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Climate change and seaports: hazards, impacts and policies and legislation for adaptation

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Abstract

Seaports are critical for global trade and development but are at risk of climate change-driven damages, operational disruptions and delays with extensive related economic losses. The aim of the present contribution is to (a) provide an overview of the main impacts of climate variability and change (CV&C) on ports; (b) present recent research on trends and projections involving the main climatic factors/hazards affecting global ports; (c) provide an analytical overview of emerging international and regional policies and legislation relevant to port risk assessment and resilience-building under climate change; and (d) consider issues and areas for further action. As shown by projections under different climatic scenarios and timelines, many global ports will increasingly be exposed to significantly growing hazards under increasing CV&C, including extreme sea levels (ESLs), waves, and extreme heat events. Depending on scenario (RCP 4.5 and RCP 8.5) by 2050, 55% to 59% of the 3630 global ports considered could face ESLs in excess of 2 m above the baseline mean sea levels (mean of the 1980–2014 period); by 2100, between 71% and 83% of ports could face ESLs of this magnitude. Ports in most tropical/sub-tropical settings will face the baseline (mean of the 1976 – 2005 period) 1-in-100 year extreme heat every 1 – 5 years, whereas with 3 °C global warming, most global ports (except some in higher latitudes) could experience the baseline 1-in-100 years extreme heat event every 1 – 2 years. A range of policy and legal instruments to support climate change adaptation, resilience-building and disaster risk reduction have been agreed internationally as well as at regional levels. At the EU level, relevant legal obligations and related normative technical guidance aimed at ensuring the climate proofing of new infrastructure are already in place as a matter of supra-national law for 27 EU Member States. These could significantly enhance levels of climate-resilience and preparedness for ports within the EU, as well as for EU funded port projects in other countries, and may serve as useful examples of good practices for other countries. However, further action is needed to advance and accelerate the implementation of effective adaptation measures for ports across regions.

Keywords Seaports, Climate change, Adaptation, Seaport resilience, Policy, Legal framework

[†]The views expressed herein are those of the author and do not necessarily represent the views of the United Nations.

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1 Introduction

Seaports are crucial nodes in the network of global supply chains and critical gateways for access to global markets, as well as the ocean economy including, among others, fisheries, offshore mineral resource and energy development, and cruise-ship tourism. With about 80% of the volume of world merchandise trade carried by sea, ports are key assets for the current and future trade and sustainable development prospects, particularly of developing States which account for around 55% of goods loaded and 61% unloaded globally (UNCTAD 2022a). At the same time, ports are particularly exposed to various climatic hazards, due to their locations along open coasts or in low-lying estuaries and deltas that make them susceptible to the impacts of rising sea levels, storm surges, waves and winds as well as fluvial and pluvial flooding (IPCC 2018, 2019; Izaguirre et al. 2021).

Given the high value of port assets, their criticality for (international) trade and the high concentration of populations/services in the associated coastal urban/industrial clusters, the impacts of climate variability and change (CV&C) on ports and their hinterland transportation links can have broad ramifications for trade, energy and food supplies (e.g., UNECE 2015; Asariotis 2021). Therefore, enhancing the climate resilience of ports is a matter of strategic socio-economic importance, particularly for those at greatest risk of impacts and with limited capacity to respond, such as the Small Island Developing States (SIDS). In the context of climate change, risk is a function of hazard, exposure, and vulnerability (IPCC 2014). With many climate hazards relevant for ports projected to increase in frequency and intensity (e.g., Bevacqua et al. 2020; Dottori et al. 2018; Vousdoukas et al. 2018) due to global warming, associated risks are also expected to grow, unless effective measures are taken to adapt and reduce vulnerability.

Against this background, the aim of this contribution is to (a) provide an overview of the main impacts of CV&C on ports (and their hinterland connections); (b) present recent research on trends and projections involving the main climatic factors/hazards affecting global ports; (c) provide an analytical overview of emerging international and regional policies and legislation relevant to port risk assessment and resilience-building under climate change; and (d) consider issues and areas that deserve particular attention for further action by decisionmakers and port sector stakeholders with a view to enhancing the climate resilience of ports.

2 Potential impacts of climate variability and change on ports

Ports and their connecting roads, railways and inland waterways form complex transport systems that can be vulnerable to several climatic hazards and their variability and change, with some of the major potential

impacts on coastal transport infrastructure/operations summarized in Table 1. Ports are particularly exposed to rising mean sea levels, storm surges, waves and winds, fluvial and pluvial extremes as well as increasing mean and extreme temperatures (e.g., Sánchez-Arcilla et al. 2016; UNECE 2020), with the risk of related impacts set to grow under climate change, in the absence of effective adaptation measures (Izaguirre et al. 2021). In the case of large ports, which are commonly integrated within large coastal urban agglomerations, these hazards can also affect large populations and a broad range of stakeholders and socio-economic activities (e.g., Hanson et al. 2011; Becker et al. 2018), while impacts are projected to be particularly significant for ports in vulnerable SIDS due to the high concentration of population, infrastructure, and services at the coast (Monioudi et al. 2018). In addition to causing infrastructure damages, changing climatic factors can impact on operations, causing extensive disruptions and delays, as well as significant economic and trade-related losses; transportation demand may also be affected through, for example, climate-driven changes in demographics, industrial and agricultural production, trade, consumption and tourism patterns (e.g., Asariotis 2020).

Increases in the mean and extreme sea levels can cause coastal flooding and port inundation (Hanson and Nicholls 2012; Izaguirre et al. 2021), with the northwestern European, northwestern American and southeastern Asian coasts as well as those of SIDS projected to be particularly affected (e.g., Vousdoukas et al. 2018; Giardino et al. 2018). Recurring port inundation from extreme events can render transportation systems unusable for the event duration, cause damages to terminals, freight villages, storage areas, cargo and vessels and disrupt supply chains for longer time periods (UNECE 2014). Damages and operational disruptions from extreme waves that can cause coastal erosion, port defense overtopping, quay flooding and in-port wave agitation that can constrain access, vessel handling and berthing could also increase under climate change (Camus et al. 2019; Rossouw and Theron 2012). Extreme (tropical) winds can also be very damaging (Folkman et al. 2021), as they can cause infrastructure failures and operational disruptions from channel changes/silting, wind-generated debris, inability to operate cranes, vehicle blow-overs, and damages to connecting rail tracks and roads, as well as endanger berthing operations (UNECE 2015, 2014).

Increases in mean temperatures and the frequency/duration of heat waves will pose substantial challenges to the safety and health of personnel and passengers. They can endanger human health, degrade port paved areas, induce asphalt rutting, bridge damages, rail track buckling and speed restrictions, as well as equipment failures

Table 1 Major impacts on coastal transportation infrastructure and operations from changing climatic factors and hazards. Lists are not exhaustive. Adapted from UNCTAD 2020a and UNECE 2020

Factor/hazard	Seaports	Roads, railways and IWWs
Mean sea level rise	Permanent inundation requiring port elevation and coastal protection upgrades; navigational issues for ports and key transit points; insurance issues	Increased inundation/erosion of coastal road/rail networks; potential changes in IWW water levels; insurance issues
Increasing extreme sea levels (ESLs); changes in wave energy/direction	Increasing frequency/depth of inundation; chronic flooding; more frequent operational delays; increasing breakwater scouring and overtopping; wave penetration; navigation channel silting; higher insurance costs	Structural damages to roads and pavements; flooding causing costly delays/traffic diversions; structural damages to railways, embankments, earthworks; operational disruptions
Changes in frequency and intensity of extreme winds	Damages to terminals and equipment; vessel navigation and berthing issues; constraints in crane operations above certain speeds	Damages to road/rail fences; increased accidents; damages to signage; debris obstructions; bridge closures; overvoltage; rail car blow-overs; operational disruptions
Increasing mean and extreme temperatures (heat waves); changes in the distributions of warm and cool days	Pavement degrading; equipment and cargo damages; higher energy needs for cooling; health/safety issues for personnel and passengers	Asphalt rutting; bridge thermal damages; rail track buckling; speed restrictions; rolling stock failures; asset lifetime reduction; increased needs for cooling passengers/freight; health/safety issues; shorter maintenance windows; water level issues for IWWs
Changes in the mean precipitation and frequency and intensity of extremes	Infrastructure flooding damages; problems for the operation of locks, manoeuvrability of vessels due to changes in water levels and flow speed; visibility issues from increasing fog	Road flooding/wash-outs; landslides; bridge/earthwork failure; poor visibility; drainage and tunnel issues; rail embankment, earthwork, culvert damages; delays; IWW restrictions
Cryosphere: reduced polar snow cover/ice	New arctic shipping routes, longer seasons, reductions in fuel and snow/ice removal costs; but increasing marine storm hazards	Longer construction/maintenance periods; reductions in snow/ice removal costs; potentially increasing arctic river navigability; damaged integrity of ice roads
Cryosphere: permafrost degradation/thawing	Ground subsidence, slope instability and drainage affecting the structural integrity; high construction costs	Deterioration of road, rail (and IWW port) integrity and load-carrying capacity; high construction costs

(UNECE 2015), and increase energy needs and costs for cooling (Monioudi et al. 2018). Heavy rainfall (downpours) can severely impact ports and their connecting transport infrastructure. Pluvial and fluvial flooding can damage the structural integrity of the infrastructure, decrease manoeuvrability of locks and vessels, and cause accidents in connecting roads due to poor visibility and road damages. Connecting railroads could also be compromised through track and line equipment failure, flood scouring at bridges/embankments, culvert wash-outs, tunnel flooding, track obstructions, landslides/mudslides and reduced depot accessibility. Inland waterways (IWW) and canals are also affected by both floods and droughts. Floods can cause suspension of navigation, damages to port facilities and flood protection works, silting, and changes in the waterway morphology (UNECE 2014), whereas low water levels during droughts can inhibit access for larger vessels, severing significant supply lines and causing costly delay and disruption; this has been the case in 2023 for the Panama Canal which handles around 5% of world trade (Moreno 2023). Droughts are generally considered a greater hazard for European IWWs than floods (UNECE 2020).

On the other hand, global warming may create new opportunities for maritime networks and trade due to the opening of new Arctic shipping routes. However, these routes and their facilitating ports will face challenges due to (UNECE 2020): i) the projected increases in coastal erosion for the northern coastlines of Canada, the Russian Federation and the USA; and (ii) increasing difficulties in the development and maintenance of Arctic transport infrastructure due to thawing permafrost and/or changes in the ground freeze–thaw cycle that can cause ground subsidence, slope instability, drainage issues and affect the structural integrity and load-carrying capacity of transport infrastructure including the ice roads.

Economic losses from damages to infrastructure and operational disruptions/delays, with knock-on effects across interconnected global supply chains, can be extensive. A study by the Environmental Defense Fund (EDF 2022) estimated current global average annual storm damages to ports at roughly US\$ 3 billion, whereas according to Verschuur et al. (2023a) port-specific risk from natural hazards totals US\$ 7.5 billion per year, with an additional US\$ 63.1 billion of trade at risk. Annual systemic risk to global maritime transport, trade and supply-chain networks has been estimated as US\$ 81 billion, with (at least) US\$ 122 billion of economic activity on average also at risk (Verschuur et al. 2023b). These loss estimates do not, however, account for the expected increase of hazards under climate change (see e.g. Economist Impact 2023) and could be conservative, given that

losses arising from a single extreme event can lead to potentially crippling losses in regions affected, as exemplified by recent tropical cyclones. For example, the 2019 hurricane Dorian caused about US\$ 3.4 billion of losses to the Bahamas alone, with a large fraction of those associated with transport infrastructure (IDB 2020). The 2012 hurricane Sandy caused losses of over US\$ 60 billion in New York, New Jersey and Connecticut (Strauss et al. 2021), including a week-long shutdown of the major NY/NJ container port and US\$ 2.2 billion in damages and losses to the Port Authority,¹ whereas the 2013 typhoon Maemi rendered the South Korean Busan port inoperable for 91 days (Lam et al. 2017). Transport infrastructure was significantly impacted by Hurricanes Irma and Maria (that occurred in 2017), with overall losses in Dominica amounting to 226% of GDP (Government of Dominica 2017) and damages/losses in the British Virgin Islands estimated as 55% of the territory's GDP (UNECLAC 2018). Such infrastructure damages also have implications for disaster management logistics (Lawrence et al. 2019). Concerning individual ports, Cao and Lam (2018) assessed the potential typhoon losses for a Shenzhen 16-berth terminal as US\$ 0.9 billion.

As concerns potential economic losses arising from an increase of hazards for ports under climate change, Hanson et al. (2011) estimated the total value of assets exposed to coastal flooding in 136 port megacities as about 9% of the global GDP by the 2070s, whereas Lenton et al. (2009), who considered also tipping points, estimated that asset exposure to flooding in the same 136 port megacities could reach US\$ 28 trillion by 2050. Hoshino et al. (2016) estimated the potential flooding costs for the Tokyo Bay port areas from combined mean sea level rise and typhoon-induced storm surges as up to US\$ 690 billion (2016 values). A more recent estimation of the value of assets exposed to coastal flooding has suggested that, by 2100, this could amount to 12 – 20% of the global GDP, in the absence of adaptation measures (Kirezci et al. 2020).

3 Methodology

In order to assess climate change hazards on global seaports, the mean and extreme sea levels, the waves as well as the extreme heat events have been projected for 2050 and 2100 under the IPCC representative concentration pathway scenarios RCP4.5 and RCP8.5 for 3630 ports along global coastlines.

