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Compound climate risks to European ports

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Supplementary material for this article is available online

Abstract

Ports are exposed to multiple climate hazards, including windstorms, floods, and intense rainfall. These hazards often occur simultaneously, thereby amplifying their overall effects. Here, we develop a compound risk assessment that incorporates the probabilities of the joint occurrence of climate hazards and their compound effects on port infrastructure systems. We evaluated the direct infrastructure damages, revenue losses due to disruptions, and operational downtime. Furthermore, we analysed the temporal dependence of climate hazards across multiple ports to understand how compound events trigger economic impacts at the continental scale, tracing the dependency structure from hazards to impacts. This methodology was applied to the European port system, where the results show the importance of considering compound effects when evaluating climate risks. Consideration of compound effects on a continental scale adds up to €360 million in additional direct damages (35% of the annual average direct damages) and €10 million due to loss of service (6% of annual average losses). Moreover, failure to account for the interactions between co-occurring impacts results in an underestimation of €100 million in expected annual losses across European ports.

1. Introduction

The economic importance of port facilities (Becker *et al* 2012) makes them critical nodes in logistics chains (Verschuur *et al* 2022), as well as for national economies (Asariotis *et al* 2017). However, the location of ports in coastal and riverine areas exposes them to climate and geophysical hazards (Duncan Mcintosh and Becker 2017). Ports, like other coastal infrastructures, are particularly prone to the interaction of multiple hazards over time (Izaguirre *et al* 2020, Verschuur *et al* 2020), so-called compound events, given that weather-related hazards (e.g., extreme wind and rainfall) are influenced by large-scale meteorological conditions (Wahl *et al* 2015). Compound events are defined as those in which damage and loss can be influenced by more than one hazard variable (Simpson *et al* 2021). This compounding nature of hazard variables was demonstrated in events like Hurricane Katrina in 2005, which involved extreme winds, storm surges (SSs), and heavy rainfall, causing 1.7 USD billion in physical damages and additional indirect losses due to port closures (Trepte and Rice 2014).

The location and complex nature of ports (encompassing numerous interdependent assets, structures, and services) make them particularly vulnerable to the interplay of such compound events, given the multiple disruptive pathways that can cause damage or affect operations (Fernandez-Perez *et al* 2024). In this regard, when assessing the effects of compound events at a single-port scale, an integrated analysis is required to evaluate (1) the severity and probability of occurrence of multiple hazards (Zscheischler *et al* 2018) and (2) how these compound events impact port systems, considering their multiple impact pathways (Verschuur *et al* 2022).

Regarding the former, Zscheischler *et al* (2020) differentiated four types of compound events: preconditioned (or sequential, Moftakhari and Aghakouchak (2019)), multivariate (or coincident, Bevacqua *et al* (2022)), temporally compounding (disasters driven by extreme events, Raymond *et al* (2020)) and spatial compounding (events causing impacts at multiple locations, Curtis *et al* (2021)). Comparing different approaches to evaluating compound events, Moftakhari *et al* (2019) concluded that simply adding impacts from single hazard assessments can lead to an underestimation of total impacts, as the combination of hazards leads to a non-linear risk increase. These temporal correlations are likely more pronounced when exploring compound events for coastal infrastructure, as several hazard drivers (winds, waves, sea level, etc) have strong temporal correlations (Hov *et al* 2013) due to the fact that they are usually modulated by the same weather phenomena (Donat *et al* 2010, Lucio *et al* 2020).

Over the years, diverse approaches have been developed to explore the effects of hazard interactions, most of which have focused on exploring the joint probability of occurrence and severity of extreme compound events. Several statistical methods have been proposed to capture the dependence structure of different climatic hazards (Nasr *et al* 2021), copula fitting (Couasnon *et al* 2018), response functions (Santos *et al* 2021), conditional dependence models (Heffernan and Tawn 2004) and joint return periods (Jalili Pirani and Najafi 2023). Some of these models examine the joint occurrence of various climate hazards, including coastal flooding (Bruun and Tawn 1998, Gouldby *et al* 2017), fluvial-pluvial flooding (Wahl *et al* 2015, Nasr *et al* 2021, Camus *et al* 2022) and windstorms and precipitation (Martius *et al* 2016, Owen *et al* 2021), among others. While some studies have examined the interaction of these compound events with human settlements and infrastructure (Moftakhari and Aghakouchak 2019, Lucio *et al* 2024), few have specifically examined how compounding hazards amplify the impact on critical infrastructure (Verschuur *et al* 2024). An analysis of the joint impacts of concomitant hazards and their interactions in compound events remains a significant research gap (de Ruiter *et al* 2020).

Ports are widely considered a critical interdependent infrastructure (Ouyang 2014). Various methodologies have been developed to incorporate this interdependency approach into infrastructure analysis, from single-layer assessments (Cradock-Henry *et al* 2020) to more complex multilayered frameworks (Thacker *et al* 2017, Pant *et al* 2020). However, the application of such approaches to coastal and port infrastructures remains limited. For instance, Brunner *et al* (2023) evaluated disruptions due to coastal hazards across urban infrastructure systems, Verschuur *et al* (2022) integrated a complex systems approach into port facilities, and Fernandez-Perez *et al* (2024) applied these concepts to port infrastructures but restricted their analysis to a local scale. Although these studies establish a foundation for integrating compound event analyses with interdependent infrastructure systems, they fall short of demonstrating the scalability of these methodologies across diverse compound events and on wider spatial scales.

In this study, we aim to bridge these research gaps by combining statistical analysis of multi-hazards with the evaluation of their combined effects on interdependent infrastructures within ports across Europe. We explore how simultaneous hazard interactions influence port operations and compare the outcomes of single-hazard analyses with those of compound hazard occurrences. To do so, we characterized the joint likelihood and intensity of extreme multi-hazard events, following Lucio *et al* (2024), including temperature, wind, waves, sea level, precipitation, and river discharge. Similar to Fernandez-Perez *et al* (2024), we assessed the impacts derived from these hazards, accounting for infrastructure damage and repair, loss of performance, and revenue losses due to operational downtime. Subsequently, we simulate failures of interdependent port assets and services based on the framework proposed by Verschuur *et al* (2022). Using this workflow, we can evaluate the non-linear effects of concomitant hazard interactions on interdependent infrastructures and compare these outcomes with those obtained from single-hazard, single-asset impact analyses.

2. Methodology

The present methodology is depicted in figure 1, which illustrates how the compound effects of multiple hazards intersect with port assets and their functions. This framework is used to translate direct damage into functional loss.

2.1. Compound hazard assessment

The climate hazards considered here were selected based on their significance in driving impacts on port infrastructure, as discussed by Asariotis *et al* (2017) and Brooke *et al* (2020): wind gusts, waves, river discharge, precipitation, extreme temperatures (daily maximum and minimum), and sea levels (as an interaction of waves, astronomical tides (ATs), and SSs). Table 1 summarizes the main climate hazards (by IPCC typologies) and their impact pathways on port assets (e.g., breakwater and equipment)

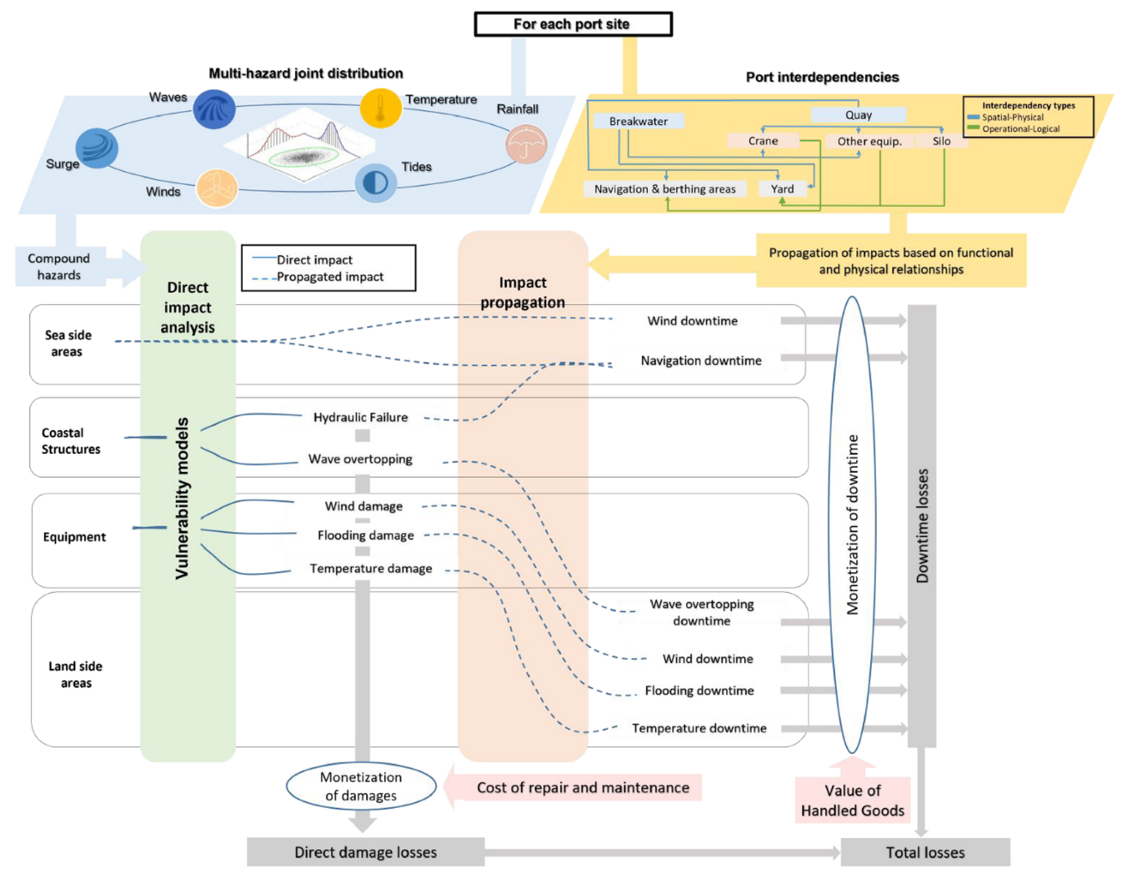

Figure 1. Integration of impact pathways with the interdependency analysis of port infrastructures for a compound risk analysis.

Table 1. Impact pathways considered in the analysis, from the hazard's typologies (IPCC 2022) to the impact modes and elements impacted.

Typology	Hazard	Variable	Impact modes		Elements impacted
Hydrological	Waves	Daily maximum significant wave height (Hs [m])	Hydraulic failure	Damage	Breakwater
			Impossibility to navigate	Downtime	Services
			Wave overtopping	Damage	Equipment
	Storm surge	Daily maximum sea level (SS + AT [m])		Downtime	Services
	Astronomical tide		Coastal flooding	Damage	Equipment
				Downtime	Services
	Precipitation	Daily mean precipitation (Pr [mm])	Precipitation flooding	Damage	Equipment
				Downtime	Services
	River discharge	Daily mean river discharge (q [m3 s^{-1}])	Riverine flooding	Damage	Equipment
				Downtime	Services
Meteorological	Wind	Daily peak wind gust (Vw [m/s])	Wind forces	Damage	Equipment
				Downtime	Services
	Temperature	Daily minimum temperature (Tmin [C])	Thermal stress	Damage	Equipment
		Daily maximum temperature (Tmax [C])		Downtime	Services

and services. Figure 2 presents the statistical distribution of the analysed climate variables across the different European climate regions (Peel *et al* 2007). Each boxplot displays the median, the interquartile range (lower and upper quartiles), and the minimum and maximum values of each variable. The

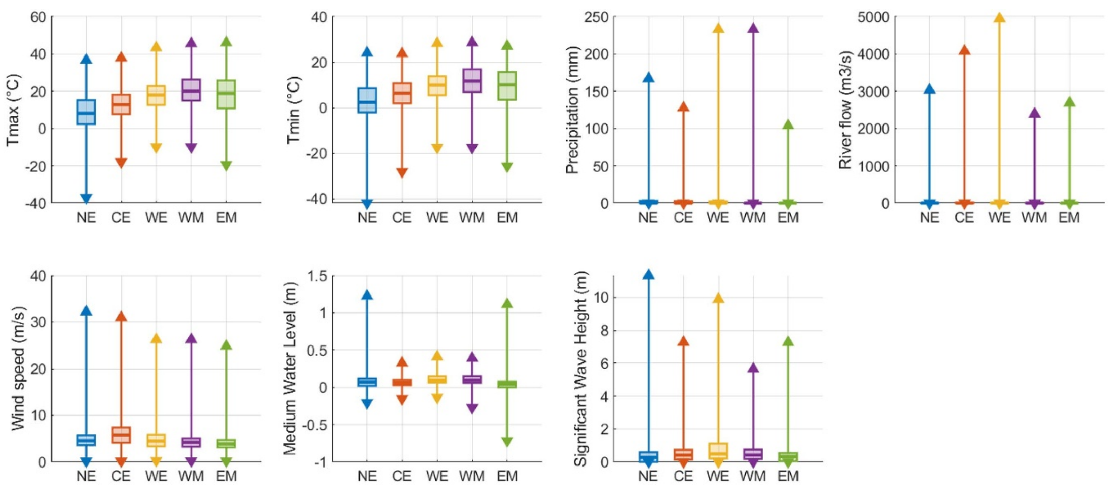

Figure 2. Boxplot of the main evaluated climatic variables for the different European regions, showing the mean, higher and lower quantile. Arrows show maximum and minimum values of each variable. (NE = North Europe & Baltic Sea [95 ports]. CE = Central Europe [126 ports], WE = Western Europe [71 ports], WM = Western Mediterranean [72 ports], EM = Eastern Mediterranean & Caspian Sea [68 ports]).

proposed methodology seeks to simulate the conditions that ports may experience over their lifespan, which include weather variability affecting day-to-day operations, along with extreme events (with longer recurrence intervals) that these infrastructures must withstand. Furthermore, incorporating extreme events into probabilistic analyses is an essential requirement for the design and verification of critical infrastructure such as ports (PIANC 2015; ROM 1.1). An exploration of the different time scales of the hazards driving impacts at port facilities, which range from year-to-year operational downtime to rare, highly damaging events, calls for a distinction between the types of events that pose risks to port facilities:

- Frequent events: Linked with the day-to-day operation of ports. They are driven by regular climate patterns and primarily cause operational downtimes.
- Episodic or extreme events, which are rare but severe. These result from extreme climatic conditions and can cause infrastructure damage and longer service delays.

Each event typology was evaluated according to its characteristic temporal scale. For the frequent events, time series were screened to evaluate the effects of current climate hazards on European port facilities. This is done based on historical reanalysis of the climate and met-ocean data, using the ERA5 dataset, which combines extensive observational data with numerical weather prediction models and provides high-resolution (31 km grid), globally consistent climate variables for the historical period. The selected variables have been modelled, calibrated, and validated at global and regional scales (Hersbach *et al* 2020), and include daily maximum and minimum temperature, daily maximum wind gust and daily cumulative precipitation (Lavers *et al* 2022), daily mean river discharge (Mazzetti *et al* 2023), wave parameters (Camus *et al* 2013), SSs (Yan *et al* 2020) and ATs (Cid *et al* 2014). Variables were extracted for each port for the years 1991–2019.

