

Article

Exposure of Greek Ports to Marine Flooding and Extreme Heat Under Climate Change: An Assessment

Isavela N. Monioudi ¹, Dimitris Chatzistratis ¹, Konstantinos Moschopoulos ¹, Adonis F. Velegrakis ^{1,*}, Amalia Polydoropoulou ², Theodoros Chalazas ³, Efstathios Bouhouras ², Georgios Papaioannou ², Ioannis Karakikes ² and Helen Thanopoulou ²

¹ Department of Marine Sciences, School of Environment, University of the Aegean, University Hill, 81100 Mytilene, Greece; imonioudi@marine.aegean.gr (I.N.M.); mard20007@aegean.gr (D.C.); k.moschopoulos@aegean.gr (K.M.)

² Laboratory of Research on Transport and Decision-Making (TRANSDM), Department of Shipping, Trade and Transport, University of the Aegean, 2a Korai Street, 82100 Chios, Greece; polydor@aegean.gr (A.P.); ebouhouras@aegean.gr (E.B.); gpapaioannou@aegean.gr (G.P.); ikarakikes@aegean.gr (I.K.); hethan@aegean.gr (H.T.)

³ Instituut voor Landbouw-, Visserij- en Voedingsonderzoek, Agrotechnology Unit, Burgemeester Van Gansberghelaan 92, BE 9820 Merelbeke, Flanders, Belgium; theodoros.chalazas@ilvo.vlaanderen.be

* Correspondence: afv@aegean.gr

Abstract

This study assesses the exposure of the 155 Greek seaports to marine flooding and extreme heat under climate change. Flood exposure was estimated through a threshold approach that compared projected mean and extreme sea levels to high-resolution port quay elevation data. It was found that while relatively few ports will face quay inundation, the majority will experience operational disruptions due to insufficient freeboard for berthing of commercial vessels under both the mean (80%) and extreme sea (96%) levels by 2050. For selected ports, 2-D flood modelling was undertaken that showed that the used ‘static’ flood threshold approach likely underestimates flood exposure. Future heat exposure was studied through the comparison of extreme temperature and humidity projections to operational and health/safety thresholds. Port infrastructure and personnel/users will be exposed to large material, operational and health risks, whereas energy demand will rise steeply. Deadly heat days (due to mean temperature/humidity combination) will increase, particularly at island ports: 20% of Greek ports might face more than 50 such days annually by end-century. As ports are associated with large urban clusters, these findings suggest a broader health risk. Our findings suggest an urgent climate adaptation need given the strategic socio-economic importance of ports.

Keywords: climate change; seaport resilience; coastal flood; extreme heat impacts; port operational thresholds



Academic Editor: Paolo Mignosa

Received: 26 May 2025

Revised: 24 June 2025

Accepted: 25 June 2025

Published: 26 June 2025

Citation: Monioudi, I.N.; Chatzistratis, D.; Moschopoulos, K.; Velegrakis, A.F.; Polydoropoulou, A.; Chalazas, T.; Bouhouras, E.; Papaioannou, G.; Karakikes, I.; Thanopoulou, H. Exposure of Greek Ports to Marine Flooding and Extreme Heat Under Climate Change: An Assessment. *Water* **2025**, *17*, 1897. <https://doi.org/10.3390/w17131897>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Ports and their linking coastal land transport networks form complex transport systems which are crucial for supply chains, provide access to markets and facilitate ocean economy sectors, such as fisheries, offshore mineral resource and energy development, and tourism [1]. These transport networks are impacted by various climatic hazards which will be likely exacerbated by climate variability and change (CV&C) [2]. Due to their coastal location, ports are particularly exposed to natural disasters caused by the relative sea level

rise (RSLR), episodic extreme sea levels (ESLs) and waves from marine storms, and the increasing mean and extreme temperatures and extreme precipitation and wind events (e.g., [3–5]).

Climatic hazards can cause extensive damages, disruptions and delays, as well as significant trade-related economic losses. Transportation demand can also be affected by climate changes impacting demographics, industrial and agricultural production, trade, consumption, and tourism patterns (e.g., [6]). Economic losses from damages to port infrastructure and operational disruptions/delays across the interconnected global supply chains can be extensive. Port-specific damages have been estimated as USD 7.5 billion per year with the annual systemic risk to global maritime transport, trade and supply chains, and economic activity estimated as USD 81 billion and 122 billion, respectively [7,8]. Under climate change, the port-affecting climatic hazards will likely be exacerbated [1,9], causing degradation of reliability and functionality of port infrastructures, as well as economic losses resulting from diminished operational capacity, requiring large investments in adaptation (e.g., [10]). Moreover, as ports are commonly integrated within coastal urban/industrial clusters, these climatic hazards also impact coastal populations as well as a broad range of stakeholders and socio-economic activities (e.g., [11]). Impacts are expected to be particularly considerable for ports in island settings, due to the high concentration of population, infrastructure and services at the islands' coasts (e.g., [12]). At the same time, island ports play a particularly significant role in the socio-economic development of their hosting islands, as they form their gateways to offshore trade, connectivity, communication and tourism, as well as being indispensable hubs for the management of and recovery from natural disasters (e.g., [13,14]).

It appears that the assessment and management of the current and, especially, the future port risks from the changing climatic factors are of high socio-economic importance. Such assessments should evaluate the CV&C port risk, on the basis of the Intergovernmental Panel on Climate Change (IPCC) risk framework [15,16]: the affecting climatic hazards; the asset exposure to these hazards; and the port vulnerability, i.e., the port's ability to withstand and/or recover from adverse climatic impacts. Such assessments will assist in the development of frameworks for port resilience building and CV&C adaptation [16,17].

An indispensable component of port risk assessments is the appraisal of the evolution of the coastal climatic hazards under CV&C and the associated port exposure to these hazards, with the tools/approaches used depending on the scale/scope of the risk assessment [1,10,18,19]. To project future hazards, the Representative Concentration Pathway (RCP) 4.5 and 8.5 scenarios are widely used, which correspond to medium- and high-end greenhouse (GHG) gas emission trajectories, respectively. Since the last IPCC report, an additional set of scenarios have been introduced, i.e., the Shared Socioeconomic Pathways (SSPs), to integrate socio-economic trends into climate modelling [2]. SSPs can be combined with RCPs to explore potential future outcomes under different socioeconomic conditions. SSP2-4.5 aligns closely with RCP4.5, both targeting a radiative forcing of 4.5 W/m^2 by 2100. Similarly, SSP5-8.5 parallels RCP8.5 in radiative forcing (8.5 W/m^2) but is driven by a distinct narrative of rapid economic growth and heavy fossil fuel use [2,20].

Port risk assessments are particularly useful at regional and/or national levels, as they assist in the development of management frameworks that can optimize port resilience planning based on their CV&C exposure; this will allow for efficient allocation of the (mostly) limited human and financial resources. Thus, the objective of the present study is to assess the CV&C hazards and exposure of the Greek ports, which comprise both mainland and island ports (Figure 1). Their resilience to CV&C hazards is very important, as in addition to their national significance for international trade and connectivity they also serve as 'lifelines' for the many Greek islands, enhancing both their socio-economic fabric

and their logistical sustainability. Island ports are particularly critical entities (e.g., [21]), as they facilitate movement of people and the supply of food and energy, medical supplies, and construction materials and play a pivotal role in tourism, the primary economic driver for many Greek islands.

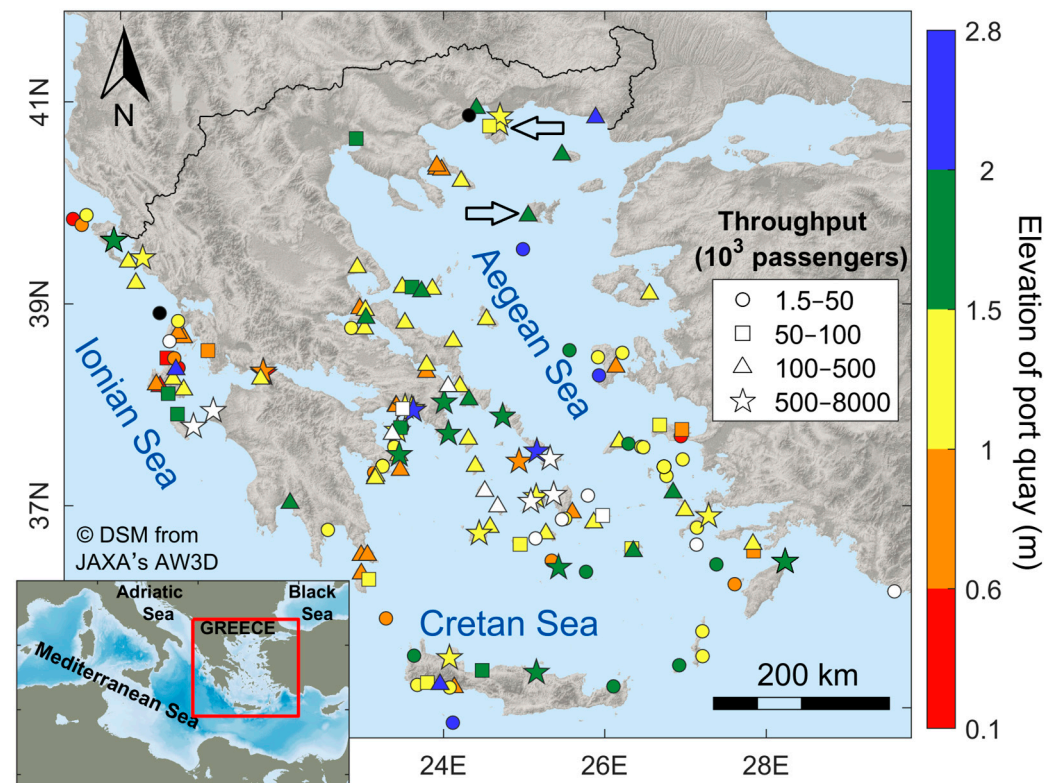


Figure 1. Location map of 155 Greek ports (Eastern Mediterranean). Passenger throughput for 2022 and the topographic elevation of port quays (Greek Cadastre) is also shown. Black circles indicate ports with no throughput information, white markers indicate ports with no quay elevation information, and the arrows show the location of the two island ports (Myrina, Limnos and Thasos), the flood exposure of which was dynamically modelled. Source: Bathymetric data of inset figure are obtained from GEBCO database [22].

2. Climate Hazards and Impacts for Seaports

Understanding the impacts of the changing climatic hazards on port operations requires an evaluation of critical environmental limits beyond which port functionality is significantly compromised (e.g., [11,23]). Climatic hazards, which are expected to generally intensify under climate variability and change (CV&C) pose serious risks for the human safety/health, the environment, the society and the economy [16,24], including for ports and their connecting coastal roads/railways (Table 1).

2.1. Coastal Floods

Presently, floods are considered as critical risk factors for the transport infrastructure. By the late century, however, they might be catastrophic under both the low- and the high-end warming scenarios [25]. Coastal transport infrastructure can be impacted by marine floods caused by the relative mean sea level rise as well as by potential increases in the frequency/intensity and duration of coastal ESLs. Extreme sea levels are induced by the compound effect of the rising mean sea levels, tides, storm surges and waves (wave set-up) (e.g., [26]). Increases in the mean and extreme sea levels could cause port inundation and damages and threaten port functionalities with serious socio-economic consequences [1,5,27,28]. Island ports are expected to be particularly affected (e.g., [18,29]).

Coastal flood hazards are projected to increase in the century. Satellite and tide gauge observations indicate that the global sea level rise rate has been accelerating in the last decade (2014–2023) to 4.77 mm/yr [30], with significant mean sea level rises (>1 m) projected by the end of the century for the high-end RCP8.5 scenario [31,32]; however, regional trends and projections should be considered (e.g., [33]). Regarding the Greek seas (northeastern Mediterranean), the offshore mean sea level trends have shown spatial variability, with the Aegean Sea showing a sea level rise rate of up to 4.6 mm/year and the Ionian Sea 2.8 mm/year [34]. By mid-century, sea levels have been projected to increase at a rate of approximately 6 mm/year in the Aegean Sea [35], whereas by the end of the century mean sea levels are expected to be 0.9–1.1 m higher than that of the end of the 20th century [36,37].

Coastal ESLs show a seasonal footprint, with extreme positives occurring mostly in autumn and winter [38]; storm surges are considered as the main controlling factor [39]. Future ESLs are projected to show spatial variability in their intensity and return periods [34]. Waves contribute to the coastal extreme sea level through the wave set-up and also affect very significantly port safety. Extreme waves can cause overtopping of protection structures, dock/quay flooding, and intensive wave disturbances within the port basin, complicating access, handling, and docking of vessels [10,40]. Fortunately, small changes in wave heights/energy are projected until the 2050s in the Greek seas [41], although changes in the coastal wave direction might also occur (e.g., [42]).

Finally, low-lying coastal areas and their infrastructure/assets can be severely affected by the concurrence and/or short successions of marine, pluvial and fluvial flooding [43–45]. However, as the drivers of compound floods are complex and spatio-temporally dynamic [46], impact assessments of compound floods require development of coupling modelling frameworks [47], which is beyond the scope of the present work.

Table 1. Summary table of climate change impacts on transportation infrastructure and operations. (Adapted from [16]). Note: List is not exhaustive.

Factor/Hazard	Impacts		
	Ports	Roads	Rail
Temperature			
Higher mean temperatures; heat waves/droughts; changes in the warm- and cool-day numbers	Damage to infrastructure, equipment (and cargo; higher energy consumption for cooling; occupational health/safety issues from extreme temperatures; insurance issues	Thermal pavement/bridge damages; asphalt rutting; asset lifetime reduction; increased cooling needs for passenger/freight; occupational health/safety issues from extreme temperatures; shorter maintenance windows; increased construction and maintenance costs; demand changes; insurance issues	Track buckling; infrastructure and rolling stock overheating; slope failures; signalling problems; speed restrictions; asset lifetime reduction; higher cooling costs; shorter maintenance windows; higher construction and maintenance costs; demand changes; occupational health and safety issues from extreme temperatures; insurance issues

Table 1. *Cont.*

Factor/Hazard	Impacts		
	Ports	Roads	Rail
Precipitation			
Changes in mean values and the intensity, type, frequency of extremes and their impacts (floods and droughts)	Port infrastructure inundation and/or damages; poor vessel port maneuverability due to increased water level/flows and poor visibility; insurance issues	Inundation, damages, wash-outs of roads/bridges; landslides; bridge scouring; earthwork failures; poor visibility; reduced vehicle traction; delays; demand changes; insurance issues	Flooding, damages, wash-outs, scouring of bridges; drainage system and tunnel flooding; landslides, mudslides, rockslides; embankment and earthwork damages; disruptions/delays; demand changes, insurance issues
Windstorms			
Changes in frequency and intensity of extreme events	Problems in vessel navigation and berthing in ports; damages to equipment; insurance issues	Fence damages; increased risk of road accidents; damages; road signage and traffic damages; road obstructions by fallen power lines/trees; bridge closures; insurance issues	Damages to installations; electricity supply issues; rail line obstructions (fallen power lines/trees); rail car blow-overs; disruption to operations; insurance issues
Mean and extreme sea levels			
Relative sea level rise (RSLR)	Port inundation; increased port protection costs; changes in port hydro- and sediment dynamics; changed dredging requirements; insurance issues	Increased risk of permanent inundation and erosion of coastal roads; damages and wash-outs of roads and bridges; insurance issues	Bridge scour, damage of coastal assets; flooding, and damages/wash-outs of tracks, embankments, bridges and culverts; tunnel flooding; insurance issues
Increased extreme sea levels (ESLs); changes in waves	Inundation; higher construction and maintenance costs; port sedimentation; potential wave penetration; vessel safety; insurance issues	Structural damages to coastal roads; temporary inundation rendering the roads unusable; delays/diversions of traffic; insurance issues	Structural damages to coastal railways, embankments and earthworks; restrictions and disruption of coastal train operations

2.2. Extreme Temperatures

Ports and other coastal transport infrastructure and operations also face challenges from increases in the mean temperatures and frequency/intensity and duration of extreme heat events [48,49]. High temperatures can degrade the paved areas of the port and other coastal transport infrastructure, induce asphalt rutting, damage bridges, cause rail track buckling and speed restrictions, and lead to equipment failure (Table 1). They can also increase energy needs/costs for cooling and create significant challenges for the health/safety of port personnel and users as well as for port productivity. Combination of extreme heat with high relative humidity will pose a major threat to port personnel/users, particularly in tropical and subtropical regions [1,50]. In Europe, the health risk posed by heat stress has been assessed as critical for the present conditions and as extremely dangerous for the future [25], particularly for its southern region (e.g., [4,51,52]). Here, a substantial increase in the occurrence of the annual number of hot days and tropical nights,

and a corresponding decrease in frost and wet days in the late century 21st century have been projected [53,54].