Relative mean sea level rise (RSLR) projections along the global coastline (25 km resolution) were obtained

¹ https://www.nj.com/news/2013/10/port_authority_sandy_22billion_outlines_recovery_measures.html.

from Jevrejeva et al. (2016) for different ice melting scenarios, and land vertical movement projections. Extreme sea-levels (ESLs) integrate the (relative) mean sea level, the astronomical tide and the episodic coastal sea level rise due to storm surges and wave set-ups. To obtain the baseline ESLs (the 1980–2014 period's mean) the mean sea levels were combined with the astronomical tidal levels obtained from the FES2014 model (<https://www.aviso.altimetry.fr/en/data/products/auxiliaryproducts/global-tide-fes.html>), whereas storm surge levels and waves were hindcasted through Delft3D-FLOW (Muis et al. 2016) and WAVEWATCH III (Tolman 2009) model simulations, respectively. Wave set-ups were estimated from the hindcasted offshore significant wave heights (H_s) using a generic approximation ($0.2 \times H_s$, CEM (2002)). ESL components and their uncertainties were then combined in Monte Carlo simulations (Vousdoukas et al. 2018), and non-stationary extreme value analysis was used to obtain the extreme sea levels with a return period of 100 years (ESL_{100}), a crucial design parameter for coastal infrastructure and protection.

ESLs for the global coastline for the twenty-first century under the IPCC RCP4.5 and RCP8.5 scenarios were then projected. RSLR projections (Jevrejeva et al. (2016) were combined with future storm surges and waves projected by the aforementioned models and forced by a six member GCM ensemble (Vousdoukas et al. 2018). As the mean sea level rise may affect tidal elevations, the DFLOW-FM model was used to assess the potential changes to the tidal elevations from their baseline values due to mean sea level rise. The future ESLs were then statistically analysed using the same techniques as for the baseline hindcasting.

In addition, as ESLs may not necessarily align with extreme waves of the same return period, bivariate copula statistics (e.g. Li et al. 2018) were used to probabilistically associate ESLs to the extreme waves which are more likely to occur concurrently. To achieve this, the total water level was correlated with wave height and period using the nonparametric Spearman correlation coefficient. The resulting pairs of values were then adjusted to fit seven different types of distributions, allowing the investigation of the degree of dependence (e.g. Monioudi et al. 2023). This analysis enabled the determination of the most probable significant wave height and period corresponding to each storm surge level value. Finally, projections of heat extremes along the global coastline under certain global warming scenarios have been abstracted from Dosio et al. (2018).

All the above projections for the global coastline were then used to assign RSLR, ESL, wave and extreme heat values at 3630 of the 3700 ports recorded in the World Port Index 2019, on the basis of their location

relative to the coastline projections. In the following section the results are presented against a background of observed trends.

4 Climatic hazards affecting ports: trends and projections

In 2022, the global mean near-surface temperature was 1.15 (1.02 – 1.28) °C above the 1850–1900 pre-industrial average (WMO 2023) and is predicted to reach 1.5 °C in the 2030s. Global warming of 2 °C above the pre-industrial level, which may be reached by 2050, has been suggested as the threshold beyond which climate change risks may become unacceptably high (IPCC 2018). By 2100, global warming around 2.7 °C is considered 'very likely' (best estimate) under an intermediate emissions scenario; this will exceed 3.3 °C under a high GHG emissions scenario (IPCC 2023a). Implementation of existing policies and pledges will only reduce this global temperature increase to 2.5 – 2.9 °C by 2100 (UNEP 2023a; CAT 2023).

Global warming induces changes in several climatic hazards, such as mean sea-level rise, extreme sea-levels, heat waves, heavy precipitation/flash floods and extreme winds. In the subsections below we summarize the state of knowledge on how hazards relevant for ports are projected to change with global warming.

4.1 Mean and extreme sea level rise, waves and winds

In the last decade the globally averaged mean sea level rise (SLR) has reached 4.62 mm/yr (WMO 2023). Global SLR projections suggest that, by 2100, mean sea level might reach up to 1.1 m higher than the mean of the 1986 – 2005 period under the high-end emission scenario, showing also high spatial variability, with sea level rise projected as significantly higher in some regions (IPCC 2019). However, projections are constrained by uncertainties in the ocean response to warming, the behaviour of the Greenland and Antarctic ice sheets, and the potential overshooting of climatic tipping points (Cheng et al. 2019; Lenton et al. 2019, 2023). Thus, the annual rate of mean sea level rise might be significantly higher, particularly if the Paris Agreement targets are exceeded (e.g. DeConto et al. 2021).

The modelling undertaken in the present study has found that by 2050, the median projections of RSLR for ports along the global coastlines will range from 0.11 – 0.21 m and 0.09 – 0.29 m under the RCP4.5 (moderate) and RCP8.5 (very high) IPCC emission scenarios, respectively. RSLR is projected to accelerate in the later part of the century. By 2100, and under RCP4.5, it is projected to range between -0.17 and 0.67 m across global ports, whereas under RCP8.5, RSLR is projected to range between -0.14 – 1.06 m, with the highest rises expected

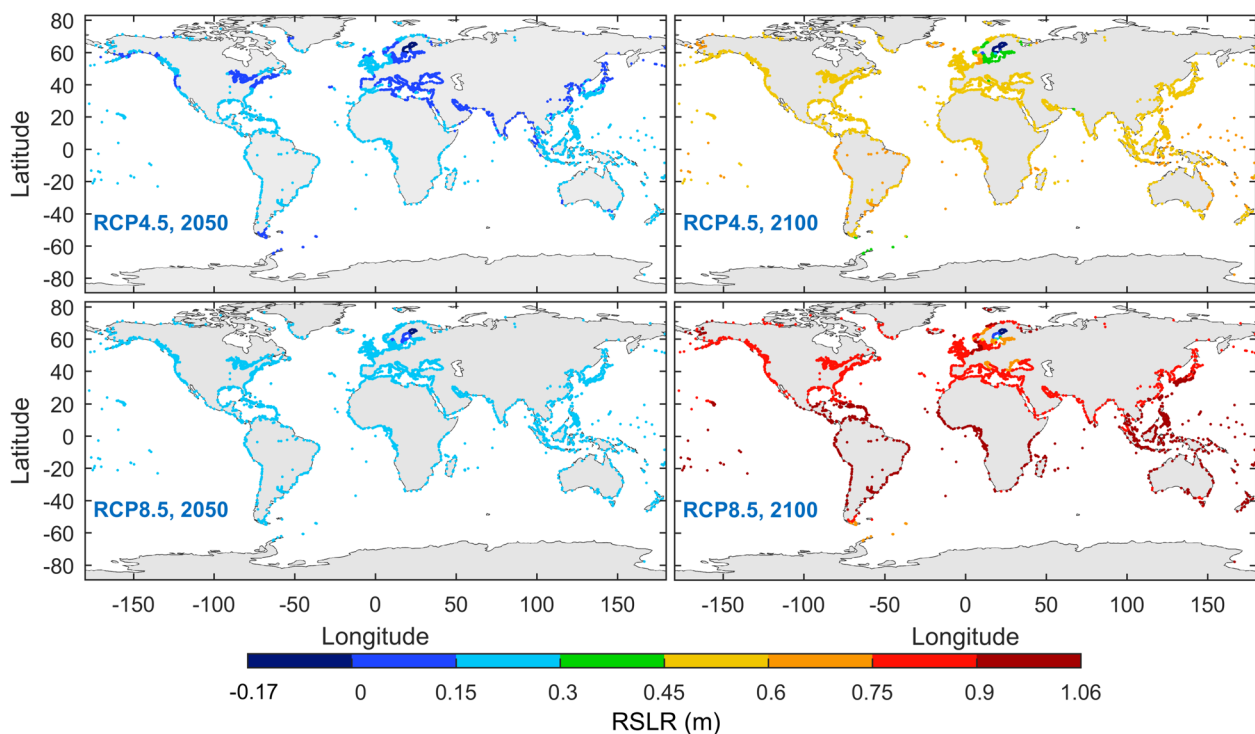


Fig. 1 RSLR median projections (2050, 2100, RCP4.5, RCP8.5) relative to the 1980 – 2014 mean (see also <https://data.jrc.ec.europa.eu/dataset/jrc-lis coast-10012>). Port locations from the World Port Index 2019 (<https://msi.nga.mil/Publications/WPI>)

at South American and African ports (Fig. 1). It should be noted, however, that local conditions, such as accelerated land subsidence e.g., in deltaic coasts, could modify the above projections upwards.

Regarding the extreme sea levels, our modelling suggests that the baseline ESL_{100} varies considerably across global seaports, with the highest levels found mostly at the seaports of northwestern Europe, northern America and East Asia (Fig. 2).

Extreme sea-levels (ESLs) will threaten ports in all regions, with effects worsening over the course of the century (Fig. 3). By 2050, ESL_{100} will increase by up to 0.5 m above the baseline values under the examined scenarios. By 2100, ESL_{100} increases will be substantial, reaching up to 1.6 m.

Our projections indicate that by 2050, under the RCP4.5 and RCP8.5 scenarios, respectively, approximately 55% and 59% of all (3630) ports, as well as around 53% and 58% of the 522 large and medium-sized ports (classification according to World Port Index), will face extreme sea levels exceeding 2 m. Looking ahead to 2100, an estimated 71% and 83% of all ports, along with roughly 70% and 81% of the (522) large and medium-sized ports, are projected to be affected by extreme sea levels exceeding 2 m (above the baseline mean sea level), under the RCP4.5 and RCP8.5 scenarios, respectively (Table 2).

Port infrastructure/operations can also be particularly impacted by extreme waves. Global multi-model wave projections under climate change have indicated increases in the annual mean significant wave height (H_s) for the southern and eastern Pacific Ocean and decreases for the north Atlantic, the northwestern Pacific and the Indian oceans, with the magnitude of the increases being about 4 times higher than those of the decreases (Camus et al. 2017). Increases of up to 30% have been projected for the extreme coastal wave energy fluxes, an important port design parameter, for most southern temperate coasts, the north-eastern Pacific and the Baltic Sea coasts, whereas wave directional changes have been also projected for some regions (Mentaschi et al. 2017). Our analysis shows that the baseline 1-in-100 year H_s varies along the global coastline, with higher waves shown for North America, West Europe and East Asia (Fig. 4).

By 2050, increases of more than 0.5 m are anticipated for only 38 and 67 ports under the RCP4.5 and RCP8.5 scenarios, respectively. By 2100, under the same scenarios, changes of more than 0.5 m are projected for 115 and 103 ports, respectively (Fig. 5). This suggests that substantial changes in wave height are not anticipated on a global scale; noteworthy variations are expected in specific regions.

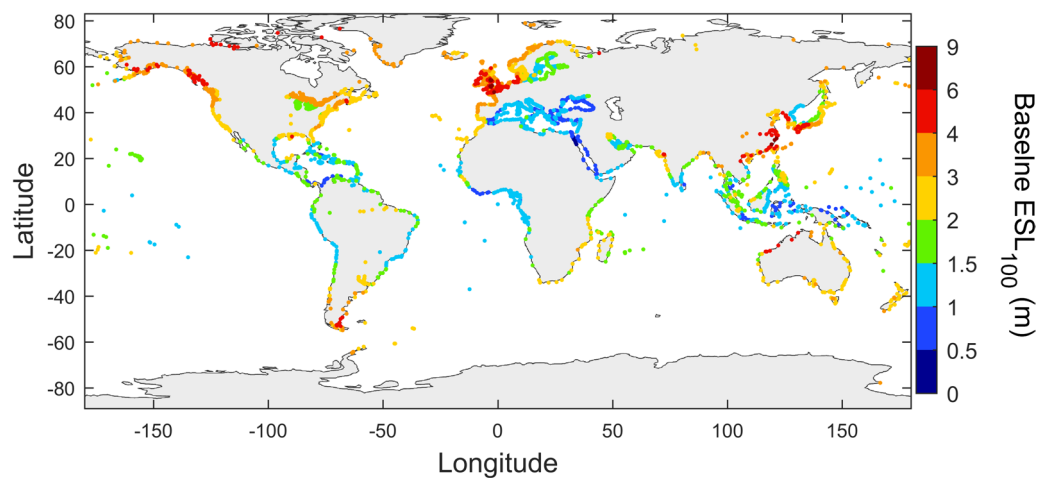


Fig. 2 Baseline 1-in-100 years extreme sea levels (ESL_{100}) at 3630 global ports. The baseline ESL_{100} are the means of the 1980–2014 period. Seaport location from World Port Index 2019 (<https://msi.nga.mil/Publications/WPI>). ESL_{100} projections for the global coastline can also be found in EC-JRC data collection (<http://data.jrc.ec.europa.eu/collection/LISCOAST>)