For extreme events, the analysis focused on extreme conditions associated with a range of return periods. To achieve this, multiple synthetic lifespans were simulated for each port, with each lifespan representing 50 years of extreme monthly events. In this framework, events are classified as extreme when they correspond to the monthly block maxima, irrespective of a predefined return period, thus capturing the most intense conditions within each temporal cluster. A multivariate extreme value distribution was fitted to the ERA5 data following the methodology of Lucio *et al* (2024). This approach captures the joint behaviour of multiple climate drivers (such as wave height, sea level, and wind) under extreme conditions. ERA5 has been shown to reliably represent both the variance and tail behaviour of climate variables on daily time-scales (Hersbach *et al* 2020). The procedure to obtain the climate hazards at port locations entails:

a. Data preparation and block maxima extraction: hourly ERA5 reanalysis data (Hersbach *et al* 2020) were pre-processed, and monthly block maxima were extracted for significant wave height (H_s), mean and peak wave periods (T_m, T_p), mean direction (Dir), SS, AT, 3-s wind gust (V_{gust}), precipitation (Pr), river discharge (Q), and air temperature (T_{min}, T_{max}).

b. Definition of compound event proxy: a monthly compound proxy (R) was defined as the normalized sum of the dominant hazards for each season (T_{min} for the winter months and T_{max} for the summer months):

$$R_k = \overline{TWL_k} + \overline{T}_k + \overline{V_{gust_k}} + \overline{Pr_k} + \overline{Q_k}$$

$\overline{TWL_k}$ is the total water level, which integrates the AT, SS and wave height (H_s).

c. Multivariate statistical modeling: marginal generalized extreme value distributions were fitted for each variable using monthly block maxima to capture intra-annual variability (Rueda *et al* 2016). Dependencies among variables were modelled with a multivariate copula based on Spearman's rank correlation, capturing non-linear and asymmetric relationships characteristic of compound extremes Zhang *et al* 2018, (Camus *et al* 2021).
d. Extreme compound events are simulated using a multi-hazard emulator (Lucio *et al* 2024), integrating wave, sea-level, atmospheric, and hydrological variables. This multivariate framework enables the generation of thousands of synthetic 50 year lifespans for each port, each simulated year containing 12 monthly extreme events. Astronomical tides were simulated independently using consistent seasonal cycles. For more information about the sampling technique and sensitivity analysis, see supplementary material (A).
e. Downscaling to port locations: the offshore synthetic events were propagated to individual ports using a hybrid approach, merging physical wave propagation with statistical techniques to obtain the hazards at port terminal locations. Wave propagation was computed using linear wave theory and GEBCO bathymetry, accounting for shoaling, refraction (Dean and Dalrymple 2001), and breaking (Goda 1975). For ports protected by breakwaters, wave attenuation and diffraction within harbour basins were modelled using Fresnel diffraction coefficients (McCormick and Kraemer 2002). Total water level (TWL) was combined with precipitation and river discharge to estimate flooding depth.
f. Compound flooding: Flood depths are derived by combining TWL, precipitation, and river discharge with high-resolution flood maps (≈30 m) for return periods between 20 and 1500 years. Flood levels for each event are interpolated from flood-frequency curves based on the return periods of q and Pr, obtaining the fluvial and pluvial flood depth $\{h_{fluvial}, h_{pluvial}\}$ and area $\{A_{fluvial}, A_{pluvial}\}$ for each event. Compound flooding is estimated by integrating the fluvial, pluvial, and coastal components to obtain the total flood depth $(h_{flood} = TWL + h_{fluvial}, +h_{pluvial})$ for each event. The compound return period is then derived by matching the resulting total flood depth (h_{flood}) with the flood-frequency curves provided by the high-resolution flood maps, thus identifying the equivalent return period associated with the combined flooding intensity and enabling the computation of the total area flooded (A_{flood}) based on those maps.

This integration of multi-variate copula modeling, non-stationary extremes, and physically based downscaling provides a consistent and spatially resolved representation of multi-hazard conditions at the port scale. More information about the sampling technique and sensitivity analysis can be found in supplementary material (A). The propagation procedure is further described in the supplementary material (B).

2.2. Exposure assessment

406 medium to large continental European ports were selected based on a global port database (Verschuur *et al* 2022). Port facilities are divided into the smallest units that are fully functional: port terminals (Verschuur *et al* 2022). Terminals encompass a specific port service, including all activities required to perform the service: the entrance of ships to the port, navigation to the mooring area, berthing, and transfer of cargo to the storage yard or land transport. The interconnected elements considered within each port boundary include coastal protection structures (e.g., breakwaters), berthing infrastructure (quays), terminal equipment (such as cranes, silos, and transport systems like straddle carriers), and operational areas (berths and storage yards). For each port, these assets and land-use zones are characterized using the geographic port database, which provides information on the location, dimensions, and elevation of the main structural components, equipment, and functional areas (protection and berthing). More information about the physical characterization and elevation of infrastructures can be found in supplementary material (C).

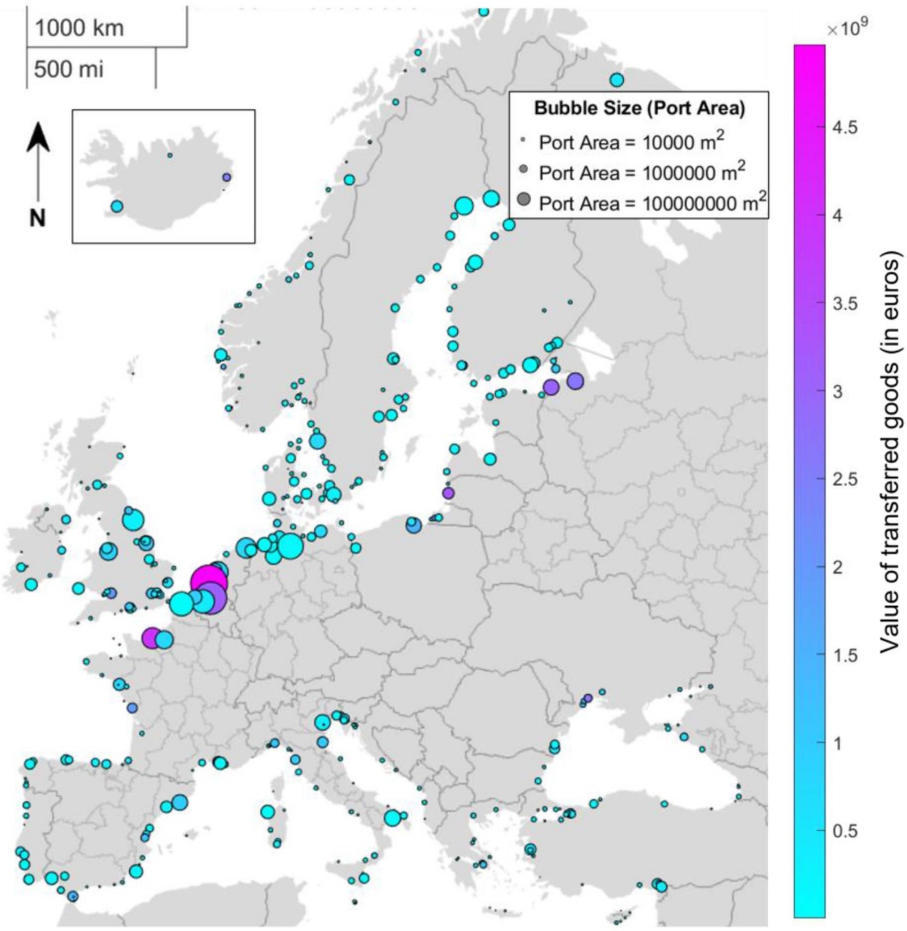

Figure 3. Spatial distribution of European ports according to their physical size and value of handled goods (VHG). Map Data Natural Earth.