2.3. Other Climatic Hazards

Heavy rainfall (downpours) can severely impact ports and their connecting transport infrastructure as it can cause flash pluvial/fluviol floods. Such events can damage the structural integrity of the infrastructure, affect operations, induce rain-related accidents as well as delays and disruptions (Table 1). In Greece, decreases in the future annual precipitation have been projected for the mid- and late century, which could reach over 40% for the seasonal precipitation in its eastern part under RCP8.5 [54–56]. Heavy precipitation events can induce floods with unprecedented footprints and devastating socio-economic impacts (e.g., the 2021 ‘Ianos’ and 2023 ‘Daniel’ storms). However, as the extreme rainfall projections appear mixed and of low reliability and depending on the local geomorphological and meteorological conditions [57], the assessment of the pluvial/fluviol flood exposure for the large number (155) of Greek ports could not be undertaken in the present work.

Strong winds can also have significant effects on port functioning, efficiency and safety. They can cause infrastructure failures and operational disruptions. Strong winds in ports can induce channel changes/silting, wind-generated debris, difficulties in crane operation and container handling, vehicle blow-overs, damages to connecting roads and rail tracks and pose large risks to port navigation and vessel mooring [58–62]. Regarding the Greek ports, those located in the south Aegean (Figure 1) are currently facing the stronger winds, with future extreme winds expected to intensify further in the Aegean Sea and decrease in the Ionian Sea [63]. Wind projections in ports are, however, very challenging. Wind speed/power cannot be estimated reasonably accurately [64], whereas wind direction projections are constrained by the variable local topography/meteorology [65]. Therefore, although extreme winds can have very significant impacts on ports and their connecting and transport networks, assessment of the wind hazard and exposure for Greek ports has also not been carried out.

3. Methodology

3.1. Assessment of the Marine Flood Exposure

Flood exposure of the Greek ports was assessed under the historical (baseline) conditions and projected scenarios of CV&C. The analysis employed a static approach, comparing projected sea levels (RSLR levels and ESLs₁₀₀) with the elevation of port quays to estimate potential exposure. To refine these estimates and capture spatial flood dynamics, a 2-D hydrodynamic flood model (LISFLOOD-FP) [66] was used in selected ports to evaluate in more detail potential port inundation during extreme storm events.

3.1.1. Marine Flood Hazard: Mean and Extreme Sea Levels

Sea level data were extracted from the European Commission’s Joint Research Centre (JRC) LISCoAST database (<https://data.jrc.ec.europa.eu/collection/liscoast>, accessed on 4 April 2025), encompassing both long-term sea level rise (RSLR) and extreme sea levels (ESLs₁₀₀) associated with 100-year return period storm events. Data were collected for a historical reference (baseline) period (1980–2014) and for future projections for 2050 and 2100, under two representative concentration pathways: a moderate scenario (RCP4.5) and a high-emissions’ scenario (RCP8.5). For each seaport, the nearest available point in the LISCoAST database was identified via GIS geospatial analysis.

Probabilistic process-based method was used to calculate the sea level for each RCP scenario studied [33,67]. Potential future land vertical motions due to tectonics and anthropogenically induced subsidence have not been included. ESLs were projected using

the numerical hydrodynamic model Delft3D-Flow driven by the wind and atmospheric pressure fields corresponding to the climate conditions of the RCP4.5 and RCP8.5 scenarios calculated by an ensemble of 8 climate models; model performance was assessed for the baseline period 1980–2014 driven by wind/atmospheric pressure fields extracted from the ERA—Interim database [68].

Flooding and associated damages/disruptions in ports can also be influenced by the complex wave dynamics within the port basins that can induce damages and disruptions by affecting vessel maneuverability, complicating berthing, and interfering with cargo handling activities [5,23,69–71]. Key wave-induced sea level altering processes in coastal areas and ports include: the wave set-up due to wave breaking and the swash; wave overtopping over the port breakwaters; wave penetration through harbour entrances [72] that can cause wave agitation at the quays/docks; generation of low frequency sea level oscillations within the basin [23]; wave reflection from solid structures [73]; and wave transmission through water renewal pipes [74].

These wave-related components were not included in the flood hazard assessment. Given the absence of detailed, high-resolution data on port bathymetry, morphology and directional wave conditions and, especially, the national-scope of the study, it was not feasible to model wave-driven processes within the ports. Instead, it was assumed that the incoming wave energy is attenuated by the existing breakwaters with no wave propagation inside the harbour basins. Thus, the sea levels at quays/docks are assumed to be driven by the RSLR, the astronomical tide and the storm surge alone, ignoring any potential wave effects. This assumption might result in conservative estimates of future port exposure to flooding/disruptions, particularly during extreme wave conditions.

3.1.2. Port Flood Threshold

The flood exposure of the Greek ports was estimated for both the historical (baseline) and projected CV&C conditions. The assessment was performed by applying a ‘static’ flood threshold, i.e., comparing the projected mean and extreme sea levels with port quay elevations. It should be noted here that, although the purpose-built port quays/docks usually have a constant elevation, the connected road network and other coastal infrastructure do not (e.g., [18]). In our case, most of the current (island) ports have a long history of development, usually constructed within existing urban environments, resulting in different land elevations in the wider port area. As the scope of the present work has been to assess port flooding at a national level, a single (average) quay/berth elevation value had to be assigned in each port.

Topographic elevation values were extracted from the Digital Elevation Model (DEM) of Greek Cadastre [75], which has been created on the basis of aerial orthophotos. The DEM has a horizontal resolution of 2 m while its increased vertical accuracy (Root Mean Square Error, RMSE = 0.38 m) allows for more accurate mapping of elevation/slopes compared to the available (European) DEMs [76]. In order to assess the risk of quay overtopping, the land pixels lying at the quay—sea boundary of each studied port were used to estimate representative values of the average, minimum and maximum elevation. In this procedure, outliers with very low elevation (<0.5 m) were masked out unless their elevation was similar to the rest of the quay area. Initial comparisons were performed between the average elevation and the projected RSLR and ESLs₁₀₀ for the baseline period and the reference years 2050 and 2100 under the RCP4.5 and RCP8.5 scenarios. The analysis covered 138 ports (34 mainland, 104 island), excluding 17 ports for which quay elevation data were unavailable.

Since quay areas with lower elevations may be more susceptible to overtopping/inundation than those with higher elevations, estimations based on the average

quay/dock elevations might underestimate the port flood exposure. To address this limitation, a sensitivity analysis was conducted by comparing the DEM's minimum and maximum quay/dock elevations in each port with the associated RSLR and ESLs, in order to estimate an envelope of flood projections.

In order to obtain further insights into the exposure of the wider port area (i.e., the exposure of older port quays and other infrastructure), detailed 2-D hydrodynamic modelling was undertaken for two island ports, which were selected on the basis that the national assessment using the averaged topographic elevation value has showed them to have quay elevations (marginally) higher than the projected sea levels.

3.1.3. Dynamic Flood Simulations

Hydrodynamic models can estimate the marine flood extent/depth with greater accuracy than static inundation approaches that rely on simplifying assumptions [77], with their performance improving significantly, albeit with increased computational costs, with the resolution/accuracy of the used topographic elevation [78]. In the present study, the two-dimensional, inertial model LISFLOOD-FP was utilized, which can simulate flood dynamics over a structured topographic elevation grid, using the water inflows at the domain boundaries [66]. The model although initially designed for flood modelling over river flood plains has been previously used to project flood exposure of coastal systems, including ports [18,79–81]. Flood simulations used the LISFLOOD-ACC solver, a simplified form of the shallow water equations, neglecting only the convective acceleration term [82]. It calculates flow between grid cells based on local friction, water surface slopes and local water acceleration, providing an efficient and consistent representation of varied flows in coastal environments [83].

In the present work, since the forcing used for the overall marine flood estimation did not include port wave effects (Section 3.1.1), the wave set-up component of the ESL, was excluded from the forcing. The simulation duration was set to 10 h, which is typical for storm events in the Eastern Mediterranean [84]. Surface roughness was derived using the Copernicus Coastal Zone Land Use/Land Cover dataset (<https://land.copernicus.eu/en/products/coastal-zones/coastal-zones-2018>, accessed on 4 April 2025), and the roughness values suggested by [85], whereas the wider port topographic elevations were based on the aforementioned Hellenic Cadastre DEM on 2 m resolution grids. A stationary approach was adopted, i.e., marine forcing remained constant during the simulations.

3.2. Heat Exposure Assessment Based on Operational and Health Thresholds

3.2.1. Heat Hazard: Extreme Temperatures

Thresholds were employed to evaluate the climatic conditions under which operations of the Greek ports might be disrupted or significantly impaired. The approach consisted of three steps. First, operational thresholds should be identified; however, since port-specific thresholds have not been available, generalized thresholds drawn from relevant literature and international guidelines were adopted instead. Secondly, the relevant current and future climatic factors, including historical trends and future projections, were sourced from regional climate models. Thirdly, the operational thresholds were compared to the projected climatic information to assess the frequency of threshold exceedances. This assessment was conducted using a 20-year analysis window, during which the average number of days per year exceeding the defined operational limits was calculated. Estimates were produced for three time periods: (i) the baseline period (1986–2005); (ii) the mid-century (2041–2060) under RCP4.5 and RCP8.5 scenarios; and (iii) the end-century (2081–2100) under the same scenarios. Climate variables—specifically daily average and maximum temperature and daily relative humidity—were obtained from the CORDEX (Coordinated Regional Climate

Downscaling Experiment) dataset and particularly through the dynamical downscaling of the CNRM-CERFACS-CM5 global climate model using the CNRM-ALADIN52 regional climate model [86]. This modelling chain provided a relatively fine resolution (0.11° , approximately 12 km over Greece), that allows for a refined representation of local (port) climatic conditions.

3.2.2. Extreme Temperatures: Exposure of and Impacts on Coastal Transport Infrastructure

The European research project ‘Extreme Weather Impacts on European Networks of Transport (EWENT)’ [87] defined a set of operational thresholds for various transport modes. From these thresholds, the exceedance of a daily maximum temperature ($T_{\max}$) of 32°C was adopted as a critical indicator of potential thermal stress of the coastal transport infrastructure. At, or above this temperature, port facilities and their connecting road and rail networks, may face material degradation (e.g., pavement softening/rutting, rail buckling) that may increase accident risk and operational disruptions [4].

Assessing the climate-driven shifts in energy demand for heating/cooling is crucial for heat-sensitive infrastructures, such as ports. As global temperatures rise, energy demand patterns will shift, with reductions in heating requirements and increases in cooling requirements expected across most regions [88,89]. A widely used method for estimating climate-sensitive energy demand is the Degree-Day approach, which provides proxies for thermal stress based on daily temperature fluctuations. Heating Degree Days (HDD) and Cooling Degree Days (CDD) indices quantify the cumulative temperature deviations from pre-defined thresholds, serving as indicators of heating and cooling requirements, respectively.

HDDs are calculated for days when the mean daily temperature (T_m) is $\leq 15^\circ\text{C}$, with the daily HDD defined as the difference between 18°C and T_m . Conversely, CDDs are calculated for days when T_m is $\geq 24^\circ\text{C}$, using a base temperature of 21°C . These thresholds follow the EUROSTAT methodology (https://ec.europa.eu/eurostat/cache/metadata/en/nrg_chdd_esms.htm, accessed on 4 April 2025) that assumes constant reference values for generalized applications across building types and regions. Thus, the calculations for Heating Degree Days (HDD) are based on the assumptions that if $T_m \leq 15^\circ\text{C}$ then $\text{HDD}_i = 18^\circ\text{C} - T_{mi}$ and if $T_m > 15^\circ\text{C}$ then $\text{HDD}_i = 0$, whereas the calculation for Cooling Degree Days (CDD) on the assumptions that if $T_m \geq 24^\circ\text{C}$, then $\text{CDD}_i = T_{mi} - 21^\circ\text{C}$, and if $T_m < 24^\circ\text{C}$, then $\text{CDD}_i = 0$. Daily values of HDD and CDD were computed for the Greek ports and aggregated over 20-year periods to evaluate the cumulative heating and cooling requirements for the historical (1986–2005) and projected climatic conditions. The resulting degree-day totals were used to estimate the relative changes ($\Delta\text{CDD}/\text{CDD}$ and $\Delta\text{HDD}/\text{HDD}$) in future energy demand under the RCP4.5 and RCP8.5 scenarios.

3.2.3. Extreme Temperatures: Health and Safety Issues

The Heat Index, also referred to as ‘apparent temperature’, is a critical metric for assessing heat-related human stress, as it reflects how hot it actually ‘feels’ when relative humidity is combined with air temperature. Heat index accounts for the reduced effectiveness of sweat evaporation under high humidity that impairs the human cooling mechanism and increases the risk of heat-related stress. For port personnel/users, exposure to elevated heat index values can significantly increase the risk of heat-related illnesses, especially during prolonged activity or direct sunlight.

In the present study, the Heat Index has been estimated using a formula developed by Rothfus [90] through multiple regression analysis for the US National Weather Service (https://www.wpc.ncep.noaa.gov/html/heatindex_equation.shtml, accessed on 4 April 2025). NOAA provides a standardized Heat Index chart that correlates air tempera-

ture and relative humidity with potential health risks. The chart assumes shaded, low-wind conditions; under sun exposure, Heat Index values can increase by up to 15 °F (~8 °C), and strong winds with hot, dry air may further exacerbate the dangerous conditions.

More importantly, climate change may increase the frequency of lethal heat conditions, i.e., conditions that exceed the limits of effective human thermo-regulation. Mora et al. [50] carried out a comprehensive global analysis of fatal heat events to define the climatic thresholds associated with human mortality. Their findings indicate specific combinations of daily mean air temperature and relative humidity which are statistically associated with increased death risk. Two ‘deadly heat’ thresholds have been recognized: a threshold that best separates lethal from non-lethal heat events and a threshold beyond which there is 95% probability for fatal outcomes. In the present study the second deadly heat threshold (red line in Figure 2) was used for the estimation of the exposure of the personnel/users of the Greek ports.

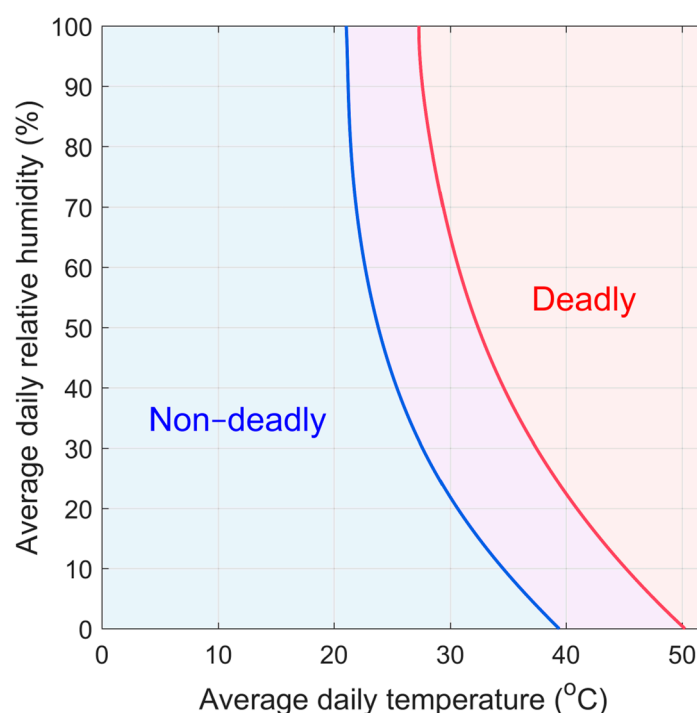


Figure 2. Thresholds for deadly heat conditions, defined by the combination of mean daily temperature and relative humidity. The blue line represents the threshold that best separates lethal from non-lethal heat events, while the red line indicates the 95% probability threshold for fatal incidents. Data extracted/adapted from Mora et al. [50].

4. Results

4.1. Flood Exposure

4.1.1. Hazards: Mean and Extreme Sea Levels

The projected evolution of extreme sea level (ESL_{100}) at Greek ports highlights the increasing exposure of coastal infrastructure to flooding under future scenarios. ESL_{100} shows a marked increase throughout the 21st century. Baseline ESL_{100} range from 0.42 m to 0.81 m above the baseline mean sea levels across the Greek ports. By 2050, this range increases to 0.54–0.92 m under RCP4.5 and to 0.60–0.99 m under RCP8.5. By the end of the century, projections indicate a further rise, reaching 0.86–1.35 m under RCP4.5 and 1.16–1.56 m under RCP8.5 (Figure 3, Table 2).

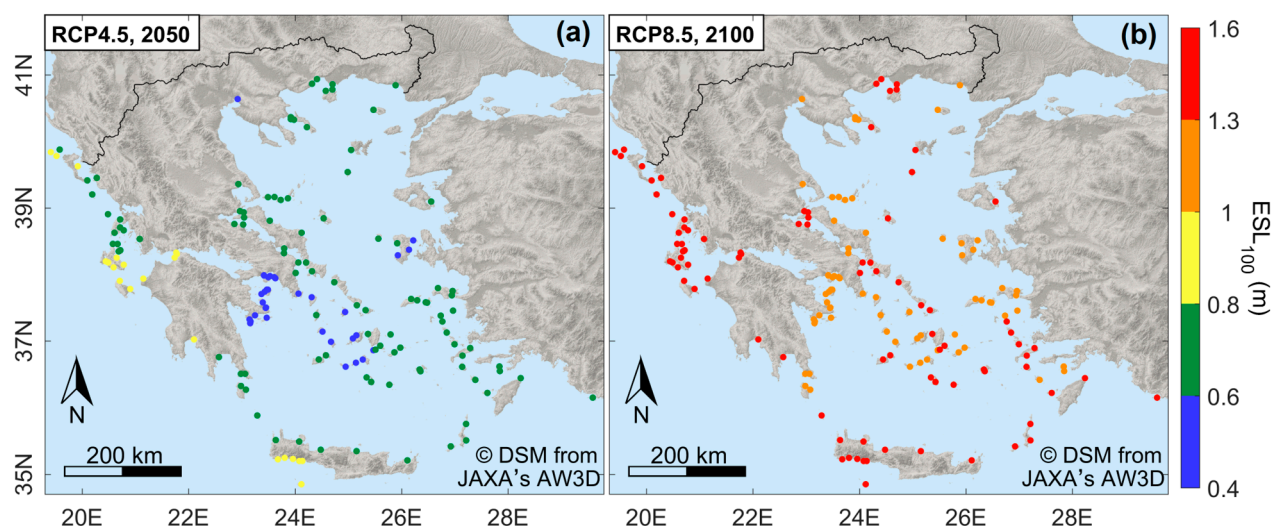


Figure 3. Projections of the 100-year extreme sea level events (ESL_{100}) (excluding the wave set-up component) at the Greek ports, for different dates and climate scenarios: (a) RCP4.5, 2050; (b) RCP8.5, 2100.

Table 2. Ranges of 100-year extreme sea level (ESL_{100}) and its components (relative sea level rise (RSLR), astronomical tide, and storm surge level (SSL), as well as of the mean (Tmean) and maximum (Tmax) temperature and relative humidity (RH%) at the Greek ports for different times and climate scenarios. Note: Projections for the flood hazards are for 2050 and 2100, whereas for temperature and humidity for the periods 2041–2060 and 2081–2100.

	Baseline	Mid-Century		End-Century	
		RCP 4.5	RCP 8.5	RCP 4.5	RCP 8.5
RSLR (m)	0	0.13–0.15	0.17–0.21	0.46–0.53	0.74–0.84
Tide (m)	0.02–0.12	0.02–0.12	0.02–0.12	0.03–0.13	0.02–0.13
SSL100 (m)	0.31–0.76	0.30–0.74	0.31–0.73	0.28–0.78	0.30–0.68
¹ ESL_{100} (m)	0.42–0.81	0.54–0.92	0.60–0.99	0.86–1.35	1.16–1.56
Tmean (°C)	12.0–19.0	13.2–20.2	13.8–20.6	14.1–21.1	15.8–22.5
Tmax (°C)	27.9–43.0	29.1–44.3	29.7–46.4	30.3–45.0	31.2–47.6
RH (%)	69.5–82.6	68.7–82.1	68.0–81.7	68.7–82.1	68.2–81.5

Note: ¹ The wave set-up component was not included.

These increases are primarily driven by the RSLR component, which increases over time and differs significantly by emission scenario. It is projected to rise to 0.13–0.15 m by 2050 under RCP4.5 and up to 0.21 m under RCP8.5. By 2100, RSLR reaches 0.46–0.53 m under RCP4.5 and 0.74–0.84 m under RCP8.5. There is some spatial variability in the RSLR projections along the Greek coastline (of the order of 0.02–0.1 m), but the overall trend shows a substantial and consistent increase, particularly under the high-emission pathway (Table 2). In contrast, the tidal and storm surge components remain relatively stable over time, with tidal ranges between 0.02 and 0.13 m and storm surge (SSL_{100}) levels fluctuating within the 0.28–0.78 m range across all scenarios (Table 2). Although storm surges continue to represent the largest contribution to ESL_{100} in absolute terms, their relative importance diminishes over time as RSLR becomes the dominant driver of extreme sea level change.

4.1.2. Flood Threshold

The current and projected mean and extreme (ESL_{100}) sea levels were then compared with the (averaged) quay/dock elevations of 138 Greek ports (Figures 1 and 4 and Table 3) for which high-resolution port elevations were available from the Greek Cadastre DEM (Section 3.1.2). Flood damages and operational disruptions are expected when the projected

sea levels reach or exceed the quay/dock topographic elevation in the absence of effective adaptation measures.

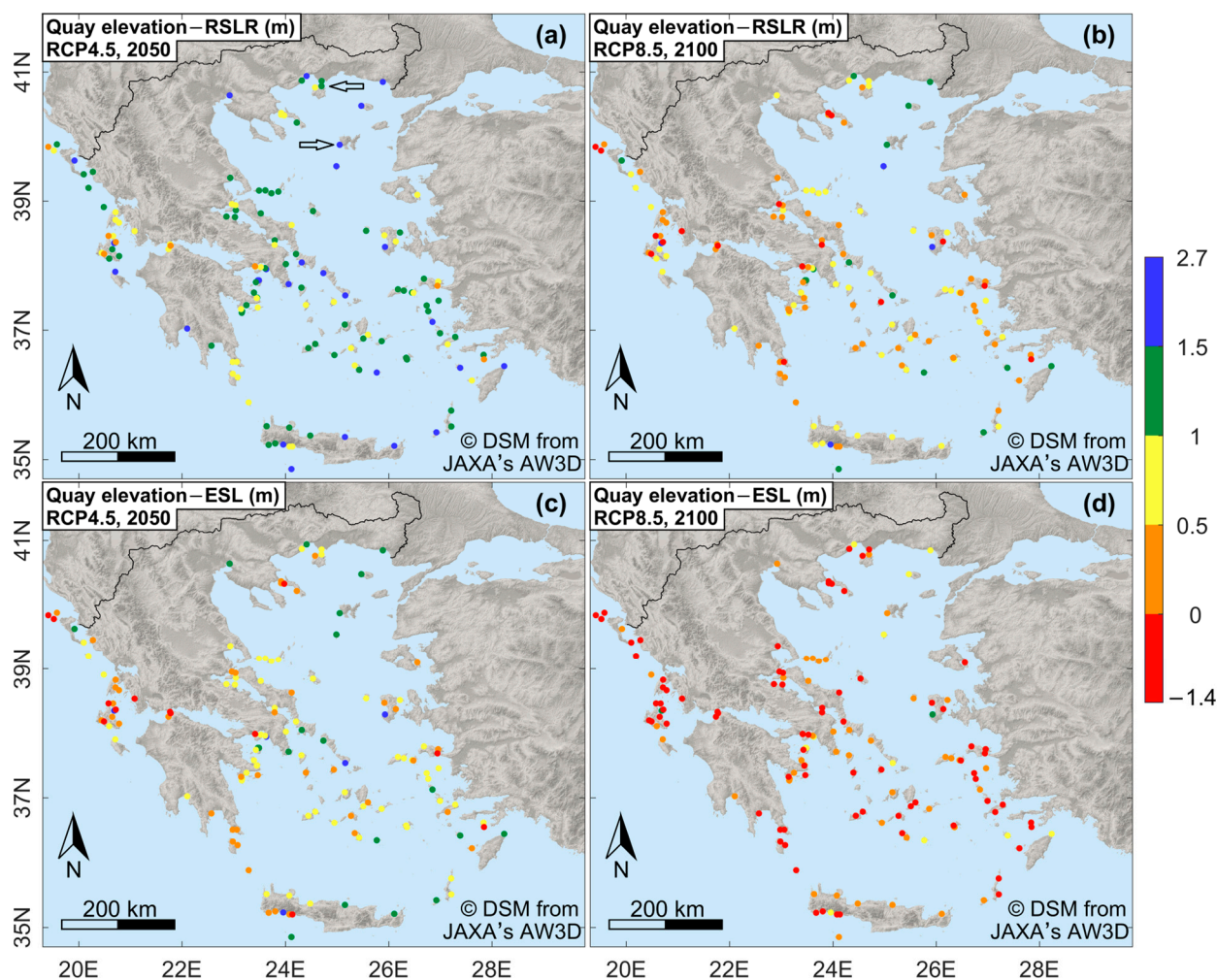


Figure 4. Difference between the (average) topographic elevation of the port quays and the projected relative sea level rise (RSLR) (a,b) and 100-year extreme sea levels (ESLs), excluding the wave set-up component (c,d), for different dates and climate scenarios.

In addition, sea level rise is projected to cause substantial constraints in the operability of the vessel berthing structures, due to insufficient vertical distance between the quay/dock surface and the peak sea level under extreme conditions (‘freeboard’). Port operations can be disrupted even in the absence of direct flooding, i.e., when sea levels do not exceed the quay/dock elevation. According to port safety guidelines [91], minimum freeboards of 1.5 m and 0.5–0.6 m must be maintained to ensure safe loading and unloading of commercial vessels (large freight and/or passenger vessels) and fishing vessels, respectively [23,92]. When the dock freeboard drops below these safety thresholds, berthing becomes unmanageable.

The following results concern the entire port network for which dock/quay elevations were available ($n = 138$); the exposure of the mainland ($n = 34$) and island ($n = 104$) ports is also presented as percentages relative to the total number of ports within each category to accurately capture their relative exposure.

The projections show that permanent inundation (from the RSLR alone) does not appear to be a challenge until 2050 (Figure 4 and Table 3). By 2100, however a small, but significant number of ports—5 and 18 ports under the RCP4.5 and RCP8.5, respectively—will be exposed to (permanent) flooding. Flooding exposure is much higher under extreme

events. Even under the baseline conditions 6 ports face quay/dock overtopping under the ESL_{100} . In 2050 and 2100, 13 (RCP4.5) and 17 (RCP4.5) ports and 42 (RCP4.5) and 80 (RCP8.5) ports will face quay overtopping, respectively.

Table 3. Results of the flood threshold. Difference between the topographic elevation of the port piers (average, minimum and maximum) and the projected relative sea level rise (RSLR) and 100-year extreme sea levels (ESLs) (excluding the wave set-up component) for different dates and climate scenarios. The table shows the number (and percentage) of the Greek ports with available freeboard less than 1.5 m and 0.5 m, as well as the number of ports projected to experience flooding (freeboard < 0 m).

Sea-Level Rise Scenario			Number (and Percentage) of Ports			
			Freeboard (Based on the Average Quay Elevation)			
Year	RCP	<1.5 m	<0.5 m	<0 m	<−0.5 m	
RSLR	Baseline	98 (71%)	5 (4%)	0	0	
	2050	4.5	111 (80%)	8 (6%)	0	0
		8.5	114 (83%)	12 (9%)	1 (0.7%)	0
	2100	4.5	131 (95%)	37 (27%)	5 (4%)	0
		8.5	135 (98%)	76 (55%)	18 (13%)	3 (2%)
	ESL ₁₀₀	Baseline	132 (96%)	43 (31%)	6 (4%)	1 (0.7%)
2050		4.5	133 (96%)	55 (40%)	13 (9%)	3 (2%)
		8.5	134 (97%)	64 (46%)	17 (12%)	3 (2%)
2100		4.5	137 (99%)	103 (75%)	42 (30%)	7 (5%)
		8.5	138 (100%)	124 (90%)	80 (58%)	23 (17%)
Freeboard (Based on Quay Elevation Range)						
Year	RCP	<1.5 m	<0.5 m	<0 m	<−0.5 m	
RSLR	Baseline	63–115 (46–83%)	3–14 (2–10%)	0	0	
	2050	4.5	94–126 (68–91%)	4–20 (3–14%)	0–1 (0–0.7%)	0
		8.5	94–126 (68–91%)	4–24 (3–17%)	0–1 (0–0.7%)	0
	2100	4.5	123–134 (89–97%)	26–64 (19–46%)	2–9 (1–7%)	0
		8.5	131–137 (95–99%)	52–107 (38–78%)	7–39 (5–28%)	1–5 (0.7–4%)
	ESL ₁₀₀	Baseline	127–136 (92–99%)	29–70 (21–51%)	3–16 (2–12%)	0–3 (0–2%)
2050		4.5	131–136 (95–99%)	36–85 (26–62%)	7–24 (5–17%)	1–3 (0.7–2%)
		8.5	131–136 (95–99%)	45–94 (33–68%)	9–28 (7–20%)	1–4 (0.7–3%)
2100		4.5	135–138 (98–100%)	80–122 (58–88%)	28–67 (20–49%)	3–16 (2–12%)
		8.5	136–138 (99–100%)	109–132 (79–96%)	56–108 (41–78%)	12–39 (9–28%)

In terms of operability constraints related to the available freeboard, the situation is worse. Even under the baseline mean sea levels, 71% of Greek ports—25 mainland ports (i.e., 74% of all mainland ports) and 73 island ports (73%)—do not meet the 1.5 m freeboard requirement for safe berthing of large commercial levels. This percentage increases to 96% (97% of mainland and 95% of island ports) under the baseline 100-year extreme sea level (ESL_{100}) (Table 3).

Future projections indicate a continuous decline in freeboard and a growing number of ports at risk. Under the RSLR alone, the percentage of ports in 2050 with freeboard below 1.5 m will reach to 80% (82% of the mainland and 80% of the island ports) under RCP4.5 and 83% (88% of the mainland and 81% of the island) under RCP8.5 (Figure 4 and Table 3). By 2100, these figures rise to 95% and 98% (with similar percentages of mainland and island ports), respectively. Five ports are projected to fall below sea level under RCP4.5 and 18 ports (13%)—8 (24%) mainland and 10 (9.6%) island—under RCP8.5 by the end of the century, indicating a crippling flooding risk in the absence of appropriate adaptation measures (Figure 4 and Table 3).

The situation is projected to be more severe when ESL_{100} are considered. By 2050, ~96% of ports fall below the 1.5 m threshold in both scenarios, with 9% and 12% experiencing overtopping under RCP4.5 and RCP8.5, respectively. By 2100, almost all (>99%) ports will be affected: by showing a freeboard below the 1.5 m threshold. Overtopping is projected for 42 (30%) ports (35% mainland, 29% island) under RCP4.5 and for 80 (58%) ports (62% mainland, 57% island) under RCP8.5 (Figure 4 and Table 3). Both mainland (2022 total passenger throughput 34,548,936) and island ports (total passenger throughput 26,431,133) evaluated are increasingly at risk of operational disruptions and flooding, with mainland ports exhibiting slightly higher exposure. It is noted that in most ports, particularly in island settings, large ferries which are projected to face problems due to decreasing freeboard form the main mode of transport not only for passengers but also for freight [93].

Further analysis was carried out to account for the elevation variability along the port quays, by comparing the minimum and maximum quay elevations of the Greek ports against projected RSLR and ESL_{100} . Under baseline conditions, the analysis revealed that while no port quays are currently overtopped, between 46% and 83% of ports already show freeboards of less than 1.5 m, and up to 10% freeboards below 0.5 m. This latent vulnerability becomes more pronounced when considering ESL_{100} , with up to 99% of ports showing freeboards below 1.5 m, and 2% to 12% already experiencing overtopping during extreme events. These findings underscore the importance of considering intra-port quay elevation variability in flood exposure assessments.

Projections for 2050 and 2100 reveal a significant exposure escalation, particularly under the high-end RCP8.5 scenario. By mid-century, the number of ports with critical or low freeboard increases substantially, especially under ESL_{100} conditions, where up to 68% are projected to have less than 0.5 m of freeboard and 20% to be flooded. By 2100, almost all ports are projected to show freeboards of less than 1.5 m across both RSLR and ESL_{100} scenarios, with up to 78% of the ports showing overtopping under RSLR and up to 96% critically low freeboards under ESL_{100} . Importantly, the number of ports with freeboards below −0.5 m—indicative of severe inundation—reaches as high as 28% in the most extreme case. These findings suggest a high and increasing flood exposure for the Greek ports, with the projections being also sensitive to spatial variability of the port quay elevations.

These results point to a widespread and intensifying risk to Greek port infrastructure, not only from direct quay inundation, but also from compromised operational safety for both the commercial vessels that transport people and goods and fishing vessels. This highlights the urgent need for adaptation measures to ensure the resilience/functionality of many Greek port facilities under future sea level conditions.

4.1.3. Dynamic Simulations for Selected Ports

As mentioned earlier (Section 3.1.2), a single (average) quay/dock elevation value had to be assigned for each port. However, as most of the current (island) ports have a long history of development, being usually constructed within existing urban clusters, quay elevations may differ within the ports with the highest topographic elevations usually found at the more modern, purpose-built commercial ports. Therefore, in order to gain further insights into the flood exposure challenge, dynamic simulations were carried out in two island ports (Myrina, Lemnos and Thasos, Thasos), which according to the flood threshold projections appeared to be reasonably safe (Figures 1 and 4).

In Myrina port (Figure 5), the elevation above mean sea level at the southwestern quay where the passenger ferries dock is 1.9 m, while at the old northern dock (where a large parking lot is also located) the elevation varies between 0.8 and 1.5 m. The projected ESL s for 2050 are 0.79 and 0.92 for the moderate and the high-end scenarios, respectively, whereas for 2100 these increase to 1.1 and 1.37 m. In 2050, under both scenarios little flooding of

the main dock is projected; however, the northern and eastern quays, show significant exposure, with more than 6500 m² and 9500 m² projected to be inundated. Projections are worse for 2100. Under RCP4.5, flooding will occur along most of the northern and eastern quays (more than 2900 m² port area inundated), whereas under RCP8.5 more severe inundation is projected (>40 m inland), that will affect also the main coastal road and other significant assets (e.g., the Town Hall). In addition, inundation is calculated also all along the main dock with an inland extent of about 8 m while in one location extends up to 30 m.

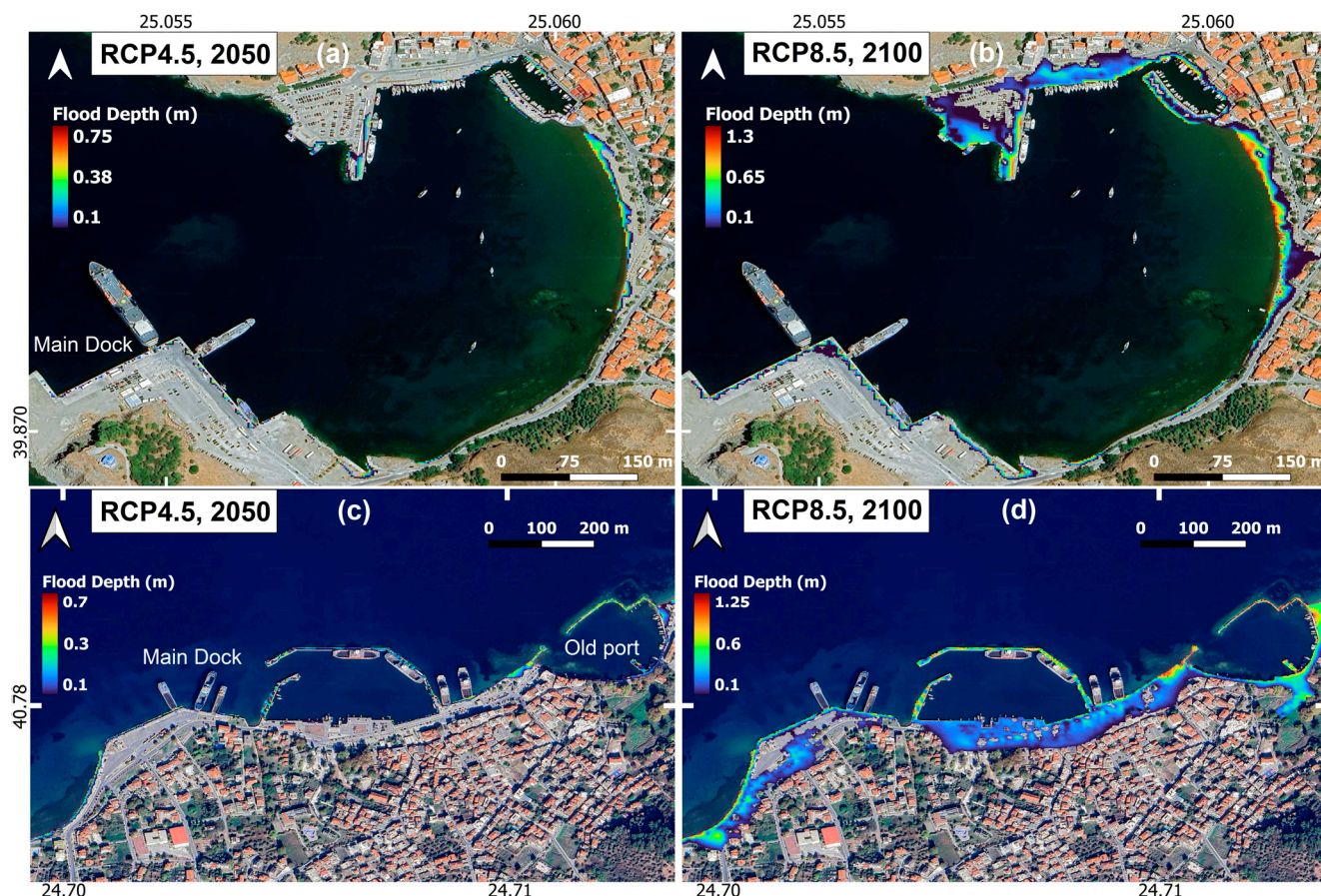


Figure 5. Flood maps under the ESL_{100} for the island ports of Myrina, Lemnos (a,b) and Thasos (c,d) (see also Figure 1). Flood extent and depth are presented for 2050 under RCP4.5 (a,c) and 2100 under RCP8.5 (b,d). Topographic elevations used are from the Greek Cadastre DEM (see text). Note: ESL s do not include the wave set-up.

Thasos port lies on the northern coast of the island and consists of the main quay used by the passenger ferries at the western side, a marina in the middle and the old harbour which is now used mainly as a fishing port. According to the Greek Cadastre DEM, the topographic elevation at the quay where the passenger ferries dock ranges between 1.2 and 1.5 m, at the marina 1–1.5 m, whereas at the old port quay the topographic elevations can be less than 0.6 m. The projected ESL_{100} for 2050 are 0.72 and 0.86 under the RCP4.5 and RCP8.5 scenarios, whereas for 2100 these increase to 1 and 1.28 m, respectively. The simulations for 2050 show insignificant flooding of the main passenger and marina quays for both RCP scenarios tested, whereas the old port appears more exposed to the flood hazard as more than 2000 m² are projected to be inundated here, with maximum flood extending up to 18 and 24 m inland for the RCP4.5 and RCP8.5, respectively, affecting also other assets. For 2100 (RCP4.5), the entire old port area (4000 m²) is projected to be inundated, in contrast to the passenger and marina quays. However, parts of the coastal access road are projected to be inundated, affecting the port connectivity. Simulations show

a much worse picture under the RCP8.5 scenario. A substantial part of the main dock including also the parking facility of the port ($>8000 \text{ m}^2$) is projected to be inundated with flood extent reaching more than 100, whereas there will also be severe flooding of the Marina quay and the old port quays extending more than 80 m inland. Under this scenario, the coastal road, private assets and public spaces are projected to be severely impacted.

Dynamic simulations were also undertaken for another nine ports under the RCP8.5 scenario, which revealed substantial variability in flood exposure. In the most flood-resilient cases, inundation was projected to affect less than 1% of the port area, while the most exposed ports exhibited significant port flood extents/depths. In some case, maximum inland flood extent reached over 150 m in low-lying urban areas adjacent to the modelled ports, highlighting potential risks not only for the port infrastructure but also for residential and commercial assets. Flood depths commonly ranged between 0.3 and 0.65 m, with localized peaks exceeding 1 m in more exposed zones. Notably, while the static threshold approach used in this study indicated flooding of none and 3 of the nine ports for 2050 and 2100, respectively, the dynamic simulations projected at least partial flooding at 4 and 7 ports, respectively. Furthermore, in some cases where the static approach showed no flooding, the dynamic model projected flood extents of up to 100 m.

These results indicate that the flood exposure of and impacts on the Greek ports might be higher than those suggested by the flood thresholds which are based on single topographic elevation values (Figure 4 and Table 3).

4.2. Heat Exposure

4.2.1. Hazards

Atmospheric conditions in the study area show clear warming trends, with the historical mean temperature (T_{mean}) ranging from 12.0°C to 19.0°C (Table 2). By 2100, the T_{mean} is projected to rise to $14.1\text{--}21.1^\circ\text{C}$ and $15.8\text{--}22.5^\circ\text{C}$ under RCP4.5 and RCP8.5, respectively (Table 2, Figure 6). Similarly, maximum temperatures (T_{max}) will increase from a baseline range of $27.9\text{--}43.0^\circ\text{C}$ to $30.3\text{--}45.0^\circ\text{C}$ under RCP4.5, and up to $31.2\text{--}47.6^\circ\text{C}$ under RCP8.5 by 2100 (Table 2, Figure 6). Relative humidity (RH) is projected to show small changes across the Greek ports, being within a range of 68 and 83%, with a slight tendency toward lower maximum values under RCP8.5 (Table 2). Increasing temperature extremes, and persistent high humidities signal mounting risks to port infrastructure and operations.

Notably, mean daily temperatures are generally higher (by up to 1.6°C on average) at island ports, reflecting their maritime climate and reduced diurnal variability. In contrast, maximum daily temperatures tend to be higher (by up to 5.2°C) at mainland ports, consistent with the larger diurnal range and stronger continental heating effects (Figure 6). Increasing temperature extremes, and persistent high humidity indicate mounting risks for port and the other coastal transport infrastructure/operations, as well for the associated urban clusters.

4.2.2. Exposure of and Impacts on Transport Infrastructure

The exceedance of a daily maximum temperature (T_{max}) of 32°C is recognized as a threshold of potential thermal problems for the transport infrastructure [87]. In the case of the Greek ports (and the connecting land transport infrastructure), our analysis revealed a substantial increase in the number of days exceeding this threshold under future climate scenarios, indicating growing exposure to conditions that may compromise the functionality/safety of transport operations (Figure 7 and Table 4).

The percentages of the mainland and island ports are also presented relative to the total number of ports within each category. Historically, only 56% of the mainland and 17% of the island) ports (26% of the total) have experienced more than 10 days annually

with $T_{max} \geq 32^\circ\text{C}$, with only 1% of all ports facing such conditions for more than 50 days. By mid-century (2041–2060) this situation is projected to change. Under RCP4.5, 42% of all ports are projected to experience such temperatures for more than 10 days, 61% of the mainland and 24% of the island ports (33% of the total) for more than 20 days, and 15% of all ports for more than 50 days (Table 4 and Figure 7a).

Under RCP8.5 the threshold will be exceeded for 10 days in 75% of the ports, 20 days in 60% of the ports, and 50 days in 31% of the ports, whereas in 6% of the mainland and 8% of the island ports (14% of the total) the 32°C threshold is projected to be exceeded for more than 80 days per year (Table 4 and Figure 7b). Generally, mainland ports appear more exposed than island ports in all future scenarios.

These findings underscore a growing climate-induced strain on transport infrastructure at Greek ports. The projected increase in the days of extreme temperature suggests an elevated risk of infrastructure degradation and operational disruption, emphasizing the need for adaptation strategies to manage future heat-related impacts on port operations.

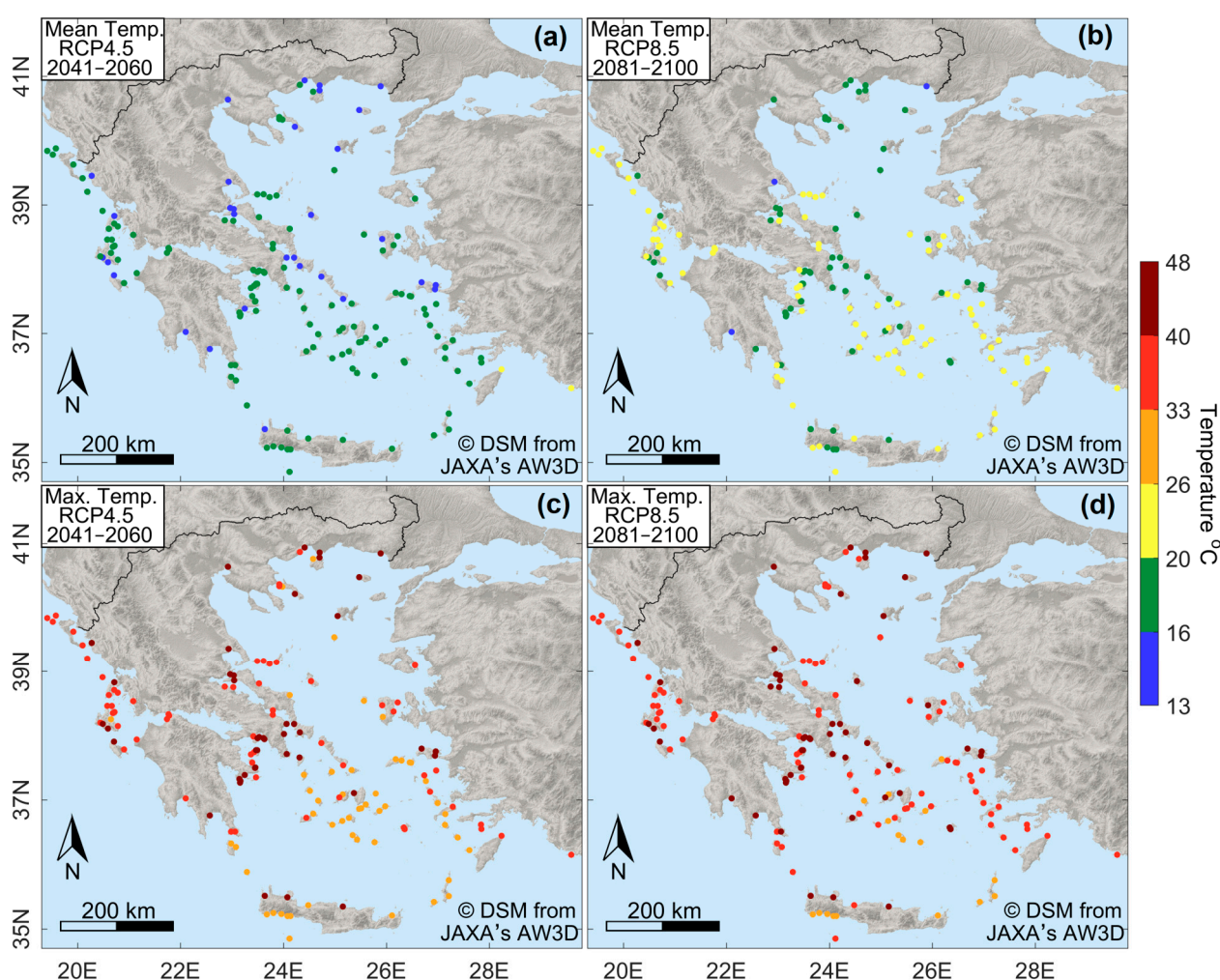


Figure 6. Projections of the twenty-year average of the mean daily temperature (a,b) and the twenty-year maximum of the daily maximum temperature (c,d) at the Greek ports, for different dates and climate scenarios.

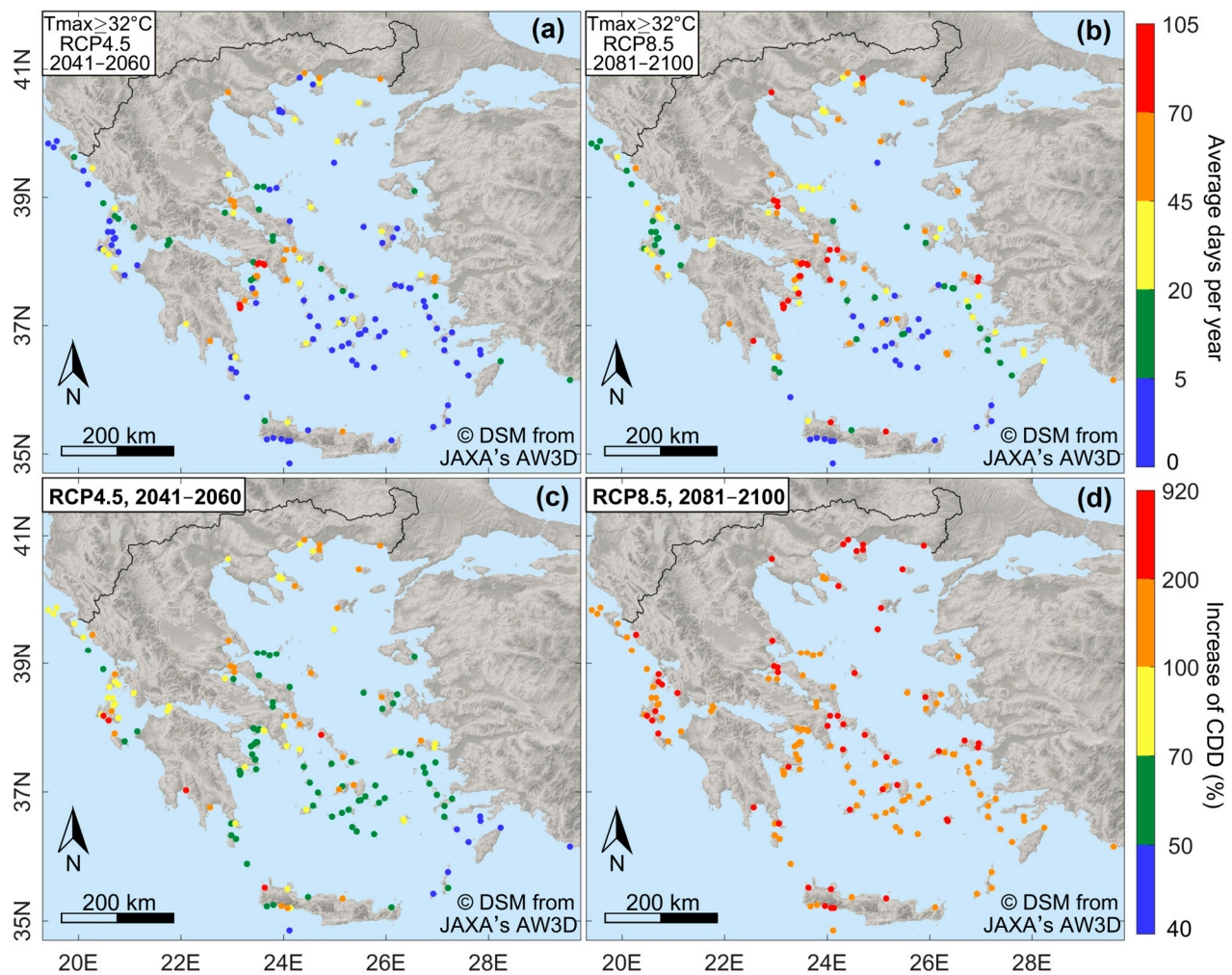


Figure 7. Projected average annual number of days with the maximum daily temperature exceeding 32°C , the threshold for potential harmful impacts on transport infrastructure and operations (a,b). Percentage relative change in Cooling Degree Days ($\Delta\text{CDD}/\text{CDD}$) for future time periods compared to the historical period (1986–2005), indicating shifts in cooling energy demand driven by climate warming (c,d).

Climate-driven potential change in energy demand for Greek ports was investigated using the relative change in Cooling Degree Days ($\Delta\text{CDD}/\text{CDD}$) and Heating Degree Days ($\Delta\text{HDD}/\text{HDD}$), compared to the historical baseline period 1986–2005. Results show a strong and consistent increase in cooling demand across all scenarios. Under RCP4.5, all mainland ports and 92% of the island ports (94% of the total) are projected to face a 50% increase in CDDs by mid-century (2041–2060), while under RCP8.5 this rises to 99%. More extreme increases ($>100\%$) are projected for 28% of the mainland and 19% of the island ports (21% the total) under RCP4.5, and 28% under RCP8.5. A small subset of ports may experience increases exceeding 200% (3% and 4% under RCP4.5 and RCP8.5, respectively) (Table 4 and Figure 7c). By the end of the century (2081–2100), the energy needs will increase further. Under RCP4.5, all ports are expected to increase their energy needs by more than 50%, with the energy needs of the 99% of the ports increasing by more than 70% and of the 59% by more than 100%. Under RCP8.5, all ports are projected to face large energy need changes, with 44% of mainland and 30% of the island ports (34% of the total) experiencing increases over 200% (Table 4 and Figure 7d).

By comparison, heating needs show a declining trend. For 2041–2060, 45% of ports will show HDD reductions greater than 10% under RCP4.5, whereas under RCP8.5 67% of

the mainland and 85% of the island ports (81% of the total) are projected to show a similar decline; reductions of more than 30% are projected for 5% and 44% of ports, respectively. By 2081–2100, 98% of ports under RCP4.5 and 100% under RCP8.5 are projected to show HDD reductions above 10%, whereas under RCP8.5, nearly one-quarter of all ports (29% of the island ports) are projected to see reductions greater than 70% (Table 4).

Table 4. The projected average annual number of days on which the maximum daily temperature exceeds 32 °C, the threshold for potential harmful impacts on transport infrastructure and operations. Percentage relative change in Cooling Degree Days ($\Delta\text{CDD}/\text{CDD}$) and Heating Degree Days ($\Delta\text{HDD}/\text{HDD}$) for future periods compared to the historical baseline (1986–2005). Values are reported as the number (and percentage) of ports exceeding each threshold.

		Number (and Percentage) of Ports			
		Average Days per Year of $T_{\text{max}} \geq 32\text{ °C}$			
Year	RCP	>10	>20	>50	>80
Historical		40 (26%)	27 (17%)	2 (1%)	0
2050	4.5	65 (42%)	51 (33%)	23 (15%)	0
	8.5	68 (44%)	53 (34%)	27 (17%)	2 (1%)
2100	4.5	81 (52%)	64 (41%)	30 (19%)	4 (3%)
	8.5	116 (75%)	93 (60%)	48 31(%)	22 (14%)
		Relative Change in CDD (%)			
Year	RCP	>50	>70	>100	>200
2050	4.5	146 (94%)	74 (48%)	33 (21%)	5 (3%)
	8.5	154 (99%)	115 (74%)	43 (28%)	6 (4%)
2100	4.5	155 (100%)	153 (99%)	92 (59%)	13 (8%)
	8.5	155 (100%)	155 (100%)	155 (100%)	52 (34%)
		Relative Change in HDD (%)			
Year	RCP	<−10	<−30	<−50	<−70
2050	4.5	70 (45%)	7 (5%)	0	0
	8.5	125 (81%)	68 (44%)	3 (2%)	0
2100	4.5	152 (98%)	99 (64%)	30 (19%)	0
	8.5	155 (100%)	153 (99%)	94 (61%)	35 (23%)

These results suggest a net increase in climate-driven energy demand, with rising energy costs primarily driven by growing cooling needs. Projected increases in Cooling Degree Days (CDD) are more pronounced at mainland ports, reflecting greater exposure to extreme high temperatures, while reductions in Heating Degree Days (HDD) are more substantial at island ports, indicating a stronger warming signal in average temperatures in these regions.

4.2.3. Human Safety/Health Risks

The analysis of heat-related risks at 155 Greek ports, based on the projected annual exceedance of the Heat Index (HI) thresholds (Figure 8 and Table 5), reveals a pronounced and escalating exposure to dangerous thermal conditions under climate change scenarios.

For the high-risk threshold (Heat Index $\geq 39.4\text{ °C}$), under the baseline conditions 44% of mainland and 14% of the island ports (21% of the total) faced more than 10 days per year above this level, with none exceeding 50 days. By mid-century (2041–2060), the number of affected ports will increase under both studied scenarios. Specifically, 34% and 35% of all ports are projected to face such conditions for more than 10 days under RCP4.5 and RCP8.5, respectively, and 19% of mainland and 5% of the island ports (8% of the total) for more than 50 days. By the end of the century (2081–2100), this trend projected to intensify. Under

RCP8.5, this threshold is projected to be exceeded for 10 days in 92% and for 20 days in 60% of the ports, whereas the personnel/users at 56% of the mainland and 24% of the island ports (31% of the total) will face such conditions for more than 50 days and at 10% of all ports for more than 70 days annually.

For the very high-risk threshold (Heat Index ≥ 46.1 °C), no Greek ports have historically exceeded this threshold. However, by 2050, 14 and 16% of all ports are projected to exceed this threshold for 10 days per year under RCP4.5 and RCP8.5, respectively. By 2100, this increases to 34% of all ports (56% of the mainland and 28% of the island ports) under RCP8.5, with 5% of ports projected to face such conditions for more than 50 days annually.

The analysis of heat-related risks at 155 Greek ports, based on projected annual exceedances of the Heat Index (HI) thresholds, reveals a pronounced and escalating exposure to dangerous thermal conditions under climate change scenarios. Strategic ports like Piraeus and Thessaloniki are among the most affected, whereas smaller ports also show a frequent exceedance of the critical HI (>39.4 °C) threshold (Figure 8). These findings underline an urgent need for targeted adaptation strategies, improved occupational safety regulations, and resilient port infrastructure to protect personnel/user health and operational.

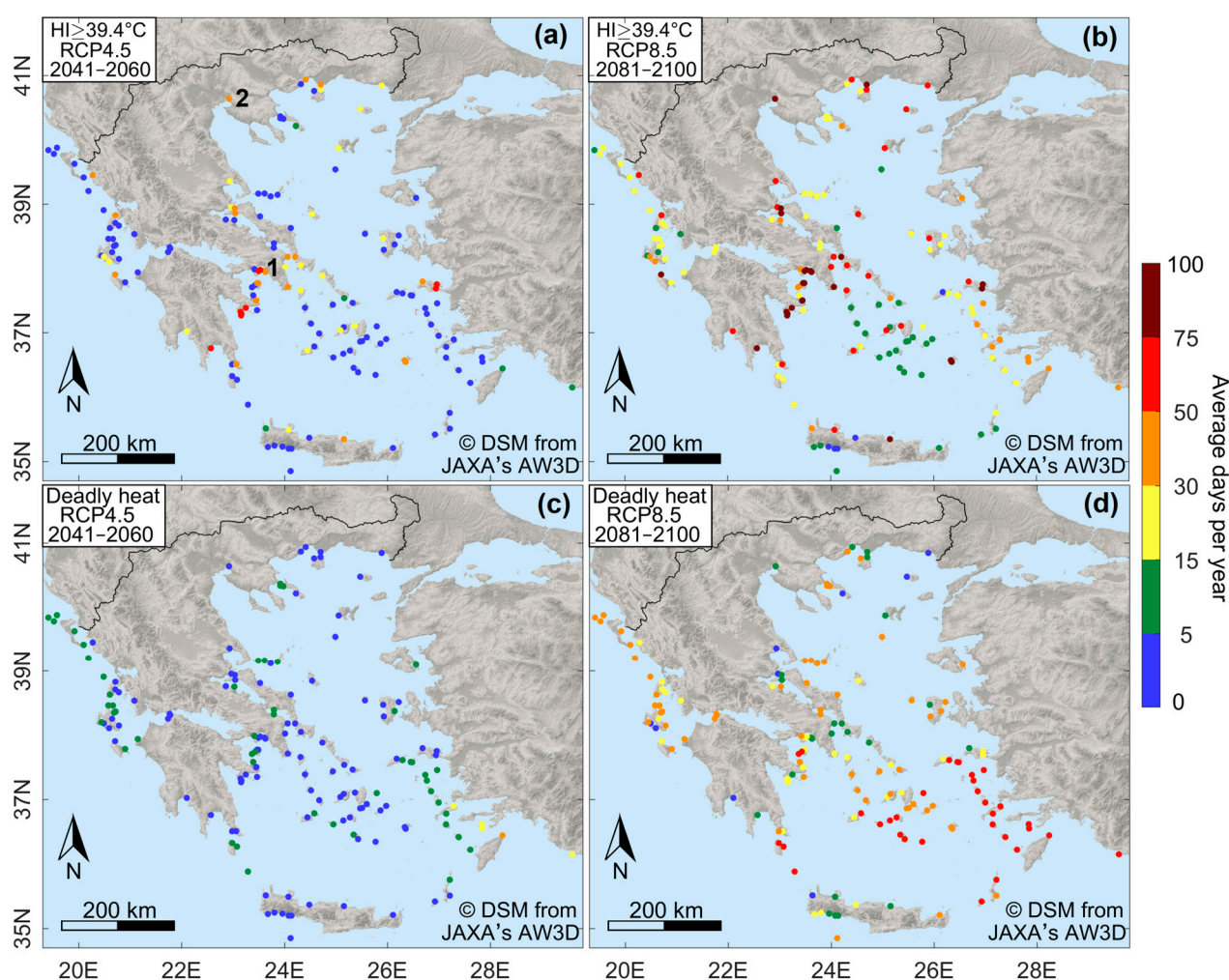


Figure 8. Average annual number of days with Heat Index exceeding 39.4 °C, indicating high-risk conditions for port personnel/users outdoors (a,b). Average annual number of days exceeding the 95% probability threshold for lethal heat conditions (c,d). Key: 1, Piraeus; 2, Thessaloniki.

In terms of deadly heat conditions, as defined by the temperature–humidity thresholds of Mora et al. [50], no such events have been estimated for the baseline conditions. By the end of the century, however, under RCP8.5, 86% of all ports are projected to experience

annually more than 10 deadly heat days, 71% more than 20 days, 20% more than 50 days, and one port more than 70 days annually. By comparison, unsafe heat conditions—defined by a lower threshold separating non-lethal but hazardous environments (Figure 2)—are already widespread. Under the baseline conditions, 95% of all ports experienced more than 50 such days annually; this will increase to 100% of all ports under all future scenarios, with up to 99% of ports exceeding 100 days and 90% exceeding 120 days per year under such conditions by the end of the century (RCP8.5).

Table 5. Projected average annual number of days with Heat Index (HI) exceeding critical thresholds at Greek ports, indicating heat-related risk levels for outdoor workers. Values are shown for thresholds of $HI \geq 39.4$ °C (high risk) and $HI \geq 46.1$ °C (very high risk), as well as for the threshold that best separates lethal from non-lethal heat events (blue line in Figure 2) and the 95% probability threshold for lethal heat conditions (red line in Figure 2). The table reports the number (and percentage) of ports facing more than 10, 20, 50, and 80 days per year for each threshold, across different dates and climate scenarios.

Threshold	Year	RCP	Number (and Percentage) of Ports			
			Average Days per Year			
			>10	>20	>50	>70
$HI \geq 39.4$ °C High risk	Historical		33 (21%)	15 (10%)	0	0
		4.5	53 (34%)	46 (30%)	9 (6%)	0
	2050	8.5	54 (35%)	50 (32%)	13 (8%)	0
		4.5	56 (36%)	52 (34%)	20 (13%)	3 (2%)
	2100	8.5	142 (92%)	93 (60%)	48 (31%)	29 (10%)
$HI \geq 46.1$ °C Very high risk	Historical		0	0	0	0
		4.5	21 (14%)	7 (5%)	0	0
	2050	8.5	25 (16%)	8 (5%)	0	0
		4.5	31 (20%)	14 (9%)	0	0
	2100	8.5	53 (34%)	44 (28%)	7 (5%)	0
Deadly heat	Historical		0	0	0	0
		4.5	14 (9%)	2 (1%)	0	0
	2050	8.5	25 (16%)	5 (3%)	0	0
		4.5	77 (50%)	21 (14%)	0	0
	2100	8.5	133 (86%)	110 (71%)	31 (20%)	1 (0.7%)
Threshold	Year	RCP	>50	>80	>100	>120
Unsafe heat	Historical		148 (95%)	113 (73%)	80 (52%)	4 (3%)
		4.5	155 (100%)	149 (96%)	117 (75%)	72 (46%)
	2050	8.5	155 (100%)	150 (97%)	127 (82%)	88 (57%)
		4.5	155 (100%)	152 (98%)	139 (90%)	99 (64%)
	2100	8.5	155 (100%)	155 (100%)	154 (99%)	139 (90%)

These findings highlight a clear escalation in heat-related risks. In two largest Greek ports (Piraeus, Thessaloniki), unsafe heat conditions are expected for more than 120 days annually. Furthermore, exposure to conditions with $\geq 95\%$ death probability is projected for approximately 10.5 days per year, posing serious risks to personnel/user safety and port operations. Public health implications extend beyond the ports, as these ports are located within the largest urban clusters in Greece with several millions of residents; more than 125,000 residents live in a 500 m radius of these facilities.