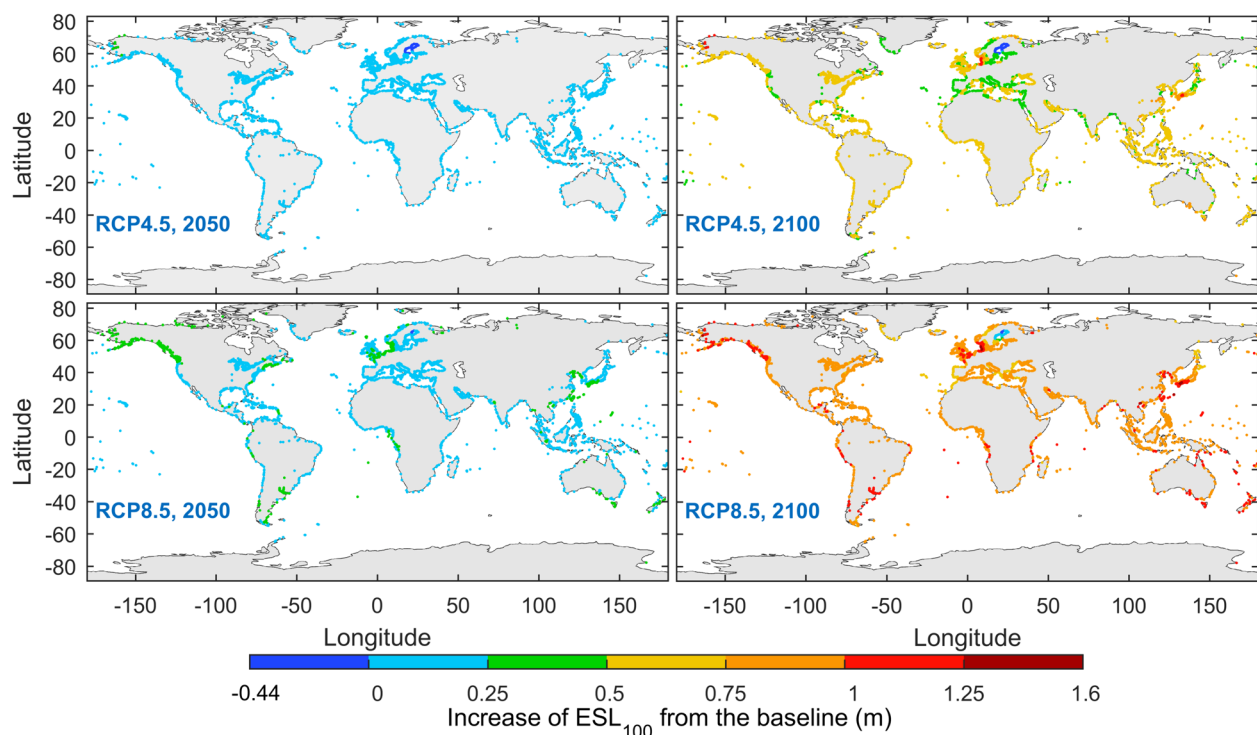


Fig. 3 Projected changes in ESL_{100} from the baseline ESL_{100} under CV & C for 3630 global ports. Seaport location from World Port Index 2019 (<https://msi.nga.mil/Publications/WPI>) and ESL_{100} projections for the global coastline from (<http://data.jrc.ec.europa.eu/collection/LISCOAST>)

It is noted that these are Hs_{100} projections, and as such, they do not account for the effects of the potential intensification of tropical storms in some regions, which already affect 38% of world's ports (and related supply chains) (Notteboom et al. 2022). Storm wind intensity, which may increase under global warming but with

large spatial variability (Trenberth et al. 2018), can also severely impact port operations and safety, through the combination of fluvial, pluvial and marine flooding and high winds (Koks et al. 2019; UNECE 2020).

Finally, it should be mentioned, that as most of the above considered hazards are projected to increase

Table 2 Percentages of global ports projected to face ESL_{100} of more than 1 and 2 m above the baseline mean sea level under Climate Variability and Change (CV&C). Port size classification according to World Port Index. Key: ESL_{100} , 1–100 year extreme sea level; RCPs, IPCC Representative Concentration Pathways representing moderate and very high emissions

Ports (no)	ESL_{100}	Percentages of ports				
		Baseline	RCP4.5, 2050	RCP4.5, 2100	RCP8.5, 2050	RCP8.5, 2100
All ports (3630)	> 1 m	92.5	96.8	99.5	98.1	100.0
	> 2 m	52.8	55.2	70.6	59.1	82.9
Large ports (160)	> 1 m	88.1	96.3	100.0	96.9	100.0
	> 2 m	50.0	53.1	66.3	56.9	75.0
Medium (362)	> 1 m	92.5	97.5	99.7	98.3	100.0
	> 2 m	51.1	53.6	72.1	57.7	82.9
Large/medium (522 total)	> 1 m	91.2	97.1	99.8	97.9	100.0
	> 2 m	50.8	53.4	70.3	57.5	80.5
Small (977)	> 1 m	93.4	97.1	99.6	98.5	100.0
	> 2 m	49.5	52.9	70.3	58.3	82.7
Very small (2125)	> 1 m	92.4	96.5	99.4	98.0	100.0
	> 2 m	54.9	56.6	70.8	59.9	83.8

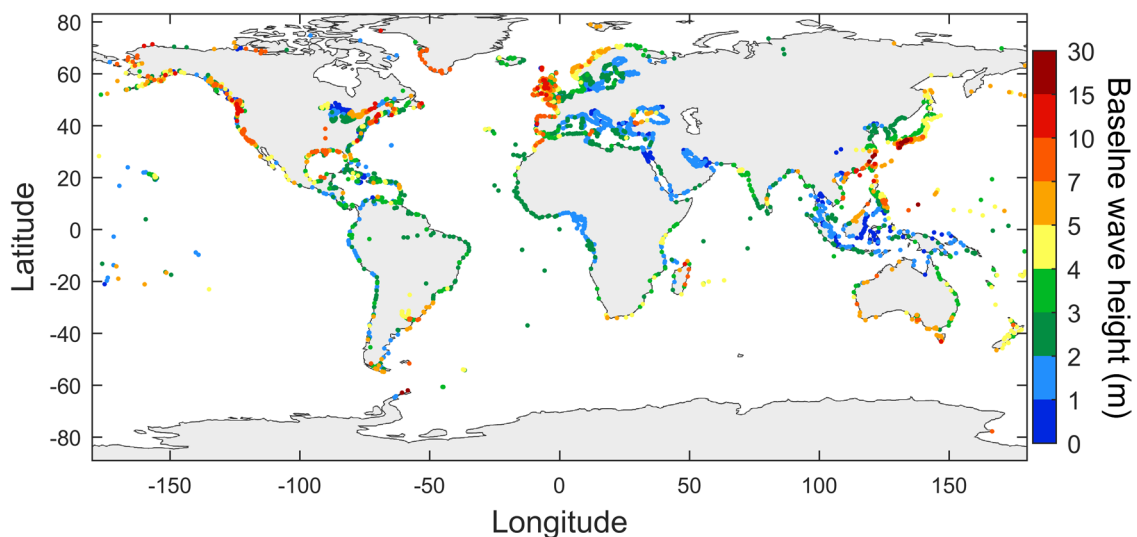


Fig. 4 Baseline (1980–2014 period) 1-in-100 years significant wave height at 3630 global ports. Seaport location from World Port Index 2019 (<https://msi.nga.mil/Publications/WPI>)

significantly between 2050 and 2100, this could have significant implications for port planning, which often accounts for projects with a designed life of (at least) 50–75 years.

4.2 Mean and extreme temperature and precipitation

The recent 10 year period has been the warmest on record (WMO 2023), with projections indicating large future increases in mean temperature depending on the scenario (IPCC 2023a). At the same time, changes are not, and will not be, uniform, with temperature rising

faster in the high latitudes. Oceans are also warming, with the last two decades showing a particularly strong increase across all water depths in ocean heat content -OHC (Cheng et al. 2019); such increases can lead to regional shifts in the oceanic/atmospheric circulation and more intense and/or frequent extreme storms and heavy precipitation events in some areas and prolonged droughts in others (WMO 2023).

Observations show increases in the frequency/intensity of heat waves in many regions (WMO 2023), with most models projecting more frequent and intense

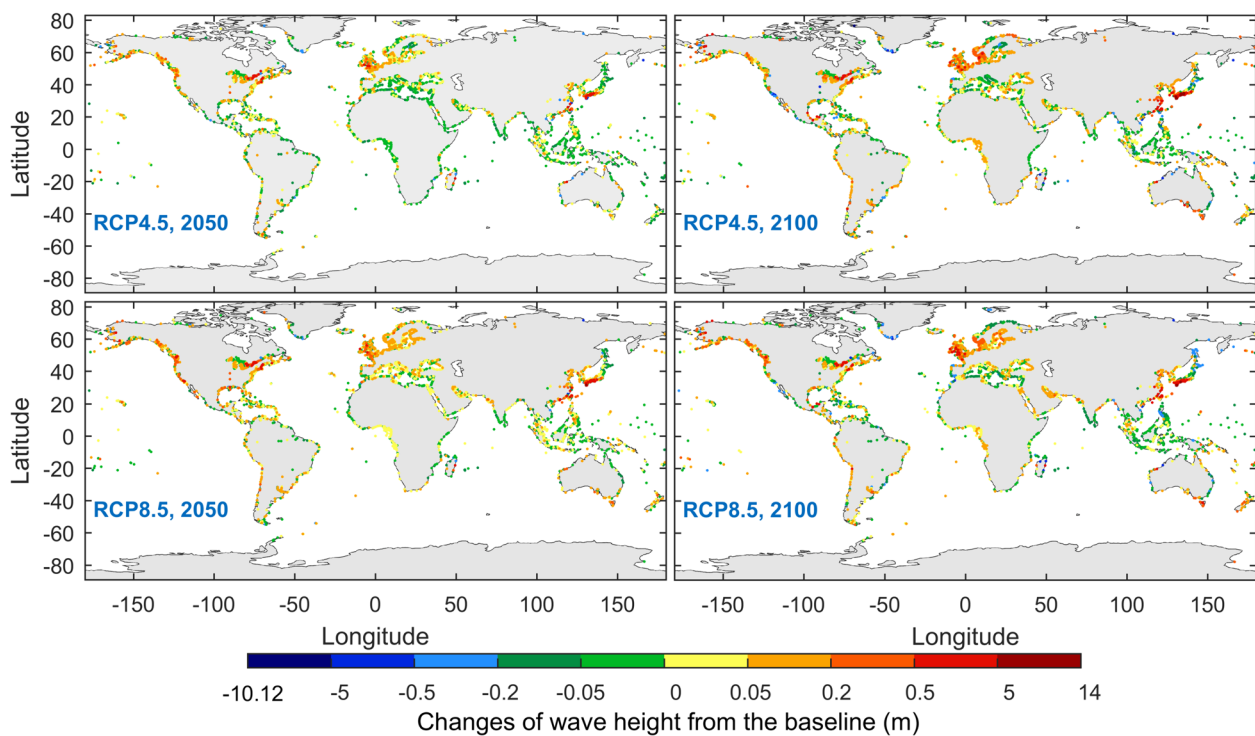


Fig. 5 Projected changes in the 1-in-100 years significant wave height from the baseline value (mean of 1980–2014) under climate change for 3630 global ports. Port location from the World Port Index 2019

heat episodes (IPCC 2018, 2023a). All global ports will be affected, with the effects worsening with increasing global warming (e.g., Dosio et al. 2108). Even with 2 °C global warming (expected by the 2050s), a present 1-in-100 year extreme heat event (mean of the 1976 – 2005 period) could happen every 1 to 5 years in most tropical/subtropical settings (Fig. 6). With 3 °C global warming, most global ports (except some ports in higher latitudes) could be exposed to heat events of this magnitude every 1 to 2 years, giving rise to extensive additional energy needs and costs. Moreover, a combination of extreme heat with high relative humidity can pose a major threat for the health and safety of personnel/passengers, with large increases projected in the number of days per year exceeding a ‘deadly temperature and humidity threshold’ particularly in the tropics and subtropics under a high emission scenario (Mora et al. 2017).

Precipitation is expected to change in a complex manner, with increases projected for some regions and decreases for others. Transport-related risks are mostly associated with heavy downpours that can result in pluvial and fluvial flooding, slope failures and landslides. These have increased in terms of frequency/intensity in several regions (Koks et al. 2019; UNECE 2020) and these trends are projected to continue under global warming, particularly over most of the mid-latitude and the wet

tropical regions (IPCC 2018; Alfieri et al. 2018; IPCC 2023b). Under such projections, many global ports will be affected, with the effects worsening with further global warming, although the changes in the extreme runoff on ports will not be as severe as that of ESL and extreme heat events.

4.3 Cryosphere

Due to the large decline in Arctic sea ice extent (SIE) since 1979, opportunities for new shipping routes have arisen. By the end of the century, minimum Arctic SIE has been projected to decrease further, (by 34 and 94% relative to the 1986– 2005 average in February and September, respectively). For stabilised warming at 1.5 °C there is a 1% probability for any given September to be sea ice free by 2100, while with stabilisation at 2 °C this probability rises to 10 – 35% (IPCC 2019). Snow cover extent has also decreased since the 1950s across the northern hemisphere (12% per decade since 1970) and more decreases are projected, whereas permafrost extent and thickness have decreased since the 1930s; by 2100, permafrost extent is projected to decrease by up to 87%, under the RCP4.5 climatic scenario (IPCC 2019). This would present very significant challenges for the development and maintenance of Arctic ports and associated transport infrastructure (Table 1).