To characterize the socio-economic exposure of European port infrastructures, each port was spatially disaggregated into functional land-use types following (Verschuur *et al* 2022). The type of cargo handled by each terminal was obtained from EUROSTAT (2023) and directly linked to the corresponding value of handled goods (*VHG*s). Terminals were classified by dominant cargo category (container, RoRo, liquid, dry bulk, or other), allowing consistent association between land-use, cargo throughput, and economic value. For terminals with incomplete data, cargo flows were estimated through Monte Carlo simulations based on correlations between terminal area and annual cargo volumes. Port structures and equipment were characterized by their repair and maintenance costs (Verschuur *et al* 2023). Supplementary material (D) describes the full valuation procedures for *VHG* and more detailed reconstruction costs.

The physical extent of the considered ports varies widely, from around 50 000 m^2 to 150 $\times$ 10^6 m^2, whereas the *VHG*s ranges from approximately €0.3 million to €5 billion. The spatial distribution of port size and *VHG* across Europe is presented in figure 3, where bubble size corresponds to port area and colour intensity reflects *VHG*.

2.3. Vulnerability assessment

Vulnerability assessment defines the set of relationships that translate hazard event severity into port infrastructure impact. These vulnerability models consist of damage curves and semi-empirical equations, many of which are derived from engineering design standards and technical manuals (e.g., PIANC and Eurocode). These sources provide established thresholds and functional relationships that allow the evaluation of the physical impacts of individual and concomitant climate hazards (Fernandez-Perez *et al* 2024).

We consider direct damage to port assets (e.g., extreme winds causing a crane to overturn and collapse, Zhang *et al* 2020, Abdelhafez *et al* 2021) and the disruption of services that result in port downtime. Downtime can occur due to adverse climate conditions that hinder normal operations (e.g., strong winds preventing crane lifting operations; Verschuur *et al* 2020) or from asset failures that halt service provision (e.g., the collapse of a crane causing operations reliant on that crane to stop; Gou and Lam 2019). The causes and economic consequences of each mode are quantified independently, and also considering their interdependencies. Damage impact modes are assessed by evaluating the level of damage (*LoD*) caused by a given hazard severity, which is directly linked to the repair and maintenance costs for each terminal. Downtime impact modes are analysed by determining the amount of time a terminal is unable to operate owing to weather conditions (caused by frequent events) or asset failures (caused by extreme events). Table 1 outlines the key impact modes, hazards triggering them, and affected assets and services, adapted from Izaguirre *et al* (2020).

Each port is characterized as a network of interconnected assets and services, with dependencies evaluated through an analysis of both physical and spatial proximity and functional contingencies (Thacker *et al* 2017). This means that assets and services that are spatially or operationally linked (as defined by Rinaldi 2004) can be significantly affected if one fails. For instance, a crane positioned behind a breakwater may be damaged if severe wave overtopping of the breakwater occurs (spatial-physical interdependency), disrupting its operation, and consequently, the services reliant on it (operational-logical interdependency). This dependency analysis provides insight into how the damage or failure of certain assets can cascade to affect others. Figure 1 (right) illustrates the general dependency structure within port facilities, which varies across terminals depending on the specific type of structure, equipment, and services involved.

Spatial interdependencies are identified by assessing the proximity of assets: terminals located within 50 m of a breakwater are considered connected to it (EurOtop 2018). For quays, a threshold of 500 m is applied, reflecting their broader but less protective effect against flooding and overtopping (Aerts *et al* 2018). The range of disruption, however, ultimately depends on local factors such as elevation, position, and flood extent computed from the return-period maps.

Operational interdependencies are assessed at the terminal level: when a key piece of equipment belongs to a specific terminal, its failure is assumed to compromise the operability of that terminal and associated services.

The impact of each climatic hazard was analysed individually, and its effects were modelled and propagated through the port's dependency graph, including compound effects. Further details regarding the impacts considered and their propagation mechanisms are provided in supplementary material (E).

2.3.1. Damage assessment

The repair and maintenance costs due to compound hazards are based on the evaluation of the affected port assets exposed to sampled hazard events. For each port, the direct consequences (*LoD*) of the events are derived on a yearly basis. For each terminal, it is assumed that infrastructure can operate despite partial damage, and only when the *LoD* reaches 100% is immediate repair required, as the terminal would no longer be able to function adequately (functional failure, PIANC 1995). In such cases, the port is considered non-operational until the necessary repairs are completed. Conversely, if the *LoD* does not reach the 100% threshold within the year, the associated repair costs are assigned to the annual maintenance program, and no operational downtime is assumed.

Integrating isolated impact models into a compound impact assessment requires a methodology that captures the interaction of impacts from concomitant hazards with the same asset. This means accounting for situations in which an asset simultaneously experiences damage from multiple hazards. Some researchers have developed numerically based fragility curves for coupled bivariate hazards (Korswagen *et al* 2019), while others have focused on analytically incorporating the effects of concomitant hazards into damage curves (Kappes *et al* 2010). In the present work, owing to the diversity of exposed elements and the presence of multiple climatic stressors, an analytical procedure to integrate a multi-hazard damage curve was developed, as depicted in equation (1) and further explained in supplementary material (F). Consideration of the interaction of concomitant hazards outputs a level of damage ($LoD \in [0,1]$) for each unit related to the occurrence of synthetic episodic events,

$$LoD_{\mathrm{tot}} = \max_{i=1}^{N} \left\{ f_i \left[\sum_{j=1}^{N} f_i^{-1} \left(f_j \left(h_j \right) \right) \right] \right\} \tag{1}$$

where h_j are the N concomitant hazards, are the corresponding damage functions (relating hazard and *LoD*). $f_i^{-1}\left(f_j\left(h_j\right)\right)$ represents the non-linear interaction of damage functions $f_j\left(h_j\right)$ and $f_i\left(h_i\right)$ under the assumption that hazard h_i occurs before hazard h_j. The damage evaluation explores all possible orders of occurrence of the hazards within the impact damage curves ($f_i[\sum_{j=1}^{N} f_i^{-1}\left(f_j\left(h_j\right)\right)]$) and selects the most limiting one (causing the maximum damage). We defined the effect of a certain impact interaction (LoD_{interact}) as the difference between the combination of impacts across different damage curves and their simple aggregation. By comparing the damage caused by the combined interaction of hazards across damage curves with the damage resulting from simply adding their individual effects, we analysed how interactions can amplify or modify the overall impact.

$$LoD_{\text{interact}} = \max_{i=1}^{N} \left\{ f_i \left[\sum_{j=1}^{N} f_i^{-1} \left(f_j \left(h_j \right) \right) \right] \right\} - \left(\sum_{j=1}^{N} f_j \left(h_j \right) \right). \quad (2)$$

2.3.2. Downtime assessment

The proposed model evaluates how operational services are affected by downtime (non-operability owing to halted working conditions) and non-functional periods owing to the time required for unplanned repairs. The first is related to the regular conditions stressing ports' operability, evaluated by comparing the hazard time-series with the operability thresholds and outputting the non-operability rate (*NOR*, or % of days in a year that the terminal cannot operate due to climate conditions) of the unit. It is assumed that when the climate conditions return to acceptable values, the operation is recovered without infrastructure damage. However, the occurrence of severe damage is assumed to cease operations until the damaged element is repaired. Then, when the *LoD* reaches 100% in any infrastructure unit, a downtime equivalent to the repair time is assumed to occur, which is evaluated through the non-availability rate (*NAR*, or % of days in a year that the terminal cannot operate because of the need for unplanned repairs) of the infrastructure.

The *LoD, NOR* and *NAR* are computed for each terminal and year over the entire lifespan of the port. Assuming equal probability of occurrence for any given year, the annual values of *LoD, NOR* and *NAR* define their probability density functions. Impacts were characterized as the expected values of all evaluated years ($E(LoD)$*,* $E(NOR)$ *and* $E(NAR)$). More information about the probabilistic framework to obtain the expected annual $E(LoD)$, $E(NOR)$ and $E(NAR)$ is found in the supplementary material (G).