Mainland ports appear more exposed when the heat index is considered (calculated using maximum temperature and relative humidity). This is attributed to the higher daytime temperature peaks typically recorded at these locations, which, when combined with humidity, elevate HI values into operationally hazardous ranges. At the same time, island ports exhibit greater exposure to deadly heat conditions, as defined by Mora et al. [50],

which are based on mean daily temperature and relative humidity. The persistently elevated mean temperatures at island locations, even in the absence of extreme maxima, increase the likelihood of exceeding the conditions associated with human thermo-regulatory failure.

These contrasting patterns indicate that mainland ports are more vulnerable to acute, short-duration heat stress, while island ports may face greater risks from sustained thermal exposure. As climate warming continues to raise temperatures, these differentiated risk profiles indicate an urgent need for tailored adaptation strategies that account for the dominant thermal stressors affecting each port type.

5. Discussion

Our results revealed an intensifying exposure of Greek ports to both flooding and extreme heat under future climate scenarios, with significant implications for infrastructure integrity, operational capability, and personnel/user safety. Concerning flood exposure, permanent quay/dock inundation will not be a problem until 2050; by 2100, however, several ports will be exposed to quay overtopping. This situation is projected to be much worse under extreme events. Quay overtopping during the ESL_{100} is projected for some ports even under the baseline conditions, whereas by 2050 and 2100 an increasing number of ports will face quay overtopping (13–17 and 42–80 ports, respectively).

In terms of quay/dock berthing constraints the situation is much worse. The majority of Greek ports (71%) do not meet the recommended freeboard (1.5 m) for safe berthing of passenger and freight vessels even under the baseline mean sea levels, a figure that rises to 98% by 2100 under RCP8.5. At that time, about 55% of ports will not be able to safely facilitate even fishing levels which require a freeboard of about 0.5–0.6 m [23]. Exposure will be more significant under the projected extreme sea levels (ESL_{100}). By 2100, ESL_{100} might reach up to 1.56 m relative to the baseline mean sea levels (RCP8.5), greatly reducing the available freeboard for berthing at the port quay/docks. Under such conditions, no ports could provide totally safe berths, even in the absence of wind and wave effects. These findings highlight the growing exposure of the Greek ports not only to quay/dock flooding, but also to operational disruptions caused by insufficient freeboards, particularly during extreme sea level events.

The above flood exposure projections are based on a ‘static’ flood threshold approach using a single (average) port/quay elevation value. Such approach cannot capture the dynamic evolution of flooding along the port quays with variable elevation. To address this limitation, a ‘sensitivity’ analysis was carried out using the minimum and maximum port quay/dock elevations. Its results showed that if the quay elevation variability is considered, flood exposure will increase. By 2100 under RCP8.5, up to 78% of Greek ports may experience partial quay inundation during the 1 in 100-year events. In any case the choice of representing the quay elevations of Greek ports by a single (average) value has been driven by the large scope (national-scale) of the study; static 2-D assessments of the flood exposure of all Greek ports would require a much greater computational effort due to large number of ports and the high resolution (2×2 m) of the DEM utilized.

In order to assess in more detail port flooding exposure, 2-D dynamic simulations are required that can account for the variable port topography. In the present study, the LISFLOOD-FP model using the acceleration solver was applied to ‘validate’ our ‘static’ flood exposure results at selected ports which were deemed reasonably safe on the basis of this analysis. Its results indicate that future inundation of the purpose-built dock/quays for commercial vessels will be (mostly) limited; in contrast the older port quays, and the adjacent roads and residential areas show much higher exposure.

While the 1-D static approach used can serve as a useful/efficient tool for initial, large-scale assessments, our dynamic simulation results from Myrina and Thasos (Figure 5)

ports and the additional 9 ports (see Supplementary Material Figures S1–S10) suggest that it tends to underestimate flood exposure, especially in quays with varying topography. In several instances, ports identified as unaffected by the 1-D static method showed partial inundation in the 2-D dynamic simulations, with flood extents reaching up to 100 m local elevation variability. Generally, our results from the dynamic modelling indicate a high flood exposure for Greek ports classified as reasonably ‘safe’ by the 1-D ‘static’ flood threshold assessment. This is likely due to the selection of the single average value to represent the quay elevation in the ports; this could result in ignoring flood penetration through quay areas with lower elevation. It is noted that previous investigations have shown an overestimation of the flood exposure by bathtub approaches compared to dynamic simulations [80,94].

Generally, the above projections of flood exposure and operability constraints could be considered as underestimations, as they do not account for wave effects within the port basins (e.g., [69]). Our national-scale assessment does not consider local and in-port wave (and wind) dynamics, that can impact on infrastructure, operational resilience and flooding (e.g., [23,95]); its objectives/scope have been to provide an initial assessment of the flood exposure of the Greek ports, indicating those in higher need for effective (and costly) flood adaptation measures (e.g., [96,97]). For port-specific exposure evaluations, detailed assessments are required that should be based on (computationally costly) high-resolution modelling that should consider the future wave energy, approach and port penetration, the complex port-basin dynamics, as well as the infrastructure particularities and vulnerabilities (e.g., [10]).

The significance of using high-resolution DEMs in such exercises cannot be overestimated (e.g., [78,80,94]). High-resolution DEMs enable more accurate estimates of potential impacts, as they can capture the intra-port quay and surrounding land topographic variability. Accuracy in topographic representation is critical, as even small variations in port quay elevations can significantly affect projections leading to under- or overestimation of port flood exposure. In this study, the high-resolution (2×2 m) Greek Cadastre DEM was used. It is also noted, however, that as the DEM used was created from orthophotos acquired in 2014–2015, potential changes in port elevation/morphology due to more recent maintenance/expansion works are yet not reflected in the DEM. Ideally, in situ topographic surveying coupled with UAV and laser scanner measurements (e.g., [76,98]) would offer the highest accuracy required for detailed flood exposure assessments; however this is not logistically feasible for assessments with a national scope. For such assessments, future improvements of the current methodology might include the division of the port quays into sections of different uses (i.e., into docks for large vessel berthing and quay sections for serving smaller vessels) that will allow for more targeted evaluation of the flood exposure [99].

Generally, potential flood impacts will likely be higher in the large Greek ports given their extensive port areas and the high densities of neighbouring infrastructure and population; extensive adaptation efforts and costs will be required to manage their flood risk under climate change (e.g., [27]). At the same time, smaller ports, particularly in island settings, will also require significant infrastructure upgrades to become flood-resilient in order to avert systemic impacts on the island sustainable development (e.g., [100]).

Regarding the Greek ports’ heat exposure under climate change, our results suggest an even higher challenge. Ports and their connecting land transport infrastructure will likely face increasing thermal stress, as the annual number of days with $T_{\max} \geq 32$ °C—a widely adopted threshold for infrastructure thermal stress [87]—will increase very significantly under climate change; up 75% of Greek ports will frequently face such conditions by the end of the century, with 31% expected to experience more than 50 such days annually

under RCP8.5. Energy demand implications will also prove to be challenging. Cooling Degree Days (CDD), will increase sharply, with over half of the Greek ports projected to face rises exceeding 100% by the end of the century under RCP8.5. As the Heating Degree Days (HDD) are projected to decline modestly, particularly at island ports, net increases in climate-driven energy demand are expected that will require effective adaptation measures (e.g., [1,101]).

At the same time, heat-related health risks for port personnel/users are also expected to rise. By the end of the century, high-risk heat index conditions ($HI \geq 39.4$ °C) are projected to occur at 92% of ports for at least 10 days annually. Deadly heat conditions [50] are projected to be even more alarming: 86% of Greek ports (and associated urban clusters) will be affected, with over 20% of all ports expected to experience more than 50 deadly heat days annually under RCP8.5. While mainland ports (with a total population of 232,300 within a radius of 500 m) will be more exposed to acute, short-duration heat stress due to the projected higher maximum temperatures, island ports (with an equivalent neighbouring population of about 137,000) will face greater health risks due to their persistently high mean temperatures. These differentiated projections present large management challenges and underscore the need for tailored evaluations and adaptation strategies that can address both the acute and chronic thermal stresses.

It should be noted that while the 12 km resolution of CORDEX RCMs (e.g., CNRM-ALADIN52) represents a substantial improvement over coarse global models and enables reasonable characterization of regional climate conditions, further downscaling techniques (dynamical or statistical) (e.g., [102]) could yield more locally representative results—especially for geo-morphologically complex coastal environments like the Greek ports. Higher resolution would increase the number of grid points covering the study area, thereby improving the spatial matching between port locations and modelled climatic data, which in turn would allow for better representation of the (expected) climatic variability. Thus, while the general conclusions of the study are expected to hold, finer-scale modelling would likely refine the projections of heat-related risks.

Generally, our results indicate an urgent need for targeted design/implementation of effective adaptation policies and measures that will enhance infrastructure resilience, as well as the health/safety of the port personnel/users and surrounding populations. However, relevant global port industry surveys [103,104] have indicated that ports are not yet adequately prepared, due to: gaps in the information/data necessary to assess reasonably accurately the flood and other climatic hazards/risks and the associated operational thresholds; knowledge dissemination barriers; stakeholder and decision-making related challenges; and limited human and financial resources (e.g., [105–107]). Due to the complexity of the port ecosystems, particular attention should be placed on understanding their different components and their interactions in order to support decision-making for port resilience (e.g., [108,109]). Pertinent policy and legislative frameworks for coastal resilience to climatic hazards (e.g., [110]) can play a crucial role in promoting/facilitating relevant research and development, and provide economic incentives to support adaptation, resilience building, and climatic risk management in ports [1].

Finally, it is noted the national assessments, such as that carried out in the present study are very useful in the context of the recent European legislation on climate change adaptation, particularly the Directive on the Resilience of Critical Entities [21]. This Directive aims to ensure the resilience of public/private infrastructures that are deemed essential for the functioning of the society and economy. Greece, in tandem with the other European Member States must identify such entities, including ports, that provide essential services and develop a national strategy to enhance their resilience on the basis of recurrent, detailed

risk assessments. Greek ports, particularly those in island settings certainly qualify for such designation.

6. Conclusions

The results of this study indicate an intensifying climate-related risk for Greek ports, as flood and heat exposure are projected to significantly increase during the 21st century. Extreme sea levels (ESLs₁₀₀) are projected to exceed current quay elevations at many ports by 2100, particularly under the high-emission RCP8.5 scenario. Moreover, port operability will be very significantly affected, as most ports (>96%) will fail to meet the 1.5 m freeboard requirement for commercial vessel berthing.

Dynamic 2-D flood simulations for selected ports revealed that the 1-D ‘static’ thresholds used in the national assessment of port flood exposure may underestimate flood exposure. Simulated events show large flood extents (>150 m inland) in some ports as well as significant variability in flood depths. This indicates that many ports identified as reasonably ‘safe’ under ‘static’ flood thresholds used may still face considerable flood exposure during future storms. In addition, as both the 1-D and 2-D projections do not account for wave effects, all results might be considered as underestimations in terms of expected impact.

Heat-related risks are also projected to rise sharply. The frequency and duration of extreme temperature events will significantly increase, exposing port infrastructure and personnel/users to intensified material, operational and health risks. Energy demands will also rise steeply, with projected increases in Cooling Degree Days exceeding 200% at many ports. The number of deadly heat days will also increase markedly, reaching more than 50 days annually at many ports, particularly at island settings. These projections suggest differentiated risk profiles for (mainland and island) ports, requiring tailored adaptation responses. Moreover, as the Greek ports are mostly located within large urban clusters, the health risks associated with such exposure could be very severe indeed.

Overall, our findings underscore an urgent need to prioritize climate adaptation measures in port infrastructure planning and operations. Well-designed physical interventions (e.g., quay/dock elevation, improved port protection, use of heat-resistant materials) and regulatory measures (e.g., updated health/safety protocols and energy resilience planning) will be required. Given the strategic role of ports in national and regional economies, failure to act will result in increased damages and increasingly frequent operational disruptions, as well as very significant health/safety risks.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/w17131897/s1>, Figure S1: Location map of the nine ports. Their database ID numbers are shown; Figure S2: Flood maps under ESLs₁₀₀ (excluding wave set-up) for the island port of Agios Kirikos, Ikaria (ID: 9); Figure S3: Flood maps under ESLs₁₀₀ (excluding wave set-up) for the port of Volos (ID: 30); Figure S4 Flood map under ESLs₁₀₀ (excluding wave set-up) for the port of Heraklion (ID: 50). The 2050 map is not presented because no flooding is projected for this year; Figure S5: Flood maps under ESLs₁₀₀ (excluding wave set-up) for the port of Athinios port, Thira (ID: 52); Figure S6: Flood maps under ESLs₁₀₀ (excluding wave set-up) for the port of Ios (ID: 57); Figure S7: Flood map under ESLs₁₀₀ (excluding wave set-up) for the port of Lavrio (ID: 78). The 2050 map is not presented because no flooding is projected for this year; Figure S8: Flood map under ESLs₁₀₀ (excluding wave set-up) for the port of Rafina (ID: 121). The 2050 map is not presented because no flooding is projected for this year; Figure S9: Flood map under ESLs₁₀₀ (excluding wave set-up) for the port of Skopelos (ID: 131). The 2050 map is not presented because no flooding is projected for this year; Figure S10: Flood maps under ESLs₁₀₀ (excluding wave set-up) for the port of Chios (ID: 151).

Author Contributions: Conceptualization, I.N.M. and A.F.V.; methodology, I.N.M., D.C., K.M. and A.F.V.; resources, I.N.M., D.C., K.M., T.C., E.B., G.P. and I.K.; data curation, I.N.M., D.C., K.M., T.C., E.B., G.P. and I.K.; writing—original draft preparation, I.N.M., D.C., K.M. and A.F.V.; writing—review and editing, I.N.M., D.C., K.M., A.F.V., A.P., T.C., E.B., H.T., G.P. and I.K.; visualization, I.N.M. and D.C.; supervision, A.F.V. and A.P.; project administration, A.P. All authors have read and agreed to the published version of the manuscript.

Funding: The research project titled “Enhancing resilience for Greek ports—ResPorts” is being implemented within the framework of the “Natural Environment and Innovative Actions 2022/Priority Axis 3: Research and Application” program, with a total budget of EUR 199,647. It is funded by the Green Fund and the beneficiary is the Department of Shipping Trade and Transport of the University of the Aegean.

