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Compound climate change risk analysis for port infrastructures

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ABSTRACT

Ports serve as essential nodes for coastal and maritime transportation and are key sources of income and economic activity in coastal zones. This significance, combined with their location in coastal areas, which are prone to climate-driven impacts, makes them highly susceptible to climate change effects. In this work, a climate change risk assessment methodology for port infrastructures that is focused on compound events analysis is presented. This approach is based on a spatial high-resolution probabilistic framework that enables the evaluation of port performance evolution under the effects of climate change. This assessment draws from a multimodel characterization of the evolution of several climate drivers for different emission scenarios and time horizons. It accounts for multiple port infrastructure risks and considers the compound effects of climate drivers and the interdependencies of infrastructures as complex systems. Performance indicators are developed for the physical assets and services at port locations on a highly granular scale, thus allowing port managers and planners to allocate reserves and develop adaptation plans that reduce climate change risks in the operations of maritime transportation nodes based on port performance forecasts. The methodology is implemented in two case studies set in the northern coast of Spain, demonstrating its applicability and replicability among several locations and scales.

1. Introduction

Climatic drivers, such as sea level rise (SLR), storm surges, waves and extreme winds, can severely affect coastal transportation (Asariotis et al., 2017). Extreme events, as enhanced by climate change (Hov et al., 2013) and the compound effects of climate drivers, can cause severe damage to coastal critical infrastructures (Vousdoukas et al., 2020). Moreover, port services are even more sensitive to climatic stressors than physical assets (UNECE, 2013). Consequently, to minimize the effects of climate change (CC) on the regular operation of critical nodal infrastructures such as ports, several national (Lawrence et al., 2018) and international (Brooke et al., 2020) coastal transportation organizations are now requiring the integration of CC risk assessments of coastal and port infrastructures into their planning strategies (Ramm et al., 2018) at different spatial scales.

Therefore, the application of risk assessment frameworks is needed to evaluate the performance of both port services and assets under the effects of diverse uncertainly changing climatic drivers. Several approaches for considering CC-induced risks and impacts on coastal structures (Raby et al., 2019; Suh et al., 2013), harbor basins (Camus et al., 2019) and berthing and storage areas (Jebbad et al., 2022) have been recently developed. Most authors aim to model the effects of CCs on coastal infrastructures, even considering the derived uncertainties through probabilistic approaches (Galiatsatou et al., 2018). Nevertheless, these researchers only evaluate the performance of individual components in a wider, more complex system and fail to account for compound and cascading risks, which is a vital consideration for coherently evaluating the consequences of climate change on critical infrastructures such as ports. Several authors have demonstrated the importance of considering compound effects when assessing extreme events (Zscheischler et al., 2018) and accounting for cascading effects between infrastructures that are thus derived (Verschuur et al., 2022). However, to date, a CC risk assessment that treats ports as complex systems has not yet been performed, thus the relationships and interactions between their structures, components and activities remain overlooked (Shadabfar et al., 2022). Overcoming this important limitation requires increasing the granularity of risk assessments focused on individual ports to evaluate their individual performance while not only considering the yield of individual components (structures, equipment, activities, etc.) but also assessing the influence they exert on one another.

Additionally, a number of uncertainty sources, which together form

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the so-called cascade of uncertainty (Robert L. Wilby and Suraje Dessai, 2010), constrain climate risk assessments at coastal locations (Toimil et al., 2020). First, when dealing with greenhouse gas (GHG) emission scenarios (van Vuuren et al., 2011) and climate projections (Morim et al., 2019), several representative concentration pathways (RCPs) and global and regional climate models (GCMs/RCMs) are independently considered. The integration of these models into a probabilistic approach enables the reduction of uncertainty effects across the decision space (Beh et al., 2015). Second, uncertainties in the characterization of regional forcing and downscaling processes can be analogously reduced by considering the probabilistic evolution of the sea level rise (SLR) over time, accounting for nonlinear wave-sea level nearshore interactions (Lucio et al., 2024). Finally, incorporating stochastic approaches in the modeling of impacts on infrastructure components (Lara et al., 2019) and coupling them with multiple climate methodologies (Lucio et al., 2020) contributes to capturing the nonlinear and joint effects of climate drivers that affect port infrastructures, reflecting the variability in the infrastructure system's performance under compound climate drivers.

Consistent with the above discussion, in the present work, port structures, equipment and services (1) are analyzed at high spatial resolution, (2) CC-induced risks are projected to future time horizons, (3) compound effects of diverse climatic drivers on their integrity and performance are considered, (4) the infrastructure component dependencies are evaluated as a unified system, (5) probabilistic impact assessment methodologies are applied, and (6) methods that consider not only the effects on infrastructures but also the ways that harbor uses and services become interrupted are used.

The remainder of this paper is organized as follows: Section 2 describes the proposed methodology for assessing the CC risk of port infrastructure that is implemented in two study cases on the north coast of Spain, which is described in Section 3. In Section 4, further approaches to implement the presented methodology in adaptation plans are analyzed. Finally, concluding remarks are offered in Section 5.

2. Methodology

In this work, climate change-induced compound risks to port infrastructures are analyzed following the application of a probabilistic approach, aimed at understanding the uncertainties in the relevant decision-making processes. The approach is formulated in a port-specific risk framework that has been developed to evaluate the local impacts induced by changes in climate-related drivers under different time horizons and emission scenarios.

2.1. Defining the risk assessment framework

2.1.1. Port infrastructures as complex systems

As a general matter, conducting a critical infrastructure risk evaluation is a necessary preliminary step in assessing the possible disruptions to the socioeconomic systems in which they are embedded. Thus, expanding the scope of the study to include the socioeconomic sphere reveals the criticality of the risk-type infrastructures to be assessed and determines the acceptable levels of risk. For instance, significant hazards that have been evaluated in regard to the infrastructure used to defend industrial activities may not be considered crucial when evaluating the infrastructure protecting tourist coastal areas, and their consequences should not be treated equally. Thus, beyond the use of technical evaluation criteria, risk level assessments should also account for the social, cultural, economic, administrative and environmental effects of the evaluated infrastructure.

For that matter, infrastructures and their elements should not be treated as isolated features but rather as part of complex systems (Kröger, 2008) whose interactions can unravel compound (Bevacqua et al., 2021) and cascading (Zorn et al., 2020) nonlinear effects. Thus, each of the infrastructure components (i.e., breakwaters, cranes, etc.) should be treated as elements of a subsystem (i.e., port terminal) that is

embedded in the infrastructure system as a whole (Thacker et al., 2017). Each subsystem, composed of a number of interdependent elements, has the capacity to homogenously provide one or a number of given services (i.e., industrial, fishing or recreational), even if an adjacent subsystem is non-operative (an independent subsystem); however, the consequences of their disruptions may be propagated throughout the entire infrastructure system (through logistic chains), with consequential effects on the socioeconomic system in particular. Altogether, impacts assessment shall account for the relationships across subsystems and infrastructure systems, coherently spreading the consequences of the evaluated impacts across the entire scheme.

2.1.2. Infrastructure element-scale risk assessment

Infrastructure analysis traditionally includes risk assessment when defining the safety factors that need to be considered during the design phase (CEN, 2002) via the allowable stress design (ASD) and the limit resistance factor design (LRFD) equations (AISC, 1994). The combination of probabilistic-based analysis with ASD approaches results in the limit state design (Burcharth, 1993). Specifically, port and coastal infrastructure design standards (e.g. (PIANC, 2016; ROM 1.0-09, 2009),) follow a limit state analysis approach through the consideration of verification procedures during several project phases (including the design, construction and operation phases). Accordingly, port project standards define the Ultimate Limit State (ULS), which determines the reliability of structural components), the serviceability limit state (SLS), which defines the functionality of equipment, and the operational limit state (OLS), which defines the operational usability of areas. In this context, when evaluating the consequences of certain climate impact drivers (i.e., high-speed winds), structural failure (i.e., the collapse of structures due to wind forces) is measured through the ULS, functional disruption (i.e., the disablement of equipment due to wind forces) is measured through the SLS and operational downtime (i.e., the stoppage of operations due to harsh working conditions) is measured through OLS analysis.

2.1.3. Climate change risk assessment

Specifically in the context of CC-derived risks, the proposed framework integrates risk definitions according to WGII AR6 (IPCC et al., 2022) and is utilized in a compound and cascading risk context: exposure (presence of goods and services that could that could be adversely affected), vulnerability (propensity of exposed elements to suffer serious consequences) and hazard (potential occurrence of a physical event that may cause damage). It focuses on risk evaluation at the subsystem scale by evaluating various risk sources to consider not only the level of reliability loss but also the functionality and operability of infrastructure (accounting for the effect of disruption effects on provided and protected services). Thus, the hazards to the exposed assets and protected services and their associated vulnerabilities, both individually and as a system, should be characterized.

Step 1: Characterization of climate hazards

The first step in the proposed methodology is the characterization of the diverse hazards for port infrastructure subsystems (i.e., waves, