postulated that, for climate change adaptation to be embedded within a port's immediate strategic priorities, it is necessary to articulate its broader value beyond immediate risk reduction. This includes highlighting its potential to ensure operational continuity, enhance reputation and support compliance with progressively stringent regulatory and legislative frameworks.

4. Discussion and Conclusions

Given ports natural exposure to coastal hazards, they have historically adapted to cope with storms and high winds, including through the implementation of defences, breakwaters, storm warning systems and operational and health and safety guidelines and thresholds. A review of three rounds of adaptation reporting by ports in the UK highlighted 150 examples of practical adaptation actions, with 94 of these already implemented. In particular, these actions related to risks from storms, flooding and SLR.

Whilst there remain large disparities in the level of implemented adaptation actions reported across ports themselves the study suggests that at least for larger UK ports that engage in the ARP process, they are engaging with climate change adaptation. The more numerous but smaller historic coastal port communities present their own adaptation challenges (Sayers et al., 2022) and are not considered here. However, Flegg et al. (2018) suggests that limited adaptation is happening beyond the larger ports in the UK with the adaptation gap remaining large for the port sector as a whole. Yet, there could be operational changes and infrastructure upgrades happening in the technical realm (e.g., generic guidance considering standard approaches to SLR (Hanson and Nicholls, 2020; Thoresen, 2014)) that are not recognised or reported by port operators as climate-related adaptation. This issue was acknowledged and discussed for coastal flood management in Jenkins et al. (2022a) but the extent of this issue for ports is difficult to evaluate.

Additionally, given the now voluntary nature of the APR reporting process, there are also differences in the number of reports submitted over time and consistency in ports reporting to subsequent rounds. This is a barrier to analyzing how ports engagement and progress in implementing adaptation may be changing over time). As such it is hard to a distinguish between reporting gaps and adaptation gaps. One area where a gap is identified is in the reporting of implemented adaptation outcomes and benefits, beyond more generic statements on reducing flood risk, reducing congestion or reducing disruption to operations. In the general framework of the ARP3 reports there is a focus on climate risk planning as opposed to monitoring of adaptation progress (Climate Change Committee, 2022). In the UK and internationally, this lack of evidence hinders the potential to develop quantitative adaptation metrics, exclusive to ports and their operations, to evaluate adaptive responses to climate change and monitor progress over time (León-Mateos et al., 2021).

Nonetheless, constructing this inventory of implemented port adaptation actions still provides a step forward in supporting the sharing of best practice which can transcend national boundaries, as well as providing an initial benchmark against which future evaluations can be made. Whilst the focus of this case study is the UK, the framework and approach to identifying and cataloging examples of adaptation is transferable to other regions where similar gray literature exists. Whilst this analysis utilizes the UKs ARP reports, which are mandated under the Climate Change Act 2008, various approaches to adaptation reporting exist in other countries (Asariotis et al., 2024). In the EU port adaptation can be included under sectoral adaptation strategies, for example, the Port of Rotterdam in the Netherlands reports on flood risk management and adaptation (Port of Rotterdam, 2025). Further sources of information could include case studies submitted via the ClimateADAPT portal (e.g., where adaptation options implemented in the Port of Rotterdam are documented). Where international ports have aligned to the Task Force on Climate-related Financial Disclosure (TCFD), reports can provide valuable insights into investment in resilience and market-based adaptation strategies. Exploration, identification and evaluation of gray literature in different regions could help build up a more in-depth picture of how ports are adapting globally.

Addressing the current gap in understanding if and how adaptation is being implemented will be significant given the UNFCCCs global goal on adaptation. Progress toward commitments is collated through the Global Adaptation Stocktake which reported for the first time in 2023 and will be repeated every 5-year thereafter (UNFCCC, 2016). Via this stocktake such evidence could enhance implementation of adaptation indirectly by distilling information on types of adaptation actions that are politically, economically and technologically feasible. Given, adaptation identification and tracking are regarded as an urgent priority to support this stocktake (Berrang-Ford et al., 2021), including for coastal areas (Magnan et al., 2023), this study contributes initial evidence on implemented adaptation by larger UK ports.

The adaptation actions identified in this study can be more generally defined as changes within the current system, focused on maintaining current and shorter-term operations, as opposed to larger, system-wide change of ports (for a full list of actions identified see Table S3 in Supporting Information S1). It is challenging to distinguish evidence of transformative adaptation from the ARP reports that would represent a fundamental shift in the structure or functioning of ports (no ARP reports use the term transformational). Barriers to transformational adaptation are likely to include the discord in investment and planning timescales and uncertainties over future infrastructure and economic implications of risks faced. In this regard similarities can be made to coastal flood management in England. In this case actions are focused on the short-to long-term, but still concentrated on business-as-usual approaches. Much less consideration is given to the need for future transitions where renewal of current defences cannot be justified economically and coastal retreat will be required (Climate Change Committee, 2018; Jenkins et al., 2025; Sayers et al., 2022). While the problem is apparent, there are few benefits to operators to address the longer-term challenges.

The focus on shorter-term adaptation plans and investment timescales is particularly relevant given the potential for lock-in due to often long-term lifespans of port assets and infrastructure (Magnan et al., 2023). PIANC (2020) suggest a toolbox of long- and short-term, low- and high-cost adaptation measures that could help address this challenge, not dissimilar to the widely discussed adaptation pathway planning approach; where combinations of measures can be explored over time (and SLR) (e.g., Fernandez-Perez, Losada et al., 2024).

Market forces are also key for determining the type and scale of port development over time. Climate adaptation represents an additional challenge for UK ports which may already be struggling to survive economically as they are generally in private ownership. Looking beyond the UK, similar challenges are likely to be widespread globally, and the ownership model will determine where these costs fall on government or the private sector. Competition between ports could also hinder longer-term thinking, including in regard to climate change adaptation (Asteris and Collins, 2007). Beyond the UK, Randrianarisoa and Zhang (2019) highlight the potential trade-off between risk reduction and port business activities, often focused on more immediate concerns of upgrading facilities in line with changing/increasing demand. However, from a positive perspective future adaptation investment decisions could also be viewed as a strategic approach to promote port reliability and reputation. High performing ports can attract significant foreign investment and support economic development, with a growing awareness of the need to incentivize resilience and enhance competitiveness (Humphreys, 2024). As noted in a study of seaport investment in the face of climate change Xia et al. (2024) report that in their game-theory model the worst scenario for a port arises when its competitor adapts to changing climate and it does not. The expansion of existing ports (including Tilbury in the UK) and the creation of completely new ports (such as London Gateway), provides another avenue where there is potential to embed flexible longer-term adaptation into the planning and construction of infrastructure from the outset. This will require further engagement with climate change adaptation, For example, the current sustainability strategy for the London Gateway only covers climate change mitigation and not adaptation (DP World, 2021WORLD, 2021).

The study does highlight some aspects of implemented adaptation that would be more aligned with transformational thinking. Namely, related to the risk assessment and adaptation planning processes themselves. For example, there is evidence in the risk assessment frameworks that ports are considering longer-term climate-related risks encompassing uncertainty, especially related to SLR. Although the diverse way in which end-users perceive and select climate and SLR projections will also have an influence on the outcomes of the climate risk assessment and subsequent case for investment in adaptation.

Reflecting on the findings of this study, one recommendation to support future port resilience is to integrate aspects of adaptation into longer-term decision making and practice, including fully exploiting the renewal and investment cycle so that new port infrastructure is climate-proofed when constructed. Long-term decision making is often incompatible with port investment timescales. As a result, there remains a need to shift thinking away from the business-as-usual approach. In doing so ports could adopt a more systematic and integrated view of short- and longer-term climate risks, adaptation planning and the longer-term economic benefits of investments. Developing a long term vision for port adaptation will be the first step to understanding how to progress toward this vision and then understanding future investment and development choices.

Improved understanding and data on the types, costs, and outcomes of implemented adaptation will be vital to help support and shift thinking in this area. In this regard, the value of being able to identify, catalog and evaluate if and how adaptation is being implemented today is clear. The study highlights the potential of gray literature to continue to contribute to this evidence gap for major ports in the UK. Furthermore, the framework is transferable given appropriate gray literature is available for other regions and could be expanded to further enhance our understanding of how ports internationally are adapting to climate change in practice.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

The data on which this article is based are available in Jenkins et al. (2022b).

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