Data Availability Statement: Data will be made available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

- Asariotis, R.; Monioudi, I.N.; Mohos Naray, V.; Velegarakis, A.F.; Vousdoukas, M.I.; Mentaschi, L.; Feyen, L. Climate Change and Seaports: Hazards, Impacts and Policies and Legislation for Adaptation. *Anthr. Coasts* **2024**, *7*, 14. [\[CrossRef\]](#)
- IPCC. Climate Change 2023: Synthesis Report. In *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, 2023.
- Sánchez-Arcilla, A.; Sierra, J.P.; Brown, S.; Casas-Prat, M.; Nicholls, R.J.; Lionello, P.; Conte, D. A Review of Potential Physical Impacts on Harbours in the Mediterranean Sea under Climate Change. *Reg. Environ. Change* **2016**, *16*, 2471–2484. [\[CrossRef\]](#)
- UNECE. *Climate Change Impacts and Adaptation for Transport Networks and Nodes*; ECE/TRANS/283; United Nations Publications: Geneva, Switzerland, 2020; ISBN 978-92-1-117237-9.
- Izaguirre, C.; Losada, I.J.; Camus, P.; Vigh, J.L.; Stenek, V. Climate Change Risk to Global Port Operations. *Nat. Clim. Chang.* **2021**, *11*, 14–20. [\[CrossRef\]](#)
- UNECE. *Transport for Sustainable Development: The Case of Inland Transport*; Transport Trends and Economics Series; ECE/TRANS/251; United Nations Publications: New York, NY, USA; Geneva, Switzerland, 2015; ISBN 978-92-1-117096-2.
- Verschuur, J.; Koks, E.E.; Hall, J.W. Systemic Risks from Climate-Related Disruptions at Ports. *Nat. Clim. Chang.* **2023**, *13*, 804–806. [\[CrossRef\]](#)
- Verschuur, J.; Koks, E.E.; Li, S.; Hall, J.W. Multi-Hazard Risk to Global Port Infrastructure and Resulting Trade and Logistics Losses. *Commun. Earth Environ.* **2023**, *4*, 5. [\[CrossRef\]](#)
- Marcos, M.; Amores, A.; Agulles, M.; Robson, J.; Feng, X. Global Warming Drives a Threefold Increase in Persistence and 1 °C Rise in Intensity of Marine Heatwaves. *Proc. Natl. Acad. Sci. USA* **2025**, *122*, e2413505122. [\[CrossRef\]](#)
- Lucio, D.; Lara, J.L.; Tomás, A.; Losada, I.J. Probabilistic Assessment of Climate-Related Impacts and Risks in Ports. *Reliab. Eng. Syst. Saf.* **2024**, *251*, 110333. [\[CrossRef\]](#)
- Becker, A.; Ng, A.K.Y.; McEvoy, D.; Mullett, J. Implications of Climate Change for Shipping: Ports and Supply Chains. *WIREs Clim. Change* **2018**, *9*, e508. [\[CrossRef\]](#)
- Asariotis, R. Climate Change Impacts on Seaports: A Growing Threat to Sustainable Trade and Development. Available online: <https://unctad.org/news/climate-change-impacts-seaports-growing-threat-sustainable-trade-and-development> (accessed on 5 December 2023).
- Tselentis, B.; Pelagidis, T.; Manologlou, S. The Role of Modern Ports and Marine Protected Areas in Eastmed’s Environmental Sustainability: The Case of Greece. In *Operational Research in Agriculture and Tourism*; Krassadaki, E., Baourakis, G., Zopounidis, C., Matsatsinis, N., Eds.; Springer: Cham, Switzerland, 2020; pp. 131–143.
- Asariotis, R. Climate Change and Adaptation for Coastal Transport Infrastructure: A Sustainable Development Challenge for SIDS in the Caribbean and Beyond. In *Coastal and Marine Environments*; Wang, Y., Ed.; CRC Press: Boca Raton, FL, USA, 2020; Volume 5, pp. 253–264.
- IPCC. *Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O., Pichs-Madruga, R., Sokona, Y., Farahani, E., Kadner, S., Seyboth, K., Adler, A., Baum, I., Brunner, S., Eickemeier, P., et al., Eds.; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; ISBN 978-1-107-05821-7.
- UNFCCC. Policy Brief: Technologies for Averting, Minimizing and Addressing Loss and Damage in Coastal Zones. In *United Nations Framework Convention On Climate Change*; Executive Committee of the Warsaw International Mechanism for Loss and Damage: Bonn, Germany, 2020.

17. Wang, N.; Wu, M.; Yuen, K.F. Assessment of Port Resilience Using Bayesian Network: A Study of Strategies to Enhance Readiness and Response Capacities. *Reliab. Eng. Syst. Saf.* **2023**, *237*, 109394. [\[CrossRef\]](#)
18. Monioudi, I.N.; Asariotis, R.; Becker, A.; Bhat, C.; Dowding-Gooden, D.; Esteban, M.; Feyen, L.; Mentaschi, L.; Nikolaou, A.; Nurse, L.; et al. 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* **2018**, *18*, 2211–2225. [\[CrossRef\]](#)
19. Bove, G.; Becker, A.; Sweeney, B.; Vousdoukas, M.; Kulp, S. 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.* **2020**, *710*, 136162. [\[CrossRef\]](#)
20. O'Neill, B.C.; Tebaldi, C.; van Vuuren, D.P.; Eyring, V.; Friedlingstein, P.; Hurtt, G.; Knutti, R.; Kriegler, E.; Lamarque, J.-F.; Lowe, J.; et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model. Dev.* **2016**, *9*, 3461–3482. [\[CrossRef\]](#)
21. EU. 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; Official Journal L 333; EU: Brussels, Belgium, 2022; pp. 164–198.
22. GEBCO. *Compilation Group The GEBCO_2024 Grid-a Continuous Terrain Model of the Global Oceans and Land*; NERC EDS British Oceanographic Data Centre NOC: Liverpool, UK, 2024. [\[CrossRef\]](#)
23. Sierra, J.P.; Sánchez-Arcilla, A.; Gironella, X.; Gracia, V.; Altomare, C.; Mössö, C.; González-Marco, D.; Gómez, J.; Barceló, M.; Barahona, C. Impact of Climate Change on Berthing Areas in Ports of the Balearic Islands: Adaptation Measures. *Front. Mar. Sci.* **2023**, *10*, 1124763. [\[CrossRef\]](#)
24. Li, P.; Tong, M.; Wu, J.; Meng, X.; Fan, X.; Sun, X.; Li, J.; Xue, T. Flood Exposure Contributes to Under-Five Mortality in Low- and Middle-Income Countries. *One Earth* **2025**, *8*, 101305. [\[CrossRef\]](#)
25. EEA. *European Climate Risk Assessment*; Publications Office of the European Union: Luxembourg, 2024.
26. Monioudi, I.N.; Velegrakis, A.F.; Chatzistratis, D.; Vousdoukas, M.I.; Savva, C.; Wang, D.; Bove, G.; Mentaschi, L.; Paprotny, D.; Morales-Nápoles, O.; et al. Climate Change—Induced Hazards on Touristic Island Beaches: Cyprus, Eastern Mediterranean. *Front. Mar. Sci.* **2023**, *10*, 1188896. [\[CrossRef\]](#)
27. Hanson, S.E.; Nicholls, R.J. Demand for Ports to 2050: Climate Policy, Growing Trade and the Impacts of Sea-Level Rise. *Earths Future* **2020**, *8*, e2020EF001543. [\[CrossRef\]](#)
28. Abdelhafez, M.A.; Ellingwood, B.; Mahmoud, H. Vulnerability of Seaports to Hurricanes and Sea Level Rise in a Changing Climate: A Case Study for Mobile, AL. *Coast. Eng.* **2021**, *167*, 103884. [\[CrossRef\]](#)
29. Vousdoukas, M.I.; Athanasiou, P.; Giardino, A.; Mentaschi, L.; Stocchino, A.; Kopp, R.E.; Menéndez, P.; Beck, M.W.; Ranasinghe, R.; Feyen, L. Small Island Developing States under Threat by Rising Seas Even in a 1.5 °C Warming World. *Nat. Sustain.* **2023**, *6*, 1552–1564. [\[CrossRef\]](#)
30. WMO. *State of the Global Climate 2024*; Chair, Publications Board, World Meteorological Organization: Geneva, Switzerland, 2024; ISBN 978-92-63-11368-5.
31. IPCC. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*; Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize, S., Osako, A., Pyrozhenko, Y., Shermanau, P., Federici, S., Eds.; IPCC: Geneva, Switzerland, 2019; ISBN 978-4-88788-232-4.
32. Slangen, A.B.A.; Palmer, M.D.; Camargo, C.M.L.; Church, J.A.; Edwards, T.L.; Hermans, T.H.J.; Hewitt, H.T.; Garner, G.G.; Gregory, J.M.; Kopp, R.E.; et al. The Evolution of 21st Century Sea-Level Projections from IPCC AR5 to AR6 and Beyond. *Camb. Prism. Coast. Futures* **2023**, *1*, e7. [\[CrossRef\]](#)
33. Jevrejeva, S.; Jackson, L.P.; Riva, R.E.M.; Grinsted, A.; Moore, J.C. Coastal Sea Level Rise with Warming above 2 °C. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 13342–13347. [\[CrossRef\]](#)
34. Velegrakis, A.F.; Monioudi, I.; Tzoraki, O.; Vousdoukas, M.I.; Tragou, E.; Hasiotis, T.; Asariotis, R.; Andreadis, O. Coastal Hazards and Related Impacts in Greece. In *The Geography of Greece: Managing Crises and Building Resilience*; Darques, R., Sidiropoulos, G., Kalabokidis, K., Eds.; Springer: Cham, Switzerland, 2024; pp. 353–370. ISBN 978-3-031-29819-6.
35. Uzun, P.; Otay, E.N. Sea-Level Change in Eastern Mediterranean, Aegean and Black Seas Analyzed at Subregional Scale of Six CORDEX Domains. *Reg. Stud. Mar. Sci.* **2025**, *83*, 104099. [\[CrossRef\]](#)
36. Cherif, S.; Doblas-Miranda, E.; Lionello, P.; Borrego, C.; Giorgi, F.; Iglesias, A.; Jebari, S.; Mahmoudi, E.; Moriondo, M.; Pringault, O.; et al. Drivers of Change. In *Climate and Environmental Change in the Mediterranean Basin—Current Situation and Risks for the Future. First Mediterranean Assessment Report*; Cramer, W., Guiot, J., Marini, K., Eds.; Union for the Mediterranean, Plan Bleu, UNEP/MAP: Marseille, France, 2021; pp. 59–180.
37. Zittis, G.; Almazroui, M.; Alpert, P.; Ciais, P.; Cramer, W.; Dahdal, Y.; Fnais, M.; Francis, D.; Hadjinicolaou, P.; Howari, F.; et al. Climate Change and Weather Extremes in the Eastern Mediterranean and Middle East. *Rev. Geophys.* **2022**, *60*, e2021RG000762. [\[CrossRef\]](#)
38. Tsimplis, M.N.; Shaw, A.G.P. Seasonal Sea Level Extremes in the Mediterranean Sea and at the Atlantic European Coasts. *Nat. Hazards Earth Syst. Sci.* **2010**, *10*, 1457–1475. [\[CrossRef\]](#)

39. Androulidakis, Y.; Christos, M.; Zisis, M.; Krestenitis, Y. Sea Level Variability and Coastal Inundation over the Northeastern Mediterranean Sea. *Coast. Eng. J.* **2023**, *65*, 514–545. [\[CrossRef\]](#)
40. Camus, P.; Tomás, A.; Díaz-Hernández, G.; Rodríguez, B.; Izaguirre, C.; Losada, I.J. Probabilistic Assessment of Port Operation Downtimes under Climate Change. *Coast. Eng.* **2019**, *147*, 12–24. [\[CrossRef\]](#)
41. Tsoukala, V.K.; Chondros, M.; Kapelonis, Z.G.; Martzikos, N.; Lykou, A.; Belibassakis, K.; Makropoulos, C. An Integrated Wave Modelling Framework for Extreme and Rare Events for Climate Change in Coastal Areas—The Case of Rethymno, Crete. *Oceanologia* **2016**, *58*, 71–89. [\[CrossRef\]](#)
42. Mentaschi, L.; Vousdoukas, M.I.; Voukouvalas, E.; Dosio, A.; Feyen, L. Global Changes of Extreme Coastal Wave Energy Fluxes Triggered by Intensified Teleconnection Patterns. *Geophys. Res. Lett.* **2017**, *44*, 2416–2426. [\[CrossRef\]](#)
43. Bevacqua, E.; Vousdoukas, M.I.; Zappa, G.; Hodges, K.; Shepherd, T.G.; Maraun, D.; Mentaschi, L.; Feyen, L. More Meteorological Events That Drive Compound Coastal Flooding Are Projected under Climate Change. *Commun. Earth Environ.* **2020**, *1*, 47. [\[CrossRef\]](#)
44. Paprotny, D.; Vousdoukas, M.I.; Morales-Nápoles, O.; Jonkman, S.N.; Feyen, L. Pan-European Hydrodynamic Models and Their Ability to Identify Compound Floods. *Nat. Hazards* **2020**, *101*, 933–957. [\[CrossRef\]](#)
45. Hao, Z.; Singh, V.P. Compound Events under Global Warming: A Dependence Perspective. *J. Hydrol. Eng.* **2020**, *25*, 03120001. [\[CrossRef\]](#)
46. Xu, K.; Wang, C.; Bin, L. Compound Flood Models in Coastal Areas: A Review of Methods and Uncertainty Analysis. *Nat. Hazards* **2023**, *116*, 469–496. [\[CrossRef\]](#)
47. Green, J.; Haigh, I.D.; Quinn, N.; Neal, J.; Wahl, T.; Wood, M.; Eilander, D.; de Ruiter, M.; Ward, P.; Camus, P. Review Article: A Comprehensive Review of Compound Flooding Literature with a Focus on coastal and Estuarine Regions. *Nat. Hazards Earth Syst. Sci.* **2025**, *25*, 747–816. [\[CrossRef\]](#)
48. Notteboom, T.; Pallis, A.; Rodrigue, J.-P. *Port Economics, Management and Policy*, 1st ed.; Routledge: London, UK, 2022; ISBN 9780429318184.
49. Liban, C.B.; Kafalenos, R.; Alessa, L.; Anenberg, S.; Chester, M.; DeFlorio, J.; Dóñez, F.J.; Flannery, A.; Sanio, M.R.; Scott, B.A.; et al. Transportation. In *Fifth National Climate Assessment*; Crimmins, A.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Stewart, B.C., Maycock, T.K., Eds.; U.S. Global Change Research Program: Washington, DC, USA, 2023.
50. Mora, C.; Dousset, B.; Caldwell, I.R.; Powell, F.E.; Geronimo, R.C.; Bielecki, C.R.; Counsell, C.W.W.; Dietrich, B.S.; Johnston, E.T.; Louis, L.V.; et al. Global Risk of Deadly Heat. *Nat. Clim. Chang.* **2017**, *7*, 501–506. [\[CrossRef\]](#)
51. Dasgupta, S.; van Maanen, N.; Gosling, S.N.; Piontek, F.; Otto, C.; Schleussner, C.-F. Effects of Climate Change on Combined Labour Productivity and Supply: An Empirical, Multi-Model Study. *Lancet Planet. Health* **2021**, *5*, e455–e465. [\[CrossRef\]](#) [\[PubMed\]](#)
52. van Daalen, K.R.; Romanello, M.; Rocklöv, J.; Semenza, J.C.; Tonne, C.; Markandya, A.; Dasandi, N.; Jankin, S.; Achebak, H.; Ballester, J.; et al. The 2022 Europe Report of the Lancet Countdown on Health and Climate Change: Towards a Climate Resilient Future. *Lancet Public Health* **2022**, *7*, e942–e965. [\[CrossRef\]](#) [\[PubMed\]](#)
53. Kostopoulou, E.; Giannakopoulos, C.; Hatzaki, M.; Karali, A.; Hadjinicolaou, P.; Lelieveld, J.; Lange, M.A. Spatio-Temporal Patterns of Recent and Future Climate Extremes in the Eastern Mediterranean and Middle East Region. *Nat. Hazards Earth Syst. Sci.* **2014**, *14*, 1565–1577. [\[CrossRef\]](#)
54. Politi, N.; Vlachogiannis, D.; Sfetsos, A.; Nastos, P.T. High Resolution Projections for Extreme Temperatures and Precipitation over Greece. *Clim. Dyn.* **2023**, *61*, 633–667. [\[CrossRef\]](#)
55. Georgoulas, A.K.; Akritidis, D.; Kalisoras, A.; Kapsomenakis, J.; Melas, D.; Zerefos, C.S.; Zanis, P. Climate Change Projections for Greece in the 21st Century from High-Resolution EURO-CORDEX RCM Simulations. *Atmos. Res.* **2022**, *271*, 106049. [\[CrossRef\]](#)
56. Kostopoulou, E.; Giannakopoulos, C. Projected Changes in Extreme Wet and Dry Conditions in Greece. *Climate* **2023**, *11*, 49. [\[CrossRef\]](#)
57. Zanis, P.; Georgoulas, A.K.; Velikou, K.; Akritidis, D.; Kalisoras, A.; Melas, D. Future Projections of Precipitation Extremes for Greece Based on an Ensemble of High-Resolution Regional Climate Model Simulations. *Atmosphere* **2024**, *15*, 601. [\[CrossRef\]](#)
58. UNECE. *Climate Change Impacts and Adaptation for International Transport Networks*; ECE/TRANS/238; United Nations Publications: New York, NY, USA; Switzerland, Geneva, 2014.
59. Folkman, D.; Gharehgozli, A.; Mileski, J.; Galvao, C.B. Port Resiliency and the Effects of Hurricanes on Port Operations. *Int. J. Adv. Oper. Manag.* **2021**, *13*, 409–430. [\[CrossRef\]](#)
60. Wu, X.; Sun, Y.; Wu, Y.; Su, N.; Peng, S. The Interference Effects of Wind Load and Wind-Induced Dynamic Response of Quayside Container Cranes. *Appl. Sci.* **2022**, *12*, 10969. [\[CrossRef\]](#)
61. Castillo, A.P.P.; Herazo, J.C.M. A Review of Wind Impact on Container Port Operations: Current Technologies, Strategies and Future Perspectives. *Procedia Comput. Sci.* **2024**, *251*, 783–788. [\[CrossRef\]](#)
62. Gu, B.; Liu, J. A Systematic Review of Resilience in the Maritime Transport. *Int. J. Logist. Res. Appl.* **2025**, *28*, 257–278. [\[CrossRef\]](#)