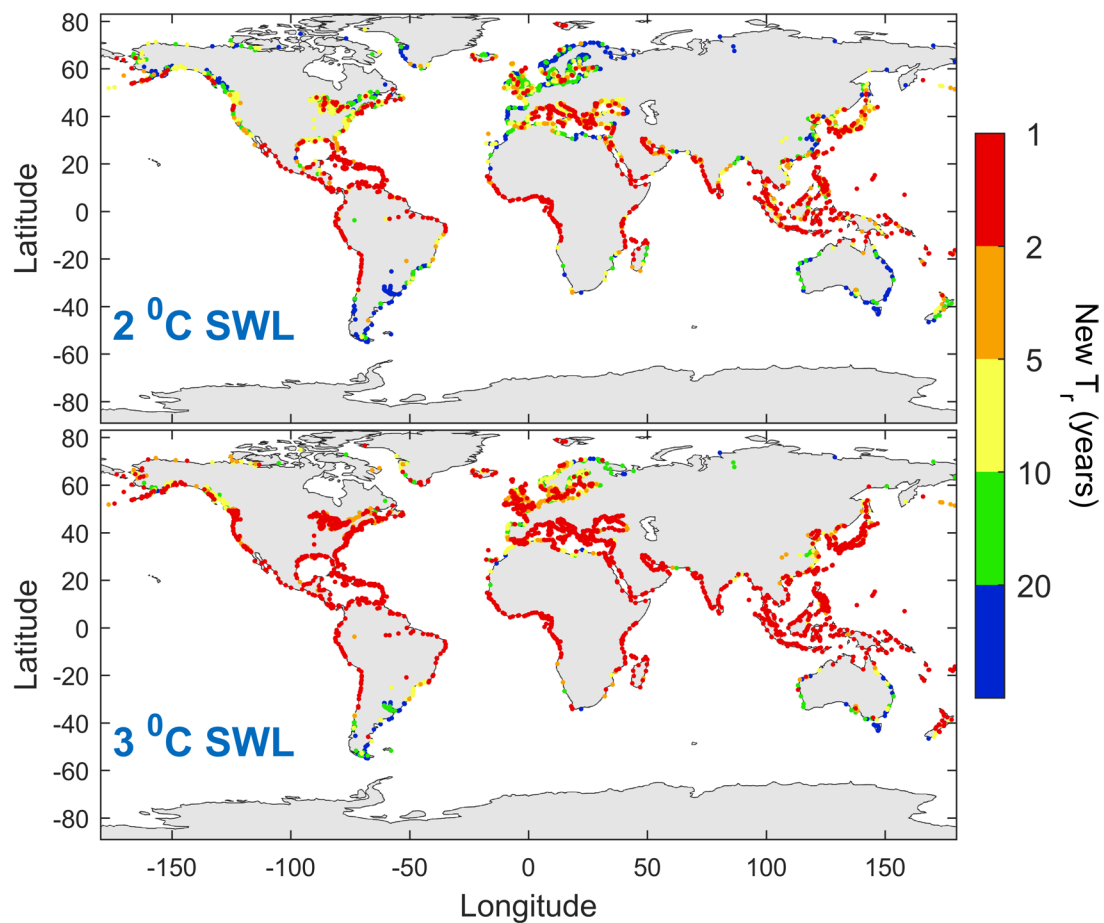


Fig. 6 Projected changes in the frequency of the baseline (mean of the period 1976–2005) 1-in-100 years extreme heat event at 3630 global ports (port location from the World Port Index 2019). Key: SWL (Specific Warming Level), global warming in $^{\circ}\text{C}$ above pre-industrial times. T_r (years), Return period. Extreme heat data for the global coastline abstracted from Dosio et al. (2018)

5 Relevant policy and legal frameworks and recent developments

The above projections have important implications for the physical and operational risks facing ports under a changing climate and illustrate the urgent need for adaptation. Ports are infrastructure assets with long lifespans, often including facilities with a design life of 50–75 years, and with long planning horizons. For example, the time horizon of a port masterplan project, describing the long-term development of a port complex, is at least two decades (Port Consultants Rotterdam 2024). Changes in the intensity/recurrence of extreme events over the coming decades will significantly increase the risk of impacts, such as flooding and operational disruptions at facility level, leading to extensive costs and economic losses, with potentially important repercussions for trade and sustainable development. Past experiences, therefore, can no longer be relied on to predict future risk exposure. Relevant risks need to be both assessed and effectively addressed before any major impacts materialize.

Supportive policy and legal frameworks have a particularly critical role to play in advancing and facilitating climate change adaptation and resilience-building on the ground (UNCTAD 2020a). Policies, strategies and plans define and formulate ambition, objectives and commitments, while legal instruments establish legally binding obligations and are powerful – and vital – tools for the implementation of agreed policy objectives. Legal instruments include national laws, as well as international (and in few cases regional) conventions and agreements that require a certain number of ratifications for their entry into force and are legally binding on all States that have ratified or acceded. In addition, at the EU level, there are legal instruments which are binding as a matter of supranational law for each of the 27 EU Member States and are enforceable in the national courts, subject to the overall oversight and jurisdiction of the European Court of Justice and enforcement actions, including by the European Commission (EU 2020, Arts. 288, 258–260). The supranational nature of EU law, effective in a large number

of States (27), and the importance of the EU as a major global trading partner and donor make relevant legal instruments both particularly efficient and coherent tools for the achievement of agreed policy commitments at the regional (EU) level and of considerable interest from a global perspective.

Both policies and legislation can provide economic incentives to support adaptation, resilience-building and Disaster Risk Reduction (DRR) efforts, promote cooperation and transfer of relevant ‘hard’ and ‘soft’ technologies, and contribute to the collection, availability and accessibility of accurate (and indispensable) climate data at different spatio-temporal scales. They are also key in ensuring accountability, public participation and non-discrimination in related decision-making processes. *Legal* instruments and requirements in particular can help create a level playing field, and promote as well as facilitate and galvanize action to reduce exposure and vulnerability to coastal floods and other climate change impacts; they can assist in both the prevention, mitigation and recovery from extreme events (i.e., support DRR) as well as help mitigate the impacts of slow-onset events.

Reflecting a growing recognition of the need for effective climate change adaptation measures, the policy and legal framework at international, regional and national levels has been strengthened over recent years, with climate change adaptation increasingly being integrated into policy and planning instruments, as well as into some legal instruments (see also UNCTAD 2020a; UNFCCC 2023; Velegakis et al. 2021). While a review of relevant national level policy and legal instruments across jurisdictions is beyond the scope of this short contribution,² examples include the UK Climate Change Act 2008 (UK 2008) which, among others, provides the basis for reporting by infrastructure operators and public bodies on the current and future predicted effects of climate change on their organisation, as well as on their proposals for adapting to climate change and related progress (Article 62)³; and the recent German Federal Climate Adaptation Law (Bundes-Klimaanpassungsgesetz, (KAnG 2023) which, among others, envisages the development of a cross-sectoral federal climate change adaptation strategy, periodic climate-risk analysis/assessment and integration of related considerations by public bodies (and private entities entrusted with public functions) into their planning and decision-making processes across disciplines and policy domains. An analytical overview of the international and regional policy and legal

framework of relevance to climate change adaptation for ports is provided below.

Key international strategies, policies and plans include the 2030 Agenda for Sustainable Development (United Nations 2015a) consisting of 17 goals and 169 targets which are “*integrated and indivisible, global in nature and universally applicable*”, including several that are of particular relevance in the present context (e.g. 1.5, 9, 13; see UNCTAD 2020b); and the Sendai Framework for Disaster Risk Reduction 2015 – 2030 (SFDRR) (United Nations 2015b), the global policy framework stipulating seven global targets and priority areas and adopting a multi-hazard and systems approach for understanding disaster risk in all its dimensions, strengthening disaster risk governance and management, investing in disaster risk reduction for resilience, and enhancing disaster preparedness for effective response and to “*build back better*”.

Relevant international legal instruments⁴ include the 1992 United Nations Framework Convention on Climate Change (UNFCCC) (United Nations 1992), which is in force for 198 Contracting Parties and provides the overarching legal framework for climate change action at the international level⁵; and the 2015 Paris Agreement (United Nations 2015c), in which its 195 Contracting Parties establish “*the global goal on adaptation of enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change*”, and commit to related action and cooperation, as well as regular reporting and assessment processes (Article 7). The Paris Agreement also envisages wide-ranging cooperation among Contracting Parties, with the aim of averting, minimizing and addressing loss and damage, including under the dedicated Warsaw International Mechanism (Art. 8; see also UNFCCC 2020). Also worth noting in this context is the 1998 Aarhus Convention on access to information, public participation in decision-making and access to justice in environmental matters (UNECE 1998), in which its 47 State Parties undertake to guarantee relevant rights in accordance with detailed provisions set out in the Convention.

² For further information, see UNCTAD 2020a, as well as the ‘Climate Change Laws of the world’ database, <https://climate-laws.org/>.

³ Recent related adaptation reports, see <https://www.gov.uk/government/collections/climate-change-adaptation-reporting-third-round-reports#harbour-authorities>.

⁴ Authoritative information on the status of ratification of international legal instruments referred to in the text is available at <https://treaties.un.org>.

⁵ The Parties commit among others to: establish, implement and update national/regional programmes containing measures to facilitate adequate adaptation to climate change; cooperate in preparing for climate change adaptation; employ impact assessments; and promote and cooperate in scientific research, systematic observation and data archives related to the climate system (Art. 4(1) (b),(e),(f) and (g)).

At regional level, relevant policy instruments include the Regional Climate Change Adaptation Framework for the Mediterranean Marine and Coastal Areas (UN Environment/MAP 2017) endorsed by the Contracting Parties of the Barcelona Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean; and the OECS Climate Change Adaptation Strategy and Action Plan (CCASAP) 2021–2026 (OECS 2021), endorsed by the OECS Council of Ministers in 2021 (D'Auvergne 2022), both of which reflect important policy commitments and strategies to building resilience to and reducing disasters from climatic hazards (including e.g., coastal flooding due to extreme events).

At the EU level, of particular relevance in terms of policies, plans and mechanisms, are the comprehensive 2021 EU Climate Change Adaptation Strategy (EU 2021a), which cuts across sectors and policy domains and aims to ensure a climate-resilient EU by 2050, “*fully adapted to the unavoidable impacts of climate change*”; the EU Action Plan on SFDRR 2015–2030 (EU 2016), which envisages a range of specific actions and measures across policy areas to implement the targets and objectives of the SFDRR; as well as the Union Civil Protection Mechanism, the main operational EU mechanism for disaster risk reduction, response and recovery, which has recently been strengthened (EU 2021b).⁶

Moreover, there are various EU legal instruments which explicitly, or implicitly, address issues of relevance to adaptation, resilience-building and DRR for ports and other infrastructure in the coastal zone and are applicable as a matter of supra-national law in all 27 EU Member States. This includes several *Directives* – which are binding across the EU as to the results to be achieved but need to be transposed into national legislation within a certain number of years, as well as some *Regulations*, which are directly applicable and effective in each EU Member States as from the date of their entry into force (see EU 2020, Art. 288).

The Floods Directive (EU 2007a) imposes a general duty on EU Member States to assess and map the coastal flood risk, affected areas, assets and humans at risk and take adequate/coordinated measures to manage and reduce the flood risk. EU Member States are required to carry out preliminary flood risk assessments, prepare comprehensive flood hazard and risk maps (FHRMs) and establish flood risk management plans (FRMPs), as well

as review and update these in recurring implementation cycles taking into account, among others, “*the likely impact of climate change on the occurrence of floods*”.⁷

The amended EIA Directive (EU 2014b) envisages that for all (public and private) projects falling within its scope, including ports, Environmental Impact Assessments (EIAs) are carried out, taking into account, among others, the risks and vulnerabilities associated with climate change (see Art. 1(a); Annex II 8.b; Annex II 10.e; Annex III 1(f)). Relevant EIAs need to “*identify, describe and assess*” direct and indirect significant effects of the project, including those deriving from the vulnerability of the project to the risk of major accidents, and/or natural-hazard related disasters, (such as flooding, sea level rise, or earthquakes), on populations, human health, biodiversity, land, soil, water, air and climate, material assets, cultural heritage and the landscape, and their interactions (Art. 3; see also preamble, para. 13 and 15).

Seaport and shipping operations can influence (and be influenced by) the offshore marine environment and, thus, EU Directives with an offshore geographical scope (1 nm from the coast) may also be worth noting. The Maritime Spatial Planning Directive (EU 2014a) requires Member States, among others, to contribute through their maritime spatial planning to the sustainable development of maritime transport, “*including resilience to climate change impacts*” (Art 5.2). Also of relevance, albeit indirectly, is the EU’s Marine Strategy Framework Directive (MSFD, EU 2008), which aims to maintain/restore the EU marine environment to a ‘good environmental status’. It requires EU Member States, *inter alia*, to develop marine strategies (Art. 5) and to make an initial assessment of their marine waters comprising of, among others, an analysis of the predominant pressures and impacts (Art. 8). While climate change is considered as a horizontal issue in the MSFD Directive with its impacts recognized in the context of evolving pressures/impacts on marine the marine environment (preamble para. 34), the Art.8 MSFD Assessment Guidance explicitly states that climate change ... “*must be considered in the marine environment assessment within the framework of the marine strategies*” and proposes monitoring and analysis of (i) the climate change-derived variations as background environmental conditions; and (ii) the current and potential impacts on marine ecosystems (EU 2022a).

Other Directives are relevant in terms of access to and the coherence of the information and data that is

⁶ See also COM Recommendation (8.2.2023, 2023/C 56/01) on ‘European Union Disaster Resilience Goals’, which has a flood relevant specific goal: Annex, Union disaster resilience goal No. 4: Respond—Enhancing the Union Civil Protection Mechanism’s response capacity, specific objective 4.2 ‘In the area of flood response’. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023H0215%2801%29&qid=1676531610023>.

⁷ Articles 4 (2); 14 (4); 16. Preliminary flood risk assessments were to be reviewed and updated by 22 December 2018; FRMPs, by 22 December 2021, taking into account the likely impact of climate change on the occurrence of floods. Further review and update is required every six years.

essential for effective flood and climate-risk assessment and management: Directive 2003/4/EC (EU 2003), which implements the 1998 Aarhus Convention (UNECE 1998) within the EU as a matter of supra-national law, and seeks to guarantee rights of access to environmental information held by (and for) public authorities, as well as to public participation in decision-making and access to justice; and the INSPIRE Directive (EU 2007b), last amended in 2019, which aims to establish compatible and usable spatial data infrastructures in a EU-wide and transboundary context.

In addition, a number of very recent legislative developments at the EU level are of special relevance to climate change adaptation for ports and therefore deserve highlighting. Of major importance is the adoption, in June 2021, of a new Regulation on a European Climate Law (EU 2021c) which envisages strong action on climate change adaptation and resilience-building (Art. 5), as well as related stocktaking, assessment and review, every five years, starting in 2023 (see Arts. 6 and 7).⁸ Among others, the Regulation requires EU institutions and Member States to “*ensure continuous progress in enhancing adaptive capacity, strengthening resilience and reducing vulnerability to climate change in accordance with Article 7 of the Paris Agreement*” (Art. 5(1)), thereby making relevant action a legal requirement, for the first time, in an important effort to facilitate coherence across policy and legal frameworks. The Regulation, which entered into force on 29 July 2021 for all 27 EU Member States is expected to have clear and important benefits for efforts at climate-resilience building and adaptation in EU coastal zones, including in respects of ports. It introduces a number of legally binding obligations and, unlike a Directive, is directly applicable and effective at national levels, without the need for the time-consuming development of potentially divergent national implementing legislation (EU 2020, Art. 288).

Importantly, Art. 5(5) of the European Climate Law mandates the European Commission to adopt “*guidelines setting out common principles and practices for the identification, classification and prudent management of material physical climate risks when planning, developing, executing and monitoring projects and programmes for projects*”. Relevant “*Technical guidance on the climate*

proofing of infrastructure in the period 2021–2027” has since been published (EU 2021d). Compliance with its detailed parameters, including climate-risk assessment and adaptation is, among others, required as part of environmental impact assessments under the EIA Directive (EU 2014b), for strategic environmental assessments under the SEA Directive (EU 2001) and for EU (internal and external) infrastructure project funding, making risk and vulnerability assessments and development of adaptation options an integral part of project planning, development and financing.

“*Climate proofing*” of infrastructure “*based on latest available best practice and guidance*”, in accordance with the EC Technical guidance is also envisaged under a proposal (EU 2021e),⁹ to revise the EU TEN-T guidelines (EU 2013) for the development of the trans-European transport (TEN-T) network, of which ports and other coastal transport infrastructure are vital components (EU 2021e, Art. 46(2) and para. 14). The proposed revised Regulation, expected to be formally adopted and enter into force in early 2024,¹⁰ will significantly strengthen implementation of climate and disaster-risk resilience considerations, in line with the objectives and requirements of the EU Adaptation Strategy, European Climate Law and international agreements, notably the 2015 SFDRR and Paris Agreement. While the legislation remains to be formally adopted, ‘*climate proofing of infrastructure based on latest available best practice and guidance*’, as set out in the EC Technical guidance on the climate proofing of infrastructure, has already become a legal requirement (as part of EIAs) for the development of new port infrastructure under EU law.

Other relevant EU legislation includes a Directive on Resilience of Critical Entities (EU 2022b; repealing the European Critical Infrastructure Directive 2008), which entered into force on 16 January 2023, and aims to ensure the resilience of public and private “*critical entities*” across sectors, including transport, against a broad range of risks that could lead to disruptions. By specified dates in 2026, Member States will need to identify the critical entities that provide essential services, develop a national strategy to enhance the resilience of critical entities and carry out a risk assessment (thereafter at least every

⁸ Where collective progress on adaptation is found to be insufficient or Union measures inconsistent with ensuring progress, the Commission shall ‘take the necessary measures in accordance with the Treaties’ (Art. 6). Where the Commission finds that a Member State’s measures are inconsistent with ensuring progress on adaptation, it may issue recommendations to that Member State, and if so, make these publicly available (Art. 7).

⁹ The proposal was amended in 2022 (COM/2022/384 final) but without changes which are material in the present context. <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52022PC0384&from=EN>.

¹⁰ The revised rules on the guidelines for the development of the trans-European transport network were adopted by the European Parliament in April 2024 and, once the Council has approved them, will enter into force 20 days after publication in the Official Journal, see <https://www.europarl.europa.eu/news/en/press-room/20240419IPR20574/european-parliament-updates-trans-european-transport-network-guidelines>.

four years).¹¹ Critical entities will need to identify risks that may significantly disrupt the provision of essential services, take appropriate measures necessary to ensure their resilience, “including measures necessary to prevent incidents from occurring, duly considering disaster risk reduction and climate adaptation measures” and notify disruptive incidents to the competent authorities (Art. 13(1)). The Directive needs to be transposed into the legislation of each EU Member State by 17 October 2024.

The introduction of further legal requirements at EU level and at national levels, along similar lines may be likely, in the light of Art. 5(4) of the European Climate Law, which requires Member States to “adopt and implement national adaptation strategies and plans taking into account the [EU Adaptation Strategy], and based on robust climate change and vulnerability analyses, progress assessments and indicators, and guided by the best available and most recent scientific evidence”. The net-upshot of the abovementioned developments is that the policy and legal framework supporting – and requiring – climate-risk assessment and adaptation for ports in the 27 EU Member States and for EU funded port infrastructure projects in third countries has been strengthened significantly. At the same time, barriers to effective national implementation of relevant EU instruments by EU Member States, including delays in transposition, inadequate application, administrative hurdles, might hamper the effectiveness of these mechanisms. The development of effective policy and legal instruments for the climate resilience of ports is an area that merits further analysis and research. However, the EU’s approach of aiming for coherence among policy and legal instruments as well as technical guidance to ensure the climate-proofing of ports and other critical infrastructure assets may serve as a useful example and could provide an important impetus for other countries considering how best to move forward.

6 Discussion and conclusions

Ports are key nodes in global supply chains and critical for global trade and sustainable development. At the same time, both infrastructure and operations of seaports and their connecting transport networks are at considerable risk of a wide range of impacts from climatic and weather-related hazards, such as (Table 1): rising mean sea levels; increasing intensities/recurrence of extreme

storm surges, waves and winds; intensifying extreme temperatures; and changes in precipitation that can cause fluvial/pluvial flooding and, at high latitudes, affect the cryosphere (ice, permafrost) dynamics. These hazards have already caused large economic damages/losses and are set to grow at an alarming rate under future climate change. As shown by projections under different climatic scenarios and timelines, many global ports will increasingly be exposed to such hazards.

For instance, the relative sea-level rise (RSLR) for 3630 global ports has been projected as up to 0.21 m (RCP 4.5) and 0.29 m (RCP 8.5) by 2050, and up to 0.67 m (RCP 4.5) and 1.06 m (RCP 8.5) by 2100, with the highest rises expected at South American and African ports. Extreme sea-levels (ESLs) will threaten ports in all regions, with effects worsening over the course of the century: by 2050, ESLs₁₀₀ will increase by up to 0.5 m above the baseline values under the examined scenarios, whereas by 2100, ESL₁₀₀ increases will be reaching up to 1.6 m. By 2050, under RCP 4.5 and RCP 8.5, respectively, approximately 55% and 59% of the 3630 ports studied (53% and 58% of the 522 large and medium-sized ports) will face ESLs exceeding 2 m above the baseline mean sea level, whereas by 2100, an estimated 71% and 83% of all ports, along with roughly 70% and 81% of the (522) large and medium-sized ports, are projected to be affected by ESLs exceeding 2 m above the baseline mean sea levels. At the same time, there will be increases in the frequency/intensity of heat waves in many regions, with the effects worsening for higher global warming: even under global warming of 2 °C (expected by the 2050s), the return period of the baseline (mean of 1976 – 2005 period) 1-in-100 year extreme heat event will decrease to 1 – 5 years in most tropical/subtropical settings, whereas with 3 °C global warming, most global ports (except some ports in higher latitudes) will experience the baseline 1-in-100 years extreme heat event every 1 – 2 years. Precipitation is expected to change in a complex manner, with increases projected for some regions and decreases for others.

With the risk of impacts being a function of hazard, exposure and vulnerability (IPCC 2014), exposure to growing hazards will result in increasing risks, unless effective action is taken to reduce vulnerability, i.e. enhance the capacity to respond. Against this background, climate change adaptation and resilience-building for ports is a matter of increasing urgency and strategic economic importance.

This is increasingly being recognized by port industry stakeholders. Thus, according to the European Sea Ports Organization (ESPO), climate change was considered as the top environmental concern of European ports in 2022 and 2023 (ESPO 2022, 2023), rising steadily in the

¹¹ Articles 4–6. See also a Commission Delegated Regulation (EU 2023) which entered into force in November 2023, establishing a non-exhaustive list of essential services in the 11 sectors covered by the Directive, including ports in the ‘transport sector/water subsector’ (Art 2. (2)(c)(ii)). This is to be used by competent authorities to carry out risk assessments by 17 January 2026 and to then identify the critical entities, by 17 July 2026.

priority ranking since 2017 when it appeared for the first time. In 2023, responses from 90 European ports in 20 countries that are members and observers of ESPO indicated that while less than half of the ports (47%) experienced climate-related operational challenges, a clear majority – 70% of respondent ports – adapt existing infrastructure to increase resilience and 76% incorporate considerations related to climate change adaptation when planning and implementing new infrastructure projects. This is encouraging and may potentially – at least in part – be a result of the new EU legislative framework and technical guidance.

However, at the global level, progress in implementing fit-for-purpose measures on the ground remains slow and recent global industry surveys by UNCTAD (Asariotis et al. 2018) – reflecting responses from ports which collectively handle more than 16% of global seaborne trade – and by industry organizations (PIANC 2024) suggest that ports – and port engineers (Sweeney and Becker 2020) are not yet adequately prepared. While many global ports are increasingly impacted by climate/weather related extremes and events which are somehow exceptional, unprecedented or otherwise out-of-the ordinary, often causing ‘significant’ or ‘critical’ delays and disruptions (Brooke 2024), there are still important knowledge gaps regarding the specific nature and extent of exposure that individual port facilities of all sizes and across regions may be facing, with important repercussions for levels of preparedness. For example, while the majority (76%) of respondent ports to the UNCTAD port industry survey had mainstreamed weather/climate related considerations in planning, design and construction of infrastructure, a significant proportion (41%) had not yet carried out any relevant work, including research, to identify and evaluate possible adaptation measures (Asariotis et al. 2018). 40% of respondent ports had not carried out or planned relevant vulnerability assessments.

Constraints in the planning and implementation of effective climatic risk assessments and adaptation measures identified in the abovementioned surveys and other literature include: gaps in the information/data necessary to assess flood and other risks, including climatic stressors, thresholds, trends, downscaled projections; knowledge dissemination barriers; stakeholder and decision-making related challenges; and limited relevant research capacity, as well as lack of human and financial resources, particularly in developing countries (Asariotis et al. 2018; Flegg et al. 2018; Panahi et al. 2020; Mclean and Becker 2020; Kalaidjian et al. 2022; Kontopyrakis et al. 2024; PIANC 2024). It is also a matter of concern that only 29% of respondents to an online survey of 85 US port and maritime infrastructure engineers indicated that their organization had an internal sea level change

(SLC) policy, design, or planning document with survey results also showing that the lack of regulatory design standards in this area leads to engineers and their clients disregarding SLC more frequently (Sweeney and Becker 2020).

Climate risks translate into business risks for individual ports (PIANC 2024; Brooke 2024); they also pose a significant threat to closely interconnected global supply-chains, with wide-ranging implications for global society and the sustainable development prospects of the most vulnerable countries and regions. In the light of long infrastructure planning horizons and lifespans and increasing climatic hazards, timely adaptation action in a systemic manner must be an urgent priority for all public and private entities with a stake in international transport and trade. Thus, all stakeholders involved in planning, development and operations of ports and other coastal transport infrastructure need to take into account the risks and impacts of CV&C as part of their decision-making processes (UNCTAD 2020a). Collaboration and the participation of a broad range of actors will be of particular importance with regard to the assessment of risks and impacts and the planning and implementation of effective adaptation measures, both at facility levels and across transport networks and systems (Becker et al. 2015; Becker et al. 2018; Morris 2020).

Policy and legal frameworks that facilitate, support and accelerate effective action on adaptation and resilience-building for ports and other critical transport infrastructure have a particularly vital role to play in strengthening risk governance and increasing resilience on the ground. Policies, strategies and plans establish agreed objectives, priorities and commitments which, among others, inform the provision and use of resources as well as institutional frameworks, and can provide important incentives for advancing port resilience. Legal frameworks are both powerful and vital tools to facilitate and advance implementation, along with accountability. To be fit for purpose and avoid maladaptation, both policies and laws need to take into account the latest available scientific information and facilitate risk-informed decision making under uncertainty. As highlighted in this contribution, a range of policy and legal instruments reflecting related commitments and objectives and fostering their implementation have been agreed internationally, including the 2015 UNFCCC Paris Agreement, the SFDRR 2015–2030 and the 2030 Agenda for Sustainable Development, as well as at regional levels. Moreover, relevant legal obligations and related technical guidance aimed at ensuring the climate proofing of new infrastructure, in line with agreed policy commitments on resilience-building, adaptation and DRR, are already in place as a matter

of supra-national law in the 27 EU Member States. These could significantly enhance levels of climate-resilience and preparedness for EU ports, as well as for EU funded port projects in other countries, and may serve as useful examples of good practices for countries in other regions.

However, in order to ensure the integrity of closely integrated global supply chains and reduce, minimize and avert extensive economic losses arising in future, much more needs to be done to advance and accelerate the implementation of effective adaptation measures for ports across regions. Effective adaptation requires multifaceted approaches, including technical measures that should involve innovative and efficient designs to avoid over-engineering, bridging of potential data and knowledge gaps, and the development of appropriate management solutions that reduce vulnerability and allow for decision-making under uncertainty (Becker et al. 2013, 2018; UNFCCC 2020; Ng et al. 2016; 2018; Izaguirre et al. 2020). In the light of the long service life of ports (and other key transport infrastructure), and the potentially major consequences of inaction, effective adaptation and resilience building requires rethinking established approaches and practices early.

Moreover, to avoid maladaptation and increase levels of preparedness on the ground, a good understanding of relevant risks, in all its dimensions, is critical. This, however, constitutes a major challenge. The potential adverse impacts of climate variability and change may be wide-ranging, but they vary considerably by physical setting, climate forcing and a range of other factors, including local conditions and the availability of redundancies. High-quality technical risk assessments at local/facility levels, using best available science are therefore urgently required. Several examples of relevant assessments carried out by ports worldwide (see the compilation in UNCTAD 2020a; Monioudi et al. 2018) may provide useful insights and inspiration to others. On the basis of such risk assessments, the probability and severity of impacts can be determined, together with the urgency of the adaptation responses, which can be defined as the ratio of the time needed to plan/implement an effective response to the time available (Lenton et al. 2019). Relevant information is needed to support on-the-ground decision-making, inform the prioritization of resources and the design of the required adaptation measures.

In this context, guidance, standards, and methodological tools to assist stakeholders on the ground have an important role to play, and some important progress has been made in this respect over the past few years. For instance, the Marrakech Partnership for Global Climate Action has developed a number of recommendations for different groups of stakeholders to advance and support transport infrastructure resilience-building,

together with milestones towards 2050 (UNFCCC 2021). The International Standardization Organization (ISO) has published two standards to assist organizations in adaptation and related vulnerability and risk-assessments (ISO 2019; 2021); and PIANC, the World Association for Waterborne Transport Infrastructure, has developed detailed industry guidance on adaptation planning for ports and inland waterways (PIANC 2020), as well as on selecting, designing and evaluating options for resilient infrastructure (PIANC 2022; Brooke et al. 2024). Worth noting is also a forthcoming PIANC technical note, which stresses the consequences of inaction; demonstrates that the benefits of improved climate change preparedness typically outweigh the costs of adaptation interventions, often substantially; and provides guidance on the potential scope of a business case assessment (PIANC 2024; Brooke 2024).

Methodological frameworks to assist in risk assessment and adaptation planning for ports include some which are cross-sectoral (e.g. Smithers and Dworak 2023) as well as those developed under the EU INTERREG ECCLIPSE¹² project (ECCLIPSE 2021), focusing on ports of Southwest Europe, including Valencia, Bordeaux and Aveiro; and by UNCTAD (UNCTAD 2018), as part of a technical assistance project focusing on ports and airports in Caribbean Small Island Developing States (<https://SIDSport-ClimateAdapt.unctad.org>). Worth highlighting in this context are also efforts to develop port resilience-related tools and indices to help address climate change impacts, such as for instance a ports resilience index (PRI) that takes into account all stakeholders associated with seaports to determine the level of operational resilience of port processes in the face of climate change (León-Mateos et al. 2021); a self-assessment tool developed for port and marine industry leaders to assess their preparedness to maintain operations during and after disasters (Morris and Sempier 2016); and a PRI developed through a participatory approach to engage port stakeholders beyond written preparedness plans toward action (Morris and Sempier 2019).

Of considerable practical significance is also the European Commission (EC) *Technical guidance on climate-proofing of infrastructure projects for the period 2021–2027* (EU 2021d), which sets out detailed protocols for climate-risk assessment and adaptation throughout the project planning and development cycle. In contrast to other technical guidelines and standards, this technical guidance has normative effect: its application is not entirely voluntary but will be required, for environmental impact assessments and the ‘climate proofing’

¹² ECCLIPSE (assEssment of CLimate change in Ports of Southwest Europe).

of new infrastructure envisaged under EU law, as well as for all EU funded infrastructure projects (including EU-external).

While guidance and tools for stakeholders can play an important role in increasing levels of preparedness, other issues are also important and deserve increasing focus/attention. This includes the generation and dissemination of more tailored data, such as infrastructure inventories, higher resolution data, including better digital elevation models (Bove et al. 2020), and research to improve the understanding of coastal processes under CV&C, as well as ecosystem approaches to adaptation that can play a significant role in reducing risks (PIANC 2020). Drawing on synergies with energy efficiency, decarbonization and renewables can also provide important co-benefits for adaptation, reduce related energy needs and costs and increase energy security (UNCTAD 2022b).

Increased investment in human resources and skills, in particular skilled coastal scientists and engineers, at regional and local levels will be critical for successful adaptation and resilience-building in the future, as will be the mainstreaming of climate change-related considerations into ordinary transport planning, operations and management and into nationally determined contributions and national adaptation plans under the Paris Agreement. Targeted capacity-building is urgently needed, in particular for the most vulnerable countries, including small island developing States (SIDS), which depend on ports (and coastal airports) for food and energy needs, external trade and – crucially – tourism, which typically accounts for a major share of their GDP, as well as in the context of DRR. For these and other developing countries – often at the frontline of impacts but with low adaptive capacity and facing a worsening debt crisis – better availability and access to infrastructure adaptation finance, including in the form of grants rather than loans will be critical (UNCTAD 2022b; see also UNCTAD 2021, at para. 87). With estimated adaptation costs in developing countries 10–18 times greater than current public adaptation finance flows (UNEP 2023b), this will require a major collaborative effort by policymakers and development partners and a shift in focus. According to OECD (2023), in 2021, total climate finance provided and mobilised by developed countries for developing countries amounted to US\$ 89.6 billion, most of which in the form of loans. Of this total, just US\$ 24.6 billion (27%) was for adaptation, and only a fraction of this amount will have been targeting climate change adaptation for ports and other critical coastal infrastructure. Despite multiple climate finance instruments and sources, including the Green Climate Fund and funding made available by multilateral development banks, accessing adequate climate finance for port

adaptation remains a major challenge for developing countries (UNCTAD 2020b); this is particularly alarming in the light of the global adaptation finance gap currently estimated at US\$194–366 billion per year (UNEP 2023b). To increase levels of preparedness and help mitigate impacts, there is also an important need to upscale support for multi-hazard Early Warning Systems (EWS) including through the Early Warnings For All (EW4All) initiative (<https://public.wmo.int/en/earlywarningsforall>) and national and regional efforts to develop EWS (see e.g. UNDRR and WMO 2022; ECFAS 2023).

In the light of what is at stake and the cost of inaction, resilience-building, adaptation and DRR for ports and other critical transport infrastructure assets should be considered a particularly valuable investment for a sustainable future. There are multiple dividends to be gained from resilience building (United Nations 2020) but above all resilience helps prevent and mitigate economic, environmental and human losses. While global investment costs for port adaptation to sea-level rise can be substantial (Hanson and Nicholls 2020), according to World Bank estimates (Hallegatte et al. 2019), overall net benefits of investing in resilient infrastructure in developing countries could amount to US\$4.2 trillion over the lifetime of new infrastructure – a US\$4 benefit for each dollar invested in resilience.

In the absence of effective adaptation action to reduce exposure and vulnerability, related physical climate-risks for ports may increasingly materialize, jeopardizing the integrity of transport networks across supply-chains and leading to significant damage, disruption and delay, as well as extensive economic losses. The risks of climate-related port damages, delays and disruptions, may also have important implications for insurance, in terms of coverage, premiums and, ultimately, insurability of losses; and for the performance of commercial contracts, as well as the rights, obligations and liabilities of contracting parties engaged in international transport and trade (Asariotis 2023). While consideration of these is beyond the scope of this contribution, relevant implications also deserve further attention and need to be better understood, to minimize economic losses, inform commercial contracting practice into the future, and to ensure that insurance cover remains available, and premiums affordable.

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Authors' contributions

RA, AFV and VMN contributed to the conception, scope and design of the study. RA performed the analyses of the policies and legal instruments. RA, AFV and VMN contributed to the results interpretation and discussion and

wrote sections of the manuscript. MIV LM and LF performed the projections of RSLR, ESLs, waves and heat waves for all the ports under different climatic scenarios. INM assessed the climate change hazards and impacts on the ports, wrote the corresponding sections of the manuscript and prepared the relevant figures. All authors commented on previous versions of the manuscript. The authors read and approved the final manuscript.

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Availability of data and material

The datasets used and/or analysed during the current study are available from the first author on reasonable request.

Declarations

Competing interests

The authors declare that they have no competing interests.

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References

- Alfieri L, Dottori F, Betts R, Salamon P, Feyen L (2018) Multi-Model Projections of River Flood Risk in Europe under Global Warming. *Climate* 6:6. <https://doi.org/10.3390/cli6010006>
- Asariotis R (2023) Climate change impacts on ports – some considerations arising for commercial maritime law. In: Athanassiou L (ed) Protecting maritime operators in a changing regulatory and technological environment. Nomiki Bibliothiki, pp 285–320
- Asariotis R (2021) Climate change impacts on seaports: A growing threat to sustainable trade and development. <https://unctad.org/news/climate-change-impacts-seaports-growing-threat-sustainable-trade-and-development>. Accessed 18 Jan 2024
- Asariotis R (2020) Climate change and adaptation for coastal transport infrastructure: A sustainable development challenge for SIDS in the Caribbean and beyond. In: Wang Y (ed) Coastal and Marine Environments, 2nd edn. CRC Press, Boca Raton, pp 253–264
- Asariotis R, Benamara H, Mohos Naray V (2018) Port Industry Survey on Climate Change Impacts and Adaptation. UNCTAD/SER.RP/2017/18/Rev.1. https://unctad.org/system/files/official-document/ser-rp-2017d18_en.pdf. Accessed 18 Jan 2024
- Becker A, Ng AKY, McEvoy D, Mullett J (2018) Implications of climate change for shipping: Ports and supply chains. *WIREs Climate Change* 9:e508. <https://doi.org/10.1002/wcc.508>
- Becker AH, Matson P, Fischer M, Mastrandrea MD (2015) Towards seaport resilience for climate change adaptation: Stakeholder perceptions of hurricane impacts in Gulfport (MS) and Providence (RI). *Prog Plann* 99:1–49. <https://doi.org/10.1016/j.progress.2013.11.002>
- Becker AH, Acciaro M, Asariotis R, Cabrera E, Cretegnay L, Crist P, Esteban M, Mather A, Messner S, Naruse S, Ng AKY, Rahmstorf S, Savonis M, Song D-W, Stenek V, Velegrakis AF (2013) A note on climate change adaptation for seaports: a challenge for global ports, a challenge for global society. *Clim Change* 120:683–695. <https://doi.org/10.1007/s10584-013-0843-z>
- Bevacqua E, Vousdoukas MI, Zappa G, Hodges K, Shepherd TG, Maraun D, Mentaschi L, Feyen L (2020) More meteorological events that drive compound coastal flooding are projected under climate change. *Commun Earth Environ* 1:47. <https://doi.org/10.1038/s43247-020-00044-z>
- Bove G, Becker A, Sweeney B, Vousdoukas M, Kulp S (2020) A method for regional estimation of climate change exposure of coastal infrastructure: Case of USVI and the influence of digital elevation models on assessments. *Sci Total Environ* 710:136162. <https://doi.org/10.1016/j.scitotenv.2019.136162>
- Brooke J, Giovando J, Dahl TA, Joyner B, Herbert L (2024) Port and inland waterway design and operation in the face of climate change uncertainty. *Proc Inst Civil Eng* 40:1–13. <https://doi.org/10.1680/jcien.23.00134>
- Brooke J (2024) Supporting the business case to adapt existing ports to the changing climate. 35th PIANC World Congress, 29 April – 23 May 2024, Cape Town
- Camus P, Losada IJ, Izaguirre C, Espejo A, Menéndez M, Pérez J (2017) Statistical wave climate projections for coastal impact assessments. *Earths Future* 5:918–933. <https://doi.org/10.1002/2017EF000609>
- Camus P, Tomás A, Díaz-Hernández G, Rodríguez B, Izaguirre C, Losada IJ (2019) Probabilistic assessment of port operation downtimes under climate change. *Coast Eng* 147:12–24. <https://doi.org/10.1016/j.coastaleng.2019.01.007>
- Cao X, Lam JSL (2018) Simulation-based catastrophe-induced port loss estimation. *Reliab Eng Syst Saf* 175:1–12. <https://doi.org/10.1016/j.res.2018.02.008>
- CAT (2023) Climate Action Tracker. <https://climateactiontracker.org/publications/no-change-to-warming-as-fossil-fuel-endgame-brings-focus-onto-false-solutions/>. Accessed 18 Jan 2024
- CEM (2002) Coastal Engineering Manual, United States Army Corps of Engineers <https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals/u43544q/636F617374616C20656E67696E656572696E67206D616E75616C/>. Accessed 18 Jan 2024
- Cheng L, Abraham J, Hausfather Z, Trenberth KE (2019) How fast are the oceans warming? *Science* 363:128–129. <https://doi.org/10.1126/science.aav7619>
- D'Auvergne C (2022) OECS Climate Change Adaptation Strategy and Action Plan 2021–2026 – Considerations for seaport resilience building and DRR. https://unctad.org/system/files/non-official-document/cimem9_2022_P20_DAUVERGNE.pdf. Accessed 18 Jan 2024
- DeConto RM, Pollard D, Alley RB, Velicogna I, Gasson E, Gomez N, Sadai S, Condrón A, Gilford DM, Ashe EL, Kopp RE, Li D, Dutton A (2021) The Paris Climate Agreement and future sea-level rise from Antarctica. *Nature* 593:83–89. <https://doi.org/10.1038/s41586-021-03427-0>
- Dosio A, Mentaschi L, Fischer EM, Wyser K (2018) Extreme heat waves under 1.5 °C and 2 °C global warming. *Environ Res Lett* 13:054006. <https://doi.org/10.1088/1748-9326/aab827>
- Dottori F, Szewczyk W, Ciscar J-C, Zhao F, Alfieri L, Hirabayashi Y, Bianchi A, Mongelli I, Frieler K, Betts RA, Feyen L (2018) Increased human and economic losses from river flooding with anthropogenic warming. *Nat Clim Chang* 8:781–786. <https://doi.org/10.1038/s41558-018-0257-z>
- ECCLIPSE (2021) Assessment of the effects of climate change on coastal-port environments. Developed as part of the ECCLIPSE project. <https://www.ecclipse.eu>. Accessed 18 Jan 2024
- ECFAS (2023) <https://www.ecfas.eu/>. Accessed 18 Jan 2024
- Economist Impact (2023) Global Maritime Trends 2050. <https://impact.economist.com/ocean/global-maritime-trends-2050/downloads/Global%20Maritime%20Trends%202050%20Report.pdf>. Accessed 18 Jan 2024
- EDF (2022) Act Now or Pay Later: The Costs of Climate Inaction for Ports and Shipping. <https://www.edf.org/sites/default/files/press-releases/RTI-EDF%20Act%20Now%20or%20Pay%20Later%20Climate%20Impact%20Shipping.pdf>. Accessed 18 Jan 2024
- ESPO (2022) Environmental Report 2022. EcoPortsInSights 2022. <https://www.espo.be/publications/espo-environmental-report-2022>. Accessed 17 Mar 2024.
- ESPO (2023) Environmental Report 2023. EcoPortsInSights 2023. <https://www.espo.be/news/espos-environmental-report-2023-climate-change-aga>. Accessed 17 Mar 2024.
- EU (2001) Directive 2001/42/EC on the assessment of the effects of certain plans and programmes on the environment (OJ L 197, 21.7.2001, p. 30). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:32001L0042>. Accessed 18 Jan 2024

- EU (2003) Directive 2003/4/EC of the European Parliament and of the Council of 28 January 2003 on public access to environmental information and repealing Council Directive 90/313/EEC. <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX%3A32003L0004>. Accessed 18 Jan 2024
- EU (2007a) Directive 2007/60/EC on the assessment and management of flood risks. <https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32007L0060>. Accessed 18 Jan 2024
- EU (2007b) Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community (INSPIRE). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02007L0002-20190626>. Accessed 18 Jan 2024
- EU (2008) Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive) (Text with EEA relevance) (OJ L 164, 25.6.2008, p. 19–40) <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32008L0056>. Accessed 29 Apr 2024.
- EU (2013) Regulation (EU) No 1315/2013 of the European Parliament and of the Council (11/12/2013) on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32013R1315&from=EN>. Accessed 18 Jan 2024
- EU (2014a) Directive 2014/89/EU of the European Parliament and of the Council of 23 July 2014 establishing a framework for maritime spatial planning (OJ L 257, 28.8.2014, p. 135–145). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0089>. Accessed 18 Jan 2024
- EU (2014b) Directive 2014/52/EU 16/4/2014 amending Directive 2011/92/EU on the assessment of the effects of certain public and private projects on the environment (OJ L 124, 25.4.2014, p. 1–18). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex%3A32014L0052>. Accessed 18 Jan 2024
- EU (2016) Action Plan on SFDRR 2015–2030. https://civil-protection-humanitarian-aid.ec.europa.eu/system/files/2016-06/1_en_document_travail_service_part1_v2.pdf. Accessed 18 Jan 2024
- EU (2020) Consolidated version of the Treaty on the Functioning of the European Union (OJ C 202, 7.6.2016, p. 47). <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A02016E02FXT-20200301>. Accessed 18 Jan 2024
- EU (2021a) Forging a climate-resilient Europe – the new EU Strategy on Adaptation to Climate Change. COM:2021/82. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:82:FIN>. Accessed 18 Jan 2024
- EU (2021b) Regulation (EU) 2021/836 of the European Parliament and of the Council of 20 May 2021 amending Regulation 1313/2013/EU on a Union Civil Protection Mechanism. <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R0836&from=EN>. Accessed 18 Jan 2024
- EU (2021c) European Climate Law. Regulation (EU) 2021/1119 30/6/2021 amending Regulations (EC) No 401/2009 and (EU) 2018/1999. OJ. 9.7.2021 L 243/11, <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32021R1119&from=EN>. Accessed 18 Jan 2024
- EU (2021d) Commission Notice – Technical guidance on the climate proofing of infrastructure in the period 2021–2027 (OJ C 373, 16.9.2021, p. 1). [https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021XC0916\(03\)&from=EN](https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021XC0916(03)&from=EN). See also Corrigendum (OJ C, C/246, 29.06.2022, p. 24). [https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021XC0916\(03\)R\(01\)](https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52021XC0916(03)R(01)). Accessed 18 Jan 2024
- EU (2021e) Proposal for a Regulation of the European Parliament and of the Council on Union guidelines for the development of the trans-European transport network, amending Regulation (EU) 2021/1153 and Regulation (EU) No 913/2010 and repealing Regulation (EU) 1315/2013. COM/2021/812 final. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2021:812:FIN>. Accessed 18 Jan 2024
- EU (2022a) European Commission. MSFD CIS Guidance Document No. 19, Article 8 MSFD, May 2022. https://www.researchgate.net/publication/361461227_European_Commission_2022_MSFD_CIS_Guidance_Document_No_19_Article_8_MSFD_May_2022#fullTextFileContent. Accessed 24 Mar 2024
- EU (2022b) Directive (EU) 2022/2557 of the European Parliament and of the Council of 14 December 2022 on the resilience of critical entities and repealing Council Directive 2008/114/EC (Text with EEA relevance) (OJ L 333, 27.12.2022, p. 164–198). <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32022L2557&from=EN>. Accessed 18 Jan 2024
- EU (2023) Commission Delegated Regulation (EU) 2023/2450 of 25 July 2023 supplementing Directive (EU) 2022/2557 of the European Parliament and of the Council by establishing a list of essential services (OJ L 2023/2450, 30.10.2023). https://eur-lex.europa.eu/eli/reg_del/2023/2450. Accessed 18 Jan 2024
- Flegg E.F., Brown S., Nicholls R.J., Tsimplis M., Burgess K. (2018) UK port preparedness for climate change: The benefits of appropriate adaptation. In: Burgess K (ed) *Coasts, Marine Structures and Breakwaters 2017*. ICE Publishing, pp 297–300
- Folkman D, Gharehgozli A, Mileski J, Galvao CB (2021) Port resiliency and the effects of hurricanes on port operations. *Int J Adv Ops Manage* 13:409–430. <https://doi.org/10.1504/IJAOM.2021.120779>
- Giardino A, Nederhoff K, Voudoukas M (2018) Coastal hazard risk assessment for small islands: assessing the impact of climate change and disaster reduction measures on Ebeye (Marshall Islands). *Reg Environ Change* 18:2237–2248. <https://doi.org/10.1007/s10113-018-1353-3>
- Government of Dominica (2017) Post-Disaster Needs Assessment Hurricane Maria, September 18, 2017 <https://www.gfdrr.org/en/publication/post-disaster-needs-assessment-dominica>. Accessed 18 Jan 2024
- Hallegatte S, Rentschler J, Rozenberg J (2019) *Lifelines: The Resilient Infrastructure Opportunity*. The World Bank, Washington, DC
- Hanson S, Nicholls R, Ranger N, Hallegatte S, Corfee-Morlot J, Herweijer C, Chateau J (2011) A global ranking of port cities with high exposure to climate extremes. *Clim Change* 104:89–111. <https://doi.org/10.1007/s10584-010-9977-4>
- Hanson S, Nicholls RJ (2012) Extreme flood events and port cities through the twenty-first century. In: Asariotis R, Benamara H (eds) *Maritime transport and the climate change challenge*. Earthscan/Routledge, London and New York, pp 243–265
- Hanson SE, Nicholls RJ (2020) Demand for Ports to 2050: Climate Policy, Growing Trade and the Impacts of Sea-Level Rise. *Earth's Future* 8:e2020EF001543. <https://doi.org/10.1029/2020EF001543>
- Hoshino S, Esteban M, Mikami T, Takagi H, Shibayama T (2016) Estimation of increase in storm surge damage due to climate change and sea level rise in the Greater Tokyo area. *Nat Hazards* 80:539–565. <https://doi.org/10.1007/s11069-015-1983-4>
- IDB (2020) Assessment of the Effects and Impacts of Hurricane Dorian in the Bahamas. <https://doi.org/10.18235/0002582>. Accessed 18 Jan 2024
- IPCC (2014) Summary for policymakers. In: Field CB, Barros VR, Dokken DJ, Mach KJ, Mastrandrea MD, Bilir TE, Chatterjee M, Ebi KL, Estrada YO, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea PR, L.L. White (eds) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp 1–32
- IPCC (2018) Summary for Policymakers. In: Masson-Delmotte V, Zhai P, Pörtner H-O, Roberts D, Skea J, Shukla PR, Pirani A, Moufouma-Okia M, Péan C, Pidcock R, Connors S, Matthews JBR, Chen Y, Zhou X, Gomis MI, Lonnoy E, Maycock T, Tignor M, Waterfield T (eds) *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*. Cambridge University Press, Cambridge, pp 1–24. <https://doi.org/10.1017/9781009157940.001>
- IPCC (2019) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, UK and New York
- IPCC (2023a) Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Lee H, Romero J (eds)]. IPCC, Geneva, Switzerland, pp 35–115. <https://doi.org/10.59327/IPCC/AR6-9789291691647>
- IPCC (2023b) Technical Summary. In: *Climate Change 2021 – The Physical Science Basis Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, pp 35–144. <https://doi.org/10.1017/9781009157896.002>
- ISO (2019) ISO 14090:2019. Adaptation to climate change — Principles, requirements and guidelines. <https://www.iso.org/standard/68507.html>. Accessed 18 Jan 2024

- ISO (2021) ISO 14091:2021. Adaptation to climate change — Guidelines on vulnerability, impacts and risk assessment. <https://www.iso.org/standards/std/68508.html>. Accessed 18 Jan 2024
- Izaguirre C, Losada IJ, Camus P, González-Lamunio P, Stenek V (2020) Seaport climate change impact assessment using a multi-level methodology. *Marit Policy Manag* 47:544–557. <https://doi.org/10.1080/03088839.2020.1725673>
- Izaguirre C, Losada IJ, Camus P, Vigh JL, Stenek V (2021) Climate change risk to global port operations. *Nat Clim Chang* 11:14–20. <https://doi.org/10.1038/s41558-020-00937-z>
- Jevrejeva S, Jackson LP, Riva REM, Grinsted A, Moore JC (2016) Coastal sea level rise with warming above 2 °C. *Proc Natl Acad Sci* 113:13342–13347. <https://doi.org/10.1073/pnas.1605312113>
- KAnG (2023). Bundes- Klimaanpassungsgesetz. BGBl. 2023 I Nr. 393 vom 22.12.2023 <https://www.recht.bund.de/bgbl/1/2023/393/VO>. Accessed 30 Apr 2024.
- Kalaidjian E, Becker A, Pinel S (2022) Operationalizing resilience planning, theory, and practice: Insights from U.S. seaports. *Front Sustain* 3:963555. <https://doi.org/10.3389/frsus.2022.963555>
- Kirezci E, Young IR, Ranasinghe R, Muis S, Nicholls RJ, Lincke D, Hinkel J (2020) Projections of global-scale extreme sea levels and resulting episodic coastal flooding over the 21st Century. *Sci Rep* 10:11629. <https://doi.org/10.1038/s41598-020-67736-6>
- Koks EE, Rozenberg J, Zorn C, Tariverdi M, Voudoukas M, Fraser SA, Hall JW, Hallegatte S (2019) A global multi-hazard risk analysis of road and railway infrastructure assets. *Nat Commun* 10:2677. <https://doi.org/10.1038/s41467-019-10442-3>
- Kontopirakis KE, Velegakis AF, Monioudi IN, Čulibrk A (2024) Prioritizing environmental policies in Greek coastal municipalities. *Anthropocene Coasts* 7:1. <https://doi.org/10.1007/s44218-023-00035-5>
- Lam JSL, Liu C, Gou X (2017) Cyclone risk mapping for critical coastal infrastructure: Cases of East Asian seaports. *Ocean Coast Manag* 141:43–54. <https://doi.org/10.1016/j.ocecoaman.2017.02.015>
- Lawrence J-M, Hossain NUI, Rinaudo CH, Buchanan RK, Jaradat R (2019) An Approach to Improve Hurricane Disaster Logistics Using System Dynamics and Information Systems. In: 18th Annual Conference on Systems Engineering Research (CSER). *Procedia Computer Science*
- León-Mateos F, Sartal A, López-Manuel L, Quintás MA (2021) Adapting our sea ports to the challenges of climate change: Development and validation of a Port Resilience Index. *Mar Policy* 130:104573. <https://doi.org/10.1016/j.marpol.2021.104573>
- Lenton T, Footitt A, Dlugolecki A (2009) Major tipping points in the earth's climate system and consequences for the insurance sector
- Lenton TM, Armstrong McKay DI, Loriani S, Abrams JF, Lade SJ, Donges JF, Milkoreit M, Powell T (2023) The Global Tipping Points Report 2023. University of Exeter, Exeter, UK
- Lenton TM, Rockstrom J, Gaffney O, Rahmstorf S, Richardson K, Steffen W, Schellnhuber HJ (2019) Climate tipping points - too risky to bet against. *Nature* 575:592–595. <https://doi.org/10.1038/d41586-019-03595-0>
- Li F, Zhou J, Liu C (2018) Statistical modelling of extreme storms using copulas: A comparison study. *Coast Eng* 142:52–61. <https://doi.org/10.1016/j.coastaleng.2018.09.007>
- McLean EL, Becker A (2020) Decision makers' barriers to climate and extreme weather adaptation: a study of North Atlantic high- and medium-use seaports. *Sustain Sci* 15:835–847. <https://doi.org/10.1007/s11625-019-00741-5>
- Mentaschi L, Voudoukas MI, Voukouvalas E, Dosio A, Feyen L (2017) Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns. *Geophys Res Lett* 44:2416–2426. <https://doi.org/10.1002/2016GL072488>
- Monioudi IN, Asariotis R, Becker A, Bhat C, Dowding-Gooden D, Esteban M, Feyen L, Mentaschi L, Nikolaou A, Nurse L, Phillips W, Smith DAY, Satoh M, Trots UOD, Velegakis AF, Voukouvalas E, Voudoukas MI, Witkop R (2018) Climate change impacts on critical international transportation assets of Caribbean Small Island Developing States (SIDS): the case of Jamaica and Saint Lucia. *Reg Environ Change* 18. <https://doi.org/10.1007/s10113-018-1360-4>
- Monioudi IN, Velegakis AF, Chatzistratis D, Voudoukas MI, Savva C, Wang D, Bove G, Mentaschi L, Paprotny D, Morales-Nápoles O, Chatzipavlis AE, Hasiotis T, Manoutsoglou E (2023) Climate change - induced hazards on touristic island beaches: Cyprus, Eastern Mediterranean. *Front Mar Sci* 10. <https://doi.org/10.3389/fmars.2023.1188896>
- Mora C, Dousset B, Caldwell IR, Powell FE, Geronimo RC, Bielecki CR, Counsell CWW, Dietrich BS, Johnston ET, Louis LV, Lucas MP, McKenzie MM, Shea AG, Tseng H, Giambelluca TW, Leon LR, Hawkins E, Trauernicht C (2017) Global risk of deadly heat. *Nat Clim Chang* 7:501–506. <https://doi.org/10.1038/nclimate3322>
- Moreno E (2023) Panama Canal water levels at historic lows, restrictions to remain. Reuters. <https://www.reuters.com/world/americas/panama-canal-water-levels-historic-lows-restrictions-remain-2023-09-06/>. Accessed 18 Jan 2024
- Morris LL (2020) Stakeholder collaboration as a pathway to climate adaptation at coastal ports. *Maritime Policy Manag* 47(7):953–967. <https://doi.org/10.1080/03088839.2020.1729435>
- Morris LL, Sempier T (2016) Ports Resilience Expert Committee. Ports Resilience Index: A Port Management Self-Assessment. GOMSG-H-16-001. <https://repository.library.noaa.gov/view/noaa/41150>. Accessed 29 April 2024
- Morris L, Sempier T (2019) The Ports Resilience Index: A participatory approach to building resilience. In: Bandana K, David MC (eds) *Risk Communication and Community Resilience*, 1st edn. Routledge, London, pp 179–197
- Muis S, Verlaan M, Winsemius HC, Aerts CJH, Ward PJ (2016) A global re-analysis of storm surges and extreme sea levels. *Nat Commun* 7:11969. <https://doi.org/10.1038/ncomms11969>
- Ng AKY, Becker A, Cahoon S, Chen S-L, Earl P, Yang Z (2016) *Climate Change and Adaptation Planning for Ports*. Routledge, New York
- Ng AKY, Zhang H, Afenyo M, Becker A, Cahoon S, Chen S, Esteban M, Ferrari C, Lau Y, Lee PT-W, Monios J, Tei A, Yang Z, Acciaro M (2018) Port Decision Maker Perceptions on the Effectiveness of Climate Adaptation Actions. *Coast Manag* 46:148–175. <https://doi.org/10.1080/08920753.2018.1451731>
- Notteboom T, Pallis A, Rodrigue J-P (2022) *Port Economics. Management and Policy*. Routledge
- OECD (2023) Climate Finance Provided and Mobilised by Developed Countries in 2013–2021: Aggregate Trends and Opportunities for Scaling Up Adaptation and Mobilised Private Finance. Climate Finance and the USD 100 Billion Goal, OECD Publishing, Paris. <https://doi.org/10.1787/e20d2bc7-en>. Accessed 29 Apr 2024
- OECS (2021) OECS Climate change adaptation strategy and action plan (CCASAP) 2021–2026. <https://rcc.cimh.edu.bb/ccasap/>. Accessed 18 Jan 2024
- PIANC (2020) Climate Change Adaptation Planning for Ports and Inland Waterways (2020). *EnviCom WG 178*. <https://www.pianc.org/publication/climate-change-adaptation-planning-for-ports-and-inland-waterways-2/>. Accessed 18 Jan 2024
- PIANC (2022) Managing Climate Change Uncertainties in Selecting, Designing and Evaluating Options for Resilient Navigation Infrastructure. PTGCC Technical Note 1. <https://www.pianc.org/publication/envicom-ptgcc-technical-note-1/>. Accessed 18 Jan 2024
- PIANC (2024) Supporting a business case to adapt. PTGCC Technical Note No.2. Forthcoming. <https://www.pianc.org/permanent-task-group-on-climate-change/>. Accessed 18 Jan 2024
- Panahi R, Ng AKY, Pang J (2020) Climate change adaptation in the port industry: A complex of lingering research gaps and uncertainties. *Transp Policy (oxf)* 95:10–29. <https://doi.org/10.1016/j.tranpol.2020.05.010>
- Port Consultants Rotterdam (2024) Developing a port masterplan. <https://portconsultantsrotterdam.org/developing-a-port-masterplan/>. Accessed 29 Apr 2024
- Rossouw M, Theron A (2012) Investigation of potential climate change impacts on ports and maritime operations around the southern African coast. In: Asariotis R, Benamara JH (eds) *Maritime Transport and the Climate Change Challenge*. Routledge/Earthscan, London and New York, pp 286–304
- Sánchez-Arcilla A, Sierra JP, Brown S, Casas-Prat M, Nicholls RJ, Lionello P, Conte D (2016) A review of potential physical impacts on harbours in the Mediterranean Sea under climate change. *Reg Environ Change* 16:2471–2484. <https://doi.org/10.1007/s10113-016-0972-9>
- Smithers RJ, Dworak T (2023) Assessing climate change risks and vulnerabilities (climate risk assessment). A DIY Manual. Version 1, November 2023. EU Mission on Adaptation to Climate Change. European Union, Brussels:

- https://adaptecca.es/sites/default/files/documentos/guide_to_climate_risk_assessment_291123_005vfinal.pdf. Accessed 29 Apr 2024
- Strauss BH, Orton PM, Bittermann K, Buchanan MK, Gilford DM, Kopp RE, Kulp S, Massey C, de Moel H, Vinogradov S (2021) Economic damages from Hurricane Sandy attributable to sea level rise caused by anthropogenic climate change. *Nat Commun* 12:2720. <https://doi.org/10.1038/s41467-021-22838-1>
- Sweeney B, Becker A (2020) Considering Future Sea Level Change in Maritime Infrastructure Design: A Survey of US Engineers. *J Waterw Port Coast Ocean Eng* 146:04020019. [https://doi.org/10.1061/\(ASCE\)WW.1943-5460.0000583](https://doi.org/10.1061/(ASCE)WW.1943-5460.0000583)
- Tolman HL (2009) User manual and system documentation of WAVEWATCH III version 3.14. Department of Commerce National Oceanic and Atmospheric Administration, National Weather Service, National Centers for Environmental Prediction, Camp Springs
- Trenberth KE, Cheng L, Jacobs P, Zhang Y, Fasullo J (2018) Hurricane Harvey Links to Ocean Heat Content and Climate Change Adaptation. *Earths Future* 6:730–744. <https://doi.org/10.1029/2018EF000825>
- UK (2008) Climate Change Act 2008. UK Public General Acts 2008 c. 27. <https://www.legislation.gov.uk/ukpga/2008/27/contents>. Accessed 30 Apr 2024.
- UNCTAD (2018) Climate Risk and Vulnerability Assessment Framework for Caribbean Coastal Transport Infrastructure. UNCTAD, UNDA project 14150. https://unctad.org/system/files/official-document/dtltlb2018d1_en.pdf. Accessed 29 Apr 2024.
- UNCTAD (2020a) Climate Change impacts and adaptation for coastal transport infrastructure: A Compilation of Policies and Practices. Transport and Trade Facilitation Series No 12. United Nations Publications, New York, USA. https://unctad.org/system/files/official-document/dtltlb2019d1_en.pdf. Accessed 29 Apr 2024
- UNCTAD (2020b) Climate change adaptation for seaports in support of the 2030 Agenda for Sustainable Development. Note by the UNCTAD Secretariat. TD/B/C.I./MEM.7/23. https://unctad.org/system/files/official-document/cimem7d23_en.pdf. Accessed 18 Jan 2024
- UNCTAD (2021) The Bridgetown Covenant. TD/541/Add.2. UNCTAD XV Outcome document. https://unctad.org/system/files/official-document/td541add2_en.pdf. Accessed 18 Jan 2024
- UNCTAD (2022a) Review of Maritime Transport. UNCTAD/RMT/2022. United Nations Publications, New York, USA. <https://unctad.org/publication/review-maritime-transport-2022>. Accessed 18 Jan 2024
- UNCTAD (2022b) Climate-resilience of seaports: Adequate finance is critical for developing countries but remains a major challenge. UNCTAD Policy Brief No. 103. <https://unctad.org/publication/climate-resilience-seaports-adequate-finance-critical-developing-countries-remains>. Accessed 18 Jan 2024
- UNDRR and WMO (2022) Global status of multi-hazard early warning systems. Target G. United Nations Office for Disaster Risk Reduction. <https://www.undrr.org/publication/global-status-multi-hazard-early-warning-systems-target-g>. Accessed 18 Jan 2024
- UNECE (1998) Aarhus Convention on access to information, public participation in decision-making and access to justice in environmental matters <https://unece.org/DAM/env/pp/documents/cep43e.pdf>. Accessed 18 Jan 2024
- UNECE (2014) Climate Change Impacts and Adaptation for International Transport Networks. United Nations Publications, New York and Geneva. https://unece.org/fileadmin/DAM/trans/main/wp5/publications/climate_change_2014.pdf. Accessed 18 Jan 2024
- UNECE (2015) Transport for Sustainable Development: The case of Inland Transport. Transport Trends and Economics Series, ECE/TRANS/251. United Nations Publications, New York and Geneva. https://unece.org/DAM/trans/publications/Transport_for_Sustainable_Development_UNECE_2015.pdf. Accessed 18 Jan 2024
- UNECE (2020) Climate Change Impacts and Adaptation for Transport Networks and Nodes. Expert Group Report ECE/TRANS/283. United Nations Publications, Geneva. https://unece.org/sites/default/files/2021-01/ECE-TRANS-283e_web.pdf. Accessed 18 Jan 2024
- UNECLAC (2018) Irma and Maria by Numbers, FOCUS, The Magazine of the Caribbean Development and Cooperation Committee, ISSUE 1 / JANUARY - MARCH 2018. Subregional Headquarters for the Caribbean. <https://repositorio.cepal.org/server/api/core/bitstreams/7f76dbd8-5d0c-480d-b165-7231b84cb4de/content>. Accessed 18 Jan 2024
- UN Environment/MAP (2017). Regional Climate Change Adaptation Framework for the Mediterranean Marine and Coastal Areas. https://wedocs.unep.org/bitstream/handle/20.500.11822/17500/rccaf_eng.pdf. Accessed 18 Jan 2024
- UNEP (2023a) Emissions Gap Report 2023. United Nations Environment Programme <https://www.unep.org/resources/emissions-gap-report-2023>. Accessed 18 Jan 2024
- UNEP (2023b) Adaptation Gap Report. <https://www.unep.org/resources/adaptation-gap-report-2023>. Accessed 18 Jan 2024
- UNFCCC (2020) Technologies for Averting, Minimizing and Addressing Loss and Damage in Coastal Zones. Policy Brief. <https://unfccc.int/documents/210342>. Accessed 18 Jan 2024
- UNFCCC (2021) Climate Action Pathway - Transport. <https://unfccc.int/climate-action/marrakech-partnership/reporting-tracking/pathways/transport-climate-action-pathway#Climate-Action-Pathway-2021>. Accessed 18 Jan 2024
- UNFCCC (2023) National Adaptation Plans. <https://unfccc.int/topics/adaptation-and-resilience/workstreams/national-adaptation-plans>. Accessed 18 Jan 2024
- United Nations (1992) United Nations Framework Convention on Climate Change (UNFCCC). <https://unfccc.int/resource/docs/convkp/conveng.pdf>. Accessed 18 Jan 2024
- United Nations (2015a) The 2030 Agenda for Sustainable Development. A/RES/70/1. <https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf>. Accessed 18 Jan 2024
- United Nations (2015b) Sendai Framework for Disaster Risk Reduction 2015 – 2030. https://www.unisdr.org/files/43291_sendaiframeworkfordrren.pdf. Accessed 18 Jan 2024
- United Nations (2015c) Paris Agreement. https://unfccc.int/sites/default/files/resource/parisagreement_publication.pdf. Accessed 18 Jan 2024
- United Nations (2020) UN Common Guidance on Helping Build Resilient Societies. <https://unsdg.un.org/download/4520/71672>. Accessed 18 Jan 2024
- Velegrakis AF, Hasiotis T, Papadatou K (2021) Coastal climate resilience: review of policies and regulations. Deliverable 2.2 – ECFAS Project (GA 101004211), www.ecfas.eu. Zenodo. <https://doi.org/10.5281/zenodo.6538546>
- Verschuur J, Koks EE, Li S, Hall JW (2023a) Multi-hazard risk to global port infrastructure and resulting trade and logistics losses. *Commun Earth Environ* 4:5. <https://doi.org/10.1038/s43247-022-00656-7>
- Verschuur J, Koks EE, Hall JW (2023b) Systemic risks from climate-related disruptions at ports. *Nat Clim Chang* 13:804–806. <https://doi.org/10.1038/s41558-023-01754-w>
- Vousdoukas MJ, Mentaschi L, Voukouvalas E, Verlaan M, Jevrejeva S, Jackson LP, Feyen L (2018) Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. *Nat Commun* 9:2360. <https://doi.org/10.1038/s41467-018-04692-w>
- WMO (2023) The State of Global Climate 2022. World Meteorological Organization Report WMO-No. 1316. https://library.wmo.int/doc_num.php?explnum_id=11593. Accessed 18 Jan 2024