2.4. Expected annual losses (EALs) analysis

To add damage- and downtime-related losses together within a single loss term, we introduce the expected annual losses (*EAL*), which are defined as the losses that would occur in any given year if damages and downtimes from all hazards were spread out equally over time. The economic consequences for the occurrence of extreme events (EAL_{dmg}, or *EAL*s due to damages) and frequent events (EAL_{dwt}, or *EAL*s due to downtimes) are computed for each port as

$$EAL_{\text{dwt}} = \sum_{\text{terminals}} \left[E(NOR)_i * VHG_i \right] \quad (3)$$

$$\text{EAL}_{\text{dmg}} = \sum_{\text{terminals}} \left[E(LoD)_i * C_i + E(NAR)_i * VHG_i \right] \quad (4)$$

$$\text{EAL} = \sum_{\text{terminals}} \left[E(LoD)_i * C_i + \left(E(NOR)_i + E(NAR)_i \right) * VHG_i \right] \quad (5)$$

where $E(LoD)_i$, $E(NOR)_i$ and $E(NAR)_i$ are the expected annual *LoD, NOR* and *NAR* obtained from the probability density functions of damages and downtimes. The level of damage is related to the reconstruction costs (C_i), and the non-operable (*NOR*) and non-available time (*NAR*) with the value of goods of the terminal (VHG_i), summed over all independent terminals within the port.

3. Results

3.1. From compound hazards to compound impacts

Figure 4 illustrates the Spearman rank correlation values that capture the dependence structure of extreme events between different pairs of climate variables. The results were classified by climate region (based on Peel *et al* (2007) European climatic regions) to explore the clustering of the correlations. Each violin plot depicts the distribution of correlation values across ports within a given region. Values close to ± 1 indicate strong positive or negative correlations, while values near zero indicate little to no correlation.

There are strong correlations between precipitation and river flow, particularly in Western Europe and the Western Mediterranean ($\rho > 0.7$), with smaller catchments driving this relationship. Waves and

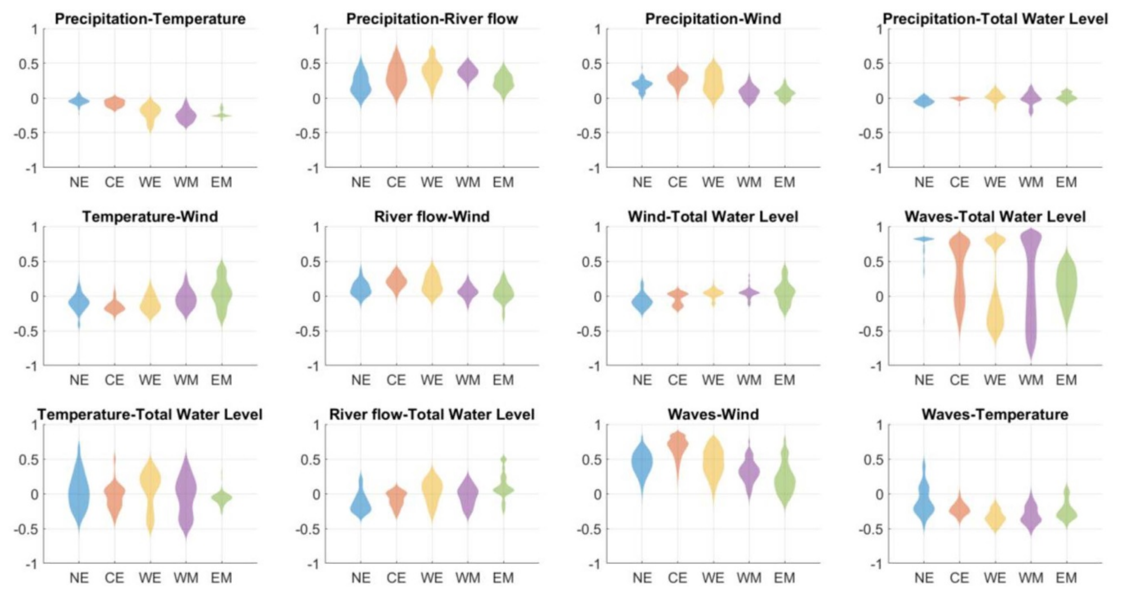

Figure 4. Distribution of Spearman's correlation 'rho' for each combination of hazard variables for the different climate European regions (NE= North Europe & Baltic Sea [95 ports]. CE = Central Europe [126 ports], WE = Western Europe [71 ports], WM = Western Mediterranean [72 ports], EM = Eastern Mediterranean & Caspian Sea [68 ports]).

wind also show a high correlation, especially in sea-wave regions such as Central Europe ($\rho > 0.7$), which is consistent with previous studies (Camus *et al* 2014, Nasr et al 2021). Waves and sea level showed notable correlations, although with a greater local variability. Medium correlations ($\rho \sim 0.5$) were observed between temperature, precipitation, *TWL*, and wind gusts. Temperature tended to be inversely correlated with the others, reflecting the occurrence of simultaneous low temperatures, heavy rainfall, extreme wind speeds, and SSs during winter storms. These correlations are more pronounced in Central and Western Europe, which are more frequently affected by storm events.

Figure 5 further explores the spatial distribution of predominant hazards and impacts. For hazard typologies, predominance is defined as the hazard contributing more than 50% to the hazard proxy (*R*□). For impact typologies, predominance is defined as the impact source contributing more than 50% of the total *LoD* for extreme events, or more than 50% of the annual *NOR* for frequent events. Figure 5(a) focuses on frequent events (exploring, for each variable, the 90th percentile on the ERA5 time series), while figure 5(b) examines extreme events (in this case, extreme events with a 250-year return period). In terms of hazards (outer circles), temperature (high temperatures in the south and low temperatures in the north) and sea level (mainly driven by SS and wave energy) dominate in the occurrence of frequent events. For extreme events, there is more heterogeneity, with similar spatial patterns in terms of temperature and sea level extremes. In both cases, the importance of compound hazards (where multiple hazards occur simultaneously) is highlighted by the predominance of outer green circles, and this predominance increases with the extremity of the events (higher in the right panel, which shows the extreme events). Regarding impact modes, for downtime modes (inner circles of figure 5(a)), compound effects are less pronounced than compound hazard occurrence (273 ports are predominantly affected by compound hazards, whereas only 1 port experiences compound impacts as the dominant effect), as the predominance of green colours for the inner circles is lower than for the outer circles. Here, modes driven by single hazards dominate: temperature downtimes are most significant for Baltic (cold temperatures) and Mediterranean ports (hot temperatures), wind-related downtimes for central European ports, navigation downtimes to West Atlantic ports, while downtime due to flooding appears more sporadically.

In contrast, the damage impact modes (inner circles in figure 5(b)) are more influenced by compound impacts and flooding, with overtopping being particularly prominent in the central Mediterranean regions. These impact modes are usually related to the simultaneous occurrence of wind, wave, and precipitation/river discharge variables; therefore, the dependence structure of these hazards (figure 4) is consistent with the results. These findings show that while compound hazards (green outer circles) occur frequently (295 ports are predominantly affected by compound hazards), the resulting damage (green inner circles) is less common (159 ports experience compound impacts as the dominant effect). This difference may be due to the strict design requirements of the critical infrastructure, which help mitigate the effects of mild impacts. Generally, ports are only significantly impacted by

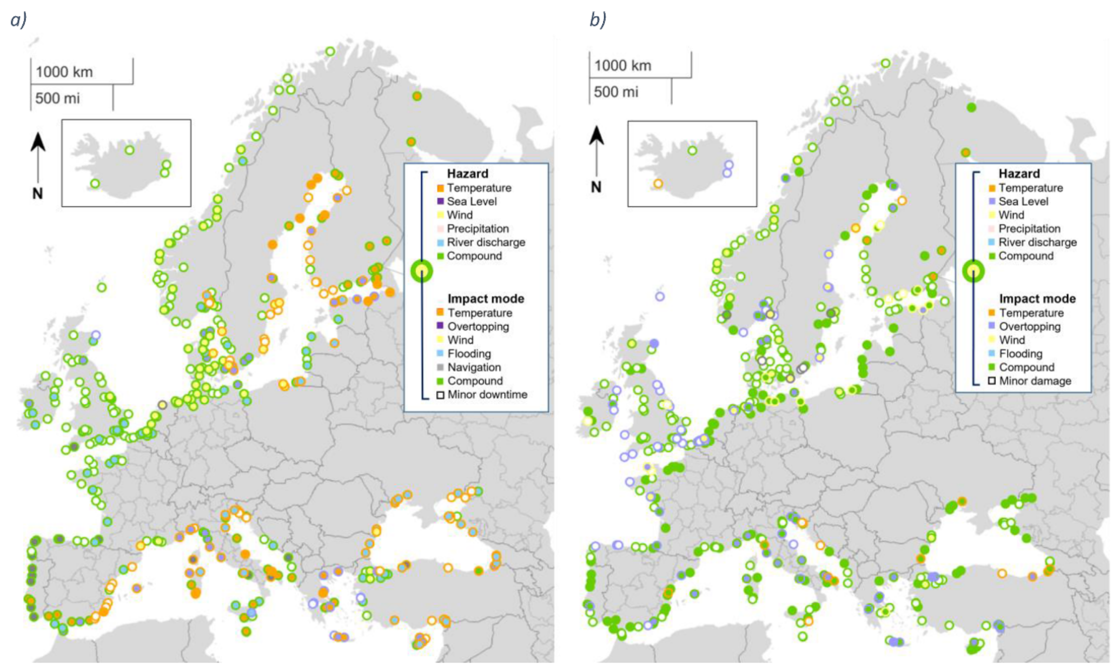

Figure 5. (a) Spatial distribution of the predominant hazards (outer colour of the marker) and impact modes (inner colour of the marker) for frequent events. (b) Spatial distribution of the predominant hazards (outer colour of the marker) and impact modes (inner colour of the marker) for extreme events. Map Data Natural Earth.

highly intense hazards. As a result, during a compound event involving multiple extreme variables, it is often the only severe variable that directly causes the impact mode rather than the compound impact. However, it is observed that the compound impact gains prominence during more extreme events (more green inner circles in figure 5(b) than in figure 5(a)), where the simultaneous effects of multiple high-intensity hazards are more likely to result in significant damage and disruption.

3.2. The expected losses due to compound events

Figure 6 presents the distribution of the *EAL* associated with downtimes (Panel a) and damage (Panel b). For downtime losses (figure 6(a)), most ports exhibit relatively low values (minor risk is defined as losses below €100 000 per year on average). Among ports with significant downtime risk, the losses are geographically concentrated: West Atlantic ports are predominantly affected by navigation downtime (high waves), Central European ports face risk primarily from wind-related downtime, and Baltic ports are vulnerable to overtopping and temperature-related downtime. The lower section of the panel illustrates the distribution of risk sources contributing to operational *EAL* from downtime (EAL_{dwt}) across all European ports. Notably, navigation-related downtimes account for nearly 70% of the EAL_{dwt}, amounting to approximately €110 million/year (M). This indicates that while navigation downtime may not dominate the risk profiles at every port, it is a significant risk factor across the continent. In terms of compound events, their contribution reached nearly €10 M/year, representing approximately 5% of the total EAL_{dwt}.

Figure 6(b) depicts the *EAL* due to damage (EAL_{dmg}), with flooding and temperature-related damage predominating, particularly in ports located in southern Europe. The lower section illustrates the distribution of EAL_{dmg} across European ports, highlighting that while riverine flooding remains the predominant risk source for many ports (causing damages worth €300 million per year on average), compound events contribute to damages across most ports, representing the largest share of the *EAL* for European ports and comprising over one-third of the annual expected damage (€350 M/year). Importantly, the effects of the interaction of compound events contribute approximately €100 M/year to the annual repair costs, a significant value often overlooked in hazard risk assessments, where hazards are typically evaluated independently. Comparing EAL_{dwt} with EAL_{dmg} (bar charts at the bottom of figures 6(a) and (b)), the cost of damage was higher for most European ports. The total *EAL* for the European port system sums up to €1.05 billion (B) per year, being €160 M/year due to operational downtime and €890 M/year due to damages.

Figure 6(c) highlights the proportion of EAL_{dwt} caused by each type of compound event for the 20 ports with the highest losses owing to downtime from compound events. The EAL_{dwt} due to compound

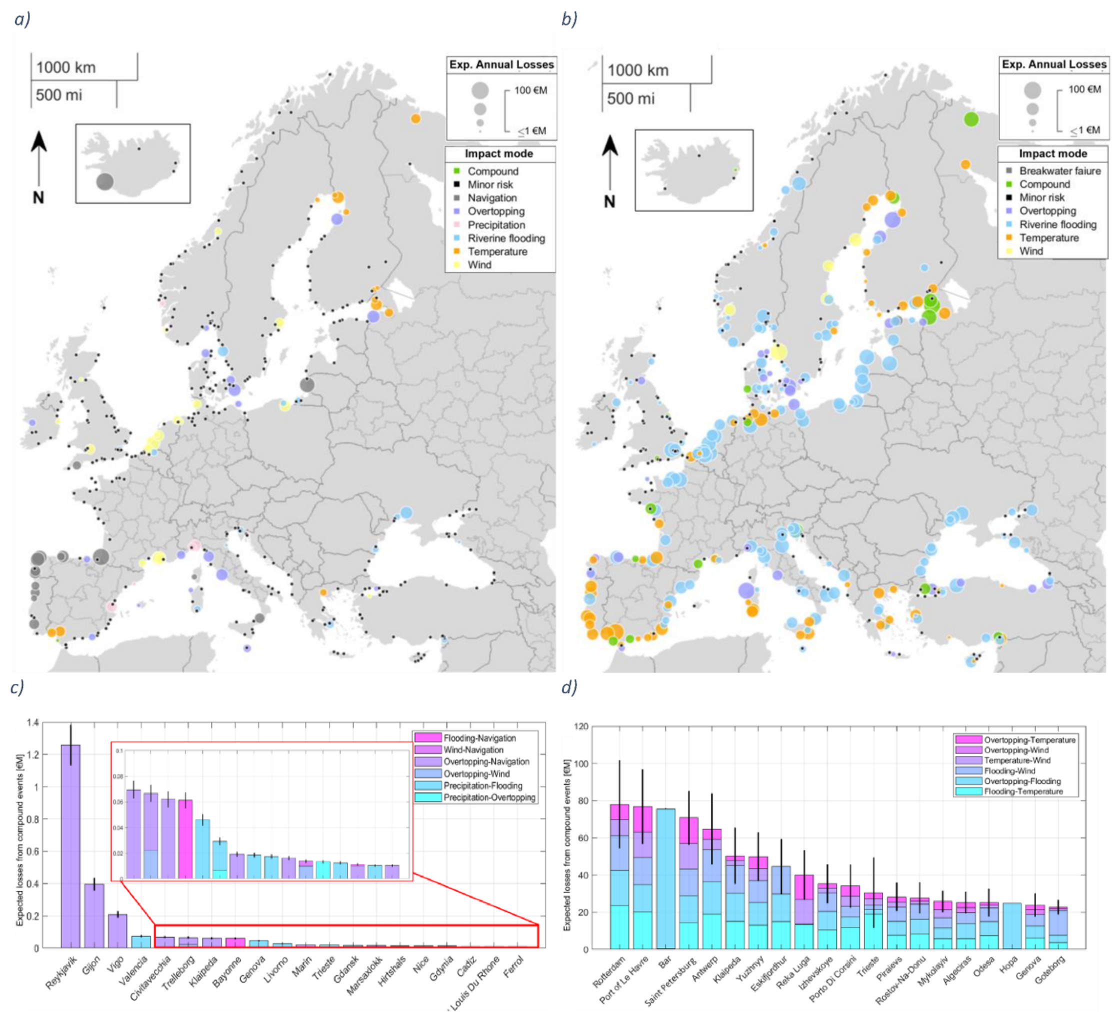

Figure 6. (a) and (b) Spatial distribution of impact modes (colour code) and EAL (marker size) due to downtimes and due to damages. (c) and (d) Compound risk profiles (by impact mode combination) for the ports with highest EAL due to compound events. 90% confidence intervals as black lines. Map Data Natural Earth.

events for these ports is below €0.5/year, except for Reykjavik (the European port with the highest loss of service due to compound events), where it reaches almost €1.5 M/year. Significant variability was found among these ports, with navigation downtime combined with overtopping, which was the most prominent contributor, followed by precipitation and flooding. Overall, navigation downtime remains the primary driver of compound downtime risk, frequently appearing alongside other impact modes in ports with elevated EAL_{dwt} due to compound events.

Figure 6(d) further explores the distribution of EAL_{dmg} due to compound events for the ports most affected by those interactions. The annual expected losses due to compound damages for those ports exceed €600 M/year for Rotterdam, Le Havre, Bar, Saint-Petersburg and Antwerp. Unlike the variability observed in downtime-related risk, damage-related losses exhibit greater homogeneity. Most ports share similar proportions of loss stemming from combinations of overtopping and temperature, temperature and wind, and temperature and flooding. This highlights the key role of extreme temperatures, not only as a direct contributor to annual expected damages (as highlighted by the red markers in figure 6(c)) but also as a major amplifier of total damages during compound events. Table 3 highlights the main compound impact figures for the European port system, showing variations by event extremity (different return periods and *EAL*s) and the relative contribution of each hazard combination in the compound effect.

We analysed how expected losses from damages vary with the extremity of events to assess the evolution of compound effects for more intense extremes. In figure 7(a), we examine the relationship between the expected losses for each event and the probability of exceedance for each damage level. This figure also illustrates how different impact modes contribute to losses across extreme events with increasing

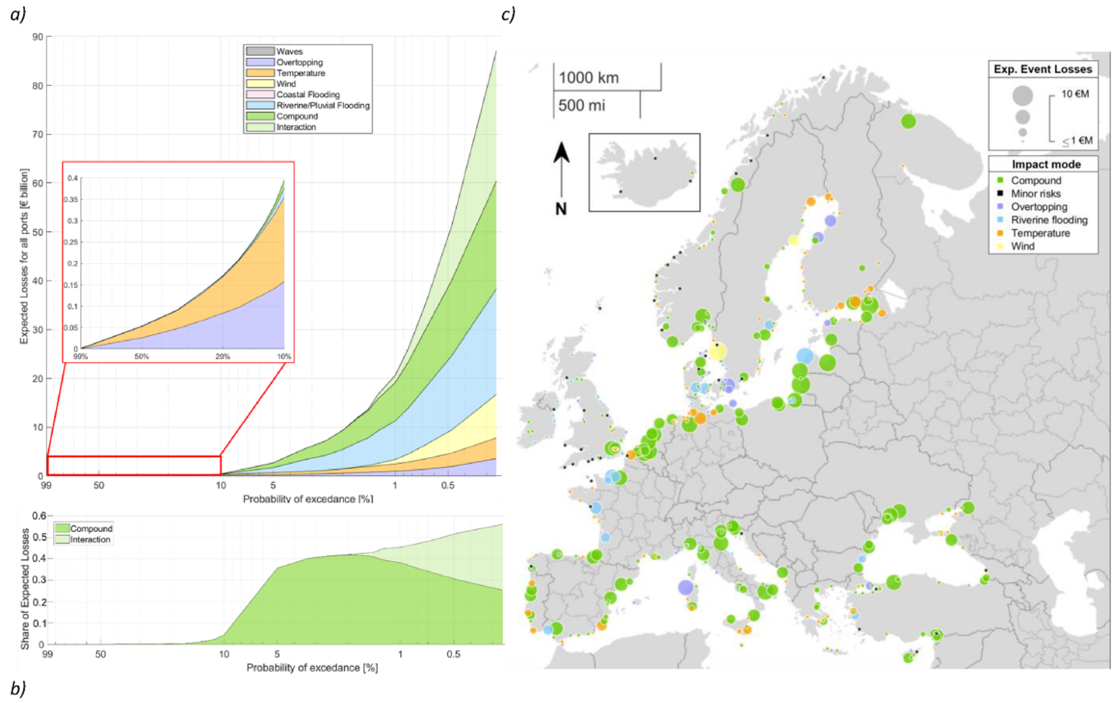

Figure 7. (a) Variation of the total expected losses by increasing intensity of the extreme events (probability of exceedance of the damage level of the event) and share (colour code) of each impact mode in the total losses. (b) Variation of the share of the total losses due to compound events for each event. (c) Spatial distribution of impact modes (colour code) and expected losses (marker size) caused by an extreme event with a damage level with a probability of exceedance of 1%. Map Data Natural Earth.

damage levels. For lower damage events (high probability of exceedance), overtopping and temperature-induced damage dominate, whereas for more extreme events (low probability of exceedance), flooding, wind, and particularly compound effects become the primary contributors to losses, The total losses for the most extreme events (with exceedance probabilities below 0.5%) reach approximately €50 billion, with compound hazards and impact interactions accounting for nearly half of that amount. Figure 7(b) shows how compound effects and impact interactions influence total damage. Interactions between different impact modes (losses computed from LoD_{interact}) can amplify the total asset damage by 15% (€10 B) for the most extreme events ($E_{0.5\%}$). These findings emphasize the escalating impact of compound hazards as event extremity increases.

To evaluate the spatial distribution of losses and the main impact modes for extreme events, figure 7(c) shows the expected losses for an event with a damage level that has a 1% probability of exceedance ($E_{1\%}$). The marker size represents the magnitude of the losses, whereas the marker colour indicates the predominant damage source for each port. The results reveal a greater predominance of compound impacts compared with milder events (figures 6(a) and (b)), reinforcing earlier results: the more extreme the event, the more significant the influence of compound effects. The figure shows that for a large share of European ports (79 out of 406), the expected losses (for the $E_{1\%}$) exceed €100 M per port, with losses surpassing €1 B in 10 of the ports. These ports are primarily located in Central Europe and the Baltic Sea, where their large size and high volume of operations contribute to large losses.

4. Discussion

We conducted a baseline analysis on how historical climate conditions have stressed the European port system, tracing the concomitant occurrence of climatic hazards and the economic losses associated with damage to port assets and operational losses due to downtime. The characteristics of damages and downtimes depend not only on the hazard intensity and recurrence but also on the exposed assets and the physical and operational features that drive infrastructure vulnerability. Identifying these port-specific risk profiles, as done in this study, can help inform actions to reduce climate-related impacts by (1) avoiding exhaustive locally focused analysis and (2) analysing possible adaptation solutions while considering the main causes and consequences of climate risks, including compounding effects.

Our analysis demonstrates the critical importance of accounting for compound effects when designing or adapting critical infrastructure. In some ports, compound events can contribute 25%–30% of the total *EAL*. Moreover, neglecting the interaction of multiple impact modes within a single asset may result in a 15% underestimation of *EAL* across the European port system. This discrepancy becomes even more pronounced, rising to over 50% of total losses attributed to compound events for the most extreme events (with a probability of exceedance below 0.5%), which are critical considerations in infrastructure design. Table 2 highlights the main loss figures for the European port system, showing variations by event extremity (different return periods and *EAL*s) and the relative contribution of each hazard source.

One of the main findings of this study is that the more extreme a hazard event, the greater the significance of compound effects on port infrastructure. Comparisons with previous research are limited, as few studies evaluate the impacts of compound events on critical infrastructure. Ganguli and Merz (2019) and Latif and Simonovic (2023) investigate the non-linear interactions of multiple hazards in coastal environments, showing how combinations of waves, precipitation, and extreme water levels can intensify flooding, increasing the impacts for the most extreme events. However, the extension from compound hazards to compound impacts on ports remains largely unexplored (Simpson *et al* 2021, Verschuur *et al* 2024). This study aims to partially address this knowledge gap.

Our assessment may serve as a foundation for future exploration of how climate change can affect the intensity and recurrence of compound hazards. Shifts in both the frequency and severity of hazard extremes, as well as their dependency structures, interact with the exposed assets and operational limits, resulting in a different distribution of damages and disruptions along the European port system. Given the scarce but growing evidence that the future distribution of compound events is different from that today (Bevacqua *et al* 2022), compound climate risk evaluation should be integrated into port climate change risk assessments (Sergent *et al* 2014).

Our work has a number of inherent limitations, starting with the omission of ports' dependence on other infrastructure sectors: rail and road networks in the hinterland of ports are not considered, nor are power and telecommunication networks. Future studies should examine how disruptions affect clusters of ports in the same region (i.e. spatial compounds as explored by Velpuri *et al* 2023) and how they can generate ripple effects on the wider logistic chain in which a port is embedded (Verschuur *et al* 2022).

Another important limitation lies in the scale of the analysis, which constrains the use of detailed, physically based models for hazard propagation and structural response. This structural response was approximated using a simplified non-linear analytical function (equation (1)). While this provides a first-order estimation of damage, it does not capture the full complexity of the compound impacts. In future work, empirically derived multi-hazard impact response functions (or multivariate vulnerability curves) should be developed and applied at finer spatial scales to improve the accuracy of compound risk assessments of infrastructure.

While our analysis does not explicitly model the temporal dynamics of disruption or the uncertainty associated with recovery processes, it nevertheless provides a robust first-order approximation of potential impacts. Future work incorporating time-dependent recovery pathways would further enhance the precision and applicability of our estimates; however, the current approach remains valuable for identifying priority areas of risk and guiding initial adaptation strategies.

Finally, this study lacks formal validation. Ideally, the validation process should involve two components. First, we compared the estimated expected annual damages and actual reconstruction and repair costs from the past five to ten years for the evaluated ports. To the best of the authors' knowledge, no open database provides such data at a pan-European scale. Second, validating service loss would require correlating the reanalysis climate variables with fluctuations in maritime trade volume. However, because trade variability is influenced by multiple factors beyond climate, this validation approach presents significant uncertainties regarding its reliability and applicability.

Despite these limitations, confidence in the results arises from several factors. The methodology is built on well-established and peer-reviewed approaches for multivariate extreme value modeling, copula-based sampling, and downscaling of climate hazards (Camus *et al* 2016, Lucio *et al* 2024), previously validated at local and regional scales. The hazard-to-impact and asset interdependency models rely on empirical damage curves, semi-empirical equations, and operational thresholds widely used in port engineering (Verschuur *et al* 2024). A sensitivity analysis on representative ports with varying characteristics confirmed that the number of synthetic lifespans provides stable estimates of compound hazard impacts.

Altogether, although formal validation remains a limitation, it also represents a broader challenge in the study of critical infrastructures, particularly within the port sector. Existing validation studies typically rely on expert interviews or case-specific assessments (Duncan Mcintosh and Becker 2017), and a clear direction for future research would be to integrate validation frameworks based on observed trade disruptions and repair expenditures across ports affected by recorded extreme events (Verschuur *et al* 2020). However, the absence of centralized data collection and the predominance of private sector

Table 2. Climate derived expected loses and damages for the European port system (annual and derived from the most extreme events) distributed by hazard source.

	Total	River Flooding	Coastal Flooding	Temperature	Overtopping	Wind	Navigation	Compound	Interaction
$EAL_{\mathbf{dwt}}$ (M €)	98.3	12.5 (12.7%)	0.01 (0.01%)	3.4 (3.5%)	8.4 (8.6%)	21 (21.4%)	45 (47%)	7.8 (8%)	—
$EAL_{\mathbf{dmg}}$ (M €)	1000	273 (27.3%)	0.7 (0.7%)	123 (12.3%)	94 (9.4%)	42 (4.2%)	3.3 (0.3%)	366 (36.6%)	105 (10%)
$Dmg_{1\%}$ (B €)	21	7.9 (37.6%)	0.001 (0%)	1.5 (7%)	0.95 (4.5%)	0.9 (4.3%)	0.03 (0%)	9.8 (46%)	1.9 (9%)
$Dmg_{0.1\%}$ (B €)	88.3	21.7 (24.6%)	0.002 (0%)	4.2 (4.8%)	3.5 (4%)	8.8 (10%)	0.04 (0%)	40.1 (46%)	28 (32%)

Table 3. Compound hazard derive expected loses and damages for the European port system (expected annual values) distributed by hazard combination.

	Total	Flooding Navigation	Flooding Temperature	Flooding Wind	Wind Navigation	Overtopping Navigation	Overtopping Wind	Overtopping Temperature	Overtopping Flooding	Temperature Wind
EAL (M €)	7.8	0.24	0.3	0.55	0.27	2.2	0.16	0.43	0.28	0.35
EAD (M €)	366	—	84	81	—	—	43	44	84	21

involvement in port operations mean that impact and recovery data are rarely made public, significantly constraining (or in many cases, preventing) validation efforts.

5. Conclusions

The great variety of climate drivers that threaten port infrastructure and operations highlights the need for risk assessment methodologies that account for compound events. In this study, we evaluate the compound risk profiles at ports to identify the dominant risk drivers. This is particularly important for infrastructure systems, such as ports, where interdependency between their assets can create unexpected interactions with compound hazards. Our analysis mapped the distribution of compound events considering the correlation between climate hazards, including temperature, winds, sea level, waves, precipitation, and river discharge. It further evaluates how port assets and operations are affected under diverse, extreme, and regular conditions. Our results highlight a medium to high correlation of hazard variables driving winter storms (low temperature, precipitation, winds, and waves), a medium correlation between sea levels and waves, and a medium correlation between river discharge and precipitation.

We further evaluated the interaction of these hazards with exposed assets and services, accounting for their physical and functional interdependencies. Extending the analysis from hazards to impacts revealed that the relationship between different hazards changes depending on the severity of the event. As events become more extreme, compound effects tend to play a larger role, accounting for an increasing share of damage and downtime. It has also been shown that compound events affect ports all over Europe, causing more than one-third of *EAL* due to damage. The most correlated damage modes are overtopping, flooding, and temperature damage, whereas navigation downtimes are usually correlated with overtopping and wind-derived downtimes.

The effects of different climate events were assessed at the European scale using a probabilistic approach to characterize the spatial distribution of damage and expected losses. For low-intensity events, the main drivers of damage are flooding in central Europe and overtopping and high temperatures in southern Europe. In these cases, compound effects account for approximately 30% of the total *EAL*s, with 10% of the total losses attributable to interactions between the impacts.

For more extreme events, compound effects become dominant, accounting for over 50% of the total losses, followed by flood-related damages at approximately 20%. Neglecting multiple impact interactions could lead to an underestimation of losses by up to 15% for the most severe events. These findings highlight the critical importance of considering compound effects in infrastructure risk assessment and design.

Altogether, our analysis provides the basis for resilience and adaptation strategies for ports and other critical coastal infrastructures, in particular, to better prepare for compound hazard events that are undervalued in traditional risk methodologies. When considering the adaptation of port facilities to extreme events—an essential element of climate change adaptation policies—a multiscale perspective is crucial. This approach ensures that financial resources are allocated effectively both spatially and temporally.

Data availability statement

The data that support the findings of this study are openly available in the supplementary files of this article.

Supplementary Information available at http://doi.org/10.1088/2752-5295/ae26bc/data1.

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