63. Vagenas, C.; Anagnostopoulou, C.; Tolika, K. Climatic Study of the Marine Surface Wind Field over the Greek Seas with the Use of a High Resolution RCM Focusing on Extreme Winds. *Climate* **2017**, *5*, 29. [\[CrossRef\]](#)
64. Ricci, A.; Vasaturo, R.; Blocken, B. An Integrated Tool to Improve the Safety of Seaports and Waterways under Strong Wind Conditions. *J. Wind Eng. Ind. Aerodyn.* **2023**, *234*, 105327. [\[CrossRef\]](#)
65. Soukissian, T.; Karathanasi, F.; Axaopoulos, P.; Voukouvalas, E.; Kotroni, V. Offshore Wind Climate Analysis and Variability in the Mediterranean Sea. *Int. J. Climatol.* **2018**, *38*, 384–402. [\[CrossRef\]](#)
66. Bates, P.D.; De Roo, A.P.J. A Simple Raster-Based Model for Flood Inundation Simulation. *J. Hydrol.* **2000**, *236*, 54–77. [\[CrossRef\]](#)
67. Jackson, L.P.; Jevrejeva, S. A Probabilistic Approach to 21st Century Regional Sea-Level Projections Using RCP and High-End Scenarios. *Glob. Planet. Change* **2016**, *146*, 179–189. [\[CrossRef\]](#)
68. Vousdoukas, M.I.; Mentaschi, L.; Voukouvalas, E.; Verlaan, M.; Jevrejeva, S.; Jackson, L.P.; Feyen, L. Global Probabilistic Projections of Extreme Sea Levels Show Intensification of Coastal Flood Hazard. *Nat. Commun.* **2018**, *9*, 2360. [\[CrossRef\]](#)
69. Sierra, J.P.; Casanovas, I.; Möso, C.; Mestres, M.; Sánchez-Arcilla, A. Vulnerability of Catalan (NW Mediterranean) Ports to Wave Overtopping Due to Different Scenarios of Sea Level Rise. *Reg. Environ. Change* **2016**, *16*, 1457–1468. [\[CrossRef\]](#)
70. Sierra, J.P.; Casas-Prat, M.; Virgili, M.; Möso, C.; Sánchez-Arcilla, A. Impacts on Wave-Driven Harbour Agitation Due to Climate Change in Catalan Ports. *Nat. Hazards Earth Syst. Sci.* **2015**, *15*, 1695–1709. [\[CrossRef\]](#)
71. Galiatsatou, P.; Makris, C.; Prinos, P. Optimized Reliability Based Upgrading of Rubble Mound Breakwaters in a Changing Climate. *J. Mar. Sci. Eng.* **2018**, *6*, 92. [\[CrossRef\]](#)
72. González-Marco, D.; Sierra, J.P.; Fernández de Ybarra, O.; Sánchez-Arcilla, A. Implications of Long Waves in Harbor Management: The Gijón Port Case Study. *Ocean Coast. Manag.* **2008**, *51*, 180–201. [\[CrossRef\]](#)
73. Dong, Y.; Zheng, Z.; Ma, Y.; Gao, J.; Ma, X.; Dong, G. Numerical Investigation on the Mitigation of Harbor Oscillations by Periodic Undulating Topography. *Ocean Eng.* **2023**, *279*, 114580. [\[CrossRef\]](#)
74. Monioudi, I.; Akyias, A.; Tsoukala, V.K.; Stamou, A.; Moutzouris, C.I. Investigation of Wave Transmission through a Renewal Pipe at Breakwaters. In Proceedings of the 4th Panhellenic Conference of Harbor Works, Athens, Greece, 20–23 November 2006.
75. Chrisafinos, D.; Kavvadas, I. Quality Assessment of the New Backgrounds LSO25. In Proceedings of the 14th National Conference on Chartography of the Greek Scientific Association of Chartography, Titled “The Chartography in a Changing World”, Thessaloniki, Greece, 2–4 November 2016; pp. 2–4.
76. Velegrakis, A.F.; Chatzistratis, D.; Chalazas, T.; Armaroli, C.; Schiavon, E.; Alves, B.; Grigoriadis, D.; Hasiotis, T.; Ieronymidi, E. Earth Observation Technologies, Policies and Legislation for the Coastal Flood Risk Assessment and Management: A European Perspective. *Anthr. Coasts* **2024**, *7*, 3. [\[CrossRef\]](#)
77. Vousdoukas, M.I.; Voukouvalas, E.; Mentaschi, L.; Dottori, F.; Giardino, A.; Bouziotas, D.; Bianchi, A.; Salamon, P.; Feyen, L. Developments in Large-Scale Coastal Flood Hazard Mapping. *Nat. Hazards Earth Syst. Sci.* **2016**, *16*, 1841–1853. [\[CrossRef\]](#)
78. Makris, C.; Mallios, Z.; Androulidakis, Y.; Krestenitis, Y. CoastFLOOD: A High-Resolution Model for the Simulation of Coastal Inundation Due to Storm Surges. *Hydrology* **2023**, *10*, 103. [\[CrossRef\]](#)
79. Bates, P.D.; Dawson, R.J.; Hall, J.W.; Horritt, M.S.; Nicholls, R.J.; Wicks, J. Mohamed Ahmed Ali Mohamed Hassan Simplified Two-Dimensional Numerical Modelling of Coastal Flooding and Example Applications. *Coast. Eng.* **2005**, *52*, 793–810. [\[CrossRef\]](#)
80. Seenath, A.; Wilson, M.; Miller, K. Hydrodynamic versus GIS Modelling for Coastal Flood Vulnerability Assessment: Which Is Better for Guiding Coastal Management? *Ocean Coast. Manag.* **2016**, *120*, 99–109. [\[CrossRef\]](#)
81. Le Gal, M.; Fernández-Montblanc, T.; Duo, E.; Montes Perez, J.; Cabrita, P.; Souto Cecon, P.; Gastal, V.; Ciavola, P.; Armaroli, C. A New European Coastal Flood Database for Low–Medium Intensity Events. *Nat. Hazards Earth Syst. Sci.* **2023**, *23*, 3585–3602. [\[CrossRef\]](#)
82. Bates, P.D.; Horritt, M.S.; Fewtrell, T.J. A Simple Inertial Formulation of the Shallow Water Equations for Efficient Two-Dimensional Flood Inundation Modelling. *J. Hydrol.* **2010**, *387*, 33–45. [\[CrossRef\]](#)
83. Shaw, J.; Kesserwani, G.; Neal, J.; Bates, P.; Sharifian, M.K. LISFLOOD-FP 8.0: The New Discontinuous Galerkin Shallow-Water Solver for Multi-Core CPUs and GPUs. *Geosci. Model. Dev.* **2021**, *14*, 3577–3602. [\[CrossRef\]](#)
84. Martzikos, N.T.; Prinos, P.E.; Memos, C.D.; Tsoukala, V.K. Statistical Analysis of Mediterranean Coastal Storms. *Oceanologia* **2021**, *63*, 133–148. [\[CrossRef\]](#)
85. Papaioannou, G.; Efstratiadis, A.; Vasiliades, L.; Loukas, A.; Papalexiou, S.M.; Koukouvinos, A.; Tsoukalas, I.; Kossieris, P. An Operational Method for Flood Directive Implementation in Ungauged Urban Areas. *Hydrology* **2018**, *5*, 24. [\[CrossRef\]](#)
86. Copernicus Climate Change Service; Climate Data Store. CORDEX Regional Climate Model Data on Single Levels. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). Available online: <https://cds.climate.copernicus.eu/datasets/projections-cordex-domains-single-levels?tab=overview> (accessed on 18 January 2025).

87. Leviäkangas, P.; Tuominen, A.; Molarius, R.; Schabel, J.; Toivonen, S.; Keränen, J.; Törnqvist, J.; Makkonen, L.; Vajda, A.; Tuomenvirta, H. *Extreme Weather Impacts on Transport Systems*; EWENT Project Deliverable D1; VTT: Espoo, Finland, 2011.
88. Deroubaix, A.; Labuhn, I.; Camredon, M.; Gaubert, B.; Monerie, P.-A.; Popp, M.; Ramarohetra, J.; Ruprich-Robert, Y.; Silvers, L.G.; Siour, G. Large Uncertainties in Trends of Energy Demand for Heating and Cooling under Climate Change. *Nat. Commun.* **2021**, *12*, 5197. [CrossRef]
89. Georgopoulou, E.; Mirasgedis, S.; Sarafidis, Y.; Giannakopoulos, C.; Varotsos, K.V.; Gakis, N. Climate Change Impacts on the Energy System of a Climate-Vulnerable Mediterranean Country (Greece). *Atmosphere* **2024**, *15*, 286. [CrossRef]
90. Rothfus, L.P.; NWS Southern Region Headquarters. The Heat Index Equation (or, More than You Ever Wanted to Know about Heat Index). *Fort Worth Tex. Natl. Ocean. Atmos. Adm. Natl. Weather Serv. Off. Meteorol.* **1990**, 9023, 640.
91. EPPE. Recommendations for Maritime Works. ROM 2.0-11, Volume I. In *Recommendations for the Design and Construction of Berthing and Mooring Structures, Translated Version of the Original Spanish Text*, 1st ed.; Organismo Público Puertos del Estado: Madrid, Spain, 2019.
92. Karditsa, A.; Roumpis, E.; Markozanes, F.; Lesioti, M.; Monioudi, I.; Poulos, S.; Hatzaki, M.; Vaggelas, G. The Impact of Sea Level Rise on the Port of Heraklio: Operational Risk Assessment and Economic Implications. *Tech. Ann.* **2024**, *1*. [CrossRef]
93. Papaioannou, G.; Polydoropoulou, A.; Tsirimpa, A. Analyzing the Passenger Traffic Demand Patterns of Greek Ferry Terminals. *Transp. Res. Procedia* **2023**, *72*, 2920–2927. [CrossRef]
94. Chatzistratis, D.; Monioudi, I.N.; Velegrakis, A.F.; Chalazas, T.; Tragou, E. Exposure to Coastal Erosion and Flooding in the Northeastern Aegean Islands, Greece. In *CIESM Monograph 52, Marine Hazards, Coastal Vulnerability, Risk (Mis) Perceptions—A Mediterranean Perspective*; Briand, F., Ed.; CIESM Publisher: Monte-Carlo, Monaco, 2024; Volume 52, pp. 115–130.
95. Galiatsatou, P.; Makris, C.; Kokkinos, D.; Prinos, P.; Krestenitis, Y. Climate Change Effects on Extreme Total Water Levels of the Greek Coastal Zone. In *Proceedings of the 1st International Scientific Conference on Design and Management of Port Coastal and Offshore Works (DMPCO)*, Athens, Greece, 8–11 May 2019; pp. 169–173.
96. Esteban, M.; Hiroshi, T.; Robert, J.N.; Dyah, F.; Munawir Bintang, P.; Shota, K.; Xiong, Y.; Izumi, I.; Takahito, M.; Paolo, V.; et al. Adapting Ports to Sea-Level Rise: Empirical Lessons Based on Land Subsidence in Indonesia and Japan. *Marit. Policy Manag.* **2020**, *47*, 937–952. [CrossRef]
97. Fernandez-Perez, A.; Losada, I.J.; Lara, J.L. A Framework for Climate Change Adaptation of Port Infrastructures. *Coast. Eng.* **2024**, *191*, 104538. [CrossRef]
98. Evagorou, E.; Hasiotis, T.; Petsimeris, I.T.; Monioudi, I.N.; Andreadis, O.P.; Chatzipavlis, A.; Christofi, D.; Kountouri, J.; Stylianou, N.; Mettas, C.; et al. A Holistic High-Resolution Remote Sensing Approach for Mapping Coastal Geomorphology and Marine Habitats. *Remote Sens.* **2025**, *17*, 1437. [CrossRef]
99. Jebbad, R.; Sierra, J.P.; Möso, C.; Mestres, M.; Sánchez-Arcilla, A. Assessment of Harbour Inoperability and Adaptation Cost Due to Sea Level Rise. Application to the Port of Tangier-Med (Morocco). *Appl. Geogr.* **2022**, *138*, 102623. [CrossRef]
100. Singh, S.J.; Huang, T.; Nagabhatla, N.; Schweizer, P.-J.; Eckelman, M.; Verschuur, J.; Soman, R. Socio-Metabolic Risk and Tipping Points on Islands. *Environ. Res. Lett.* **2022**, *17*, 065009. [CrossRef]
101. Sharifi, A. Co-Benefits and Synergies between Urban Climate Change Mitigation and Adaptation Measures: A Literature Review. *Sci. Total Environ.* **2021**, *750*, 141642. [CrossRef] [PubMed]
102. Le Roy, B.; Lemonsu, A.; Schoetter, R. A Statistical-Dynamical Downscaling Methodology for the Urban Heat Island Applied to the EURO-CORDEX Ensemble. *Clim. Dyn.* **2021**, *56*, 2487–2508. [CrossRef]
103. Asariotis, R.; Benamara, H.; Mohos, N.V. Port Industry Survey on Climate Change Impacts and Adaptation. UNCTAD/SER.RP/2017/18/Rev.1. Available online: https://unctad.org/system/files/official-document/ser-rp-2017d18_en.pdf (accessed on 18 January 2024).
104. PIANC. *Climate Change Costs to Ports and Waterways: Scoping the Business Case Assessment for Investment in Adaptation*; PTGCC Technical Note No. 2; PIANC: Brussels, Belgium, 2024.
105. Sweeney, B.; Becker, A. Considering Future Sea Level Change in Maritime Infrastructure Design: A Survey of US Engineers. *J. Waterw. Port. Coast. Ocean Eng.* **2020**, *146*, 04020019. [CrossRef]
106. Kalaidjian, E.; Robinson, S. Reviewing the Nature and Pitfalls of Multilateral Adaptation Finance for Small Island Developing States. *Clim. Risk Manag.* **2022**, *36*, 100432. [CrossRef]
107. Kontopyrakakis, K.E.; Velegrakis, A.F.; Monioudi, I.N.; Čulibrk, A. Prioritizing Environmental Policies in Greek Coastal Municipalities. *Anthr. Coasts* **2024**, *7*, 1. [CrossRef]
108. Polydoropoulou, A.; Bouhouras, E.; Papaioannou, G.; Karakikes, I. Living Labs for the Resilience of Ports against Climate Change Disruptions. *Ocean. Coast. Manag.* **2025**, *261*, 107528. [CrossRef]

109. Polydoropoulou, A.; Velegrakis, A.; Papaioannou, G.; Karakikes, I.; Bouhouras, E.; Thanopoulou, H.; Chatzistratis, D.; Monioudi, I.; Moschopoulos, K.; Chatzipavlis, A. A Composite Port Resilience Index Focused on Climate-Related Hazards: Results from Greek Ports' Living-Labs. *Marit. Transp. Res.* **2025**, *9*, 100136. [[CrossRef](#)]
110. Chatzistratis, D.; Velegrakis, A.F.; Chalazas, T.; Alves, B.; Schiavon, E.; Monioudi, I.N.; Armaroli, C. European Early Warning Systems for Coastal Floods: User Needs, System Availability and Pertinent Policy and Legislation. *Int. J. Disaster Risk Reduct.* **2025**, *126*, 105602. [[CrossRef](#)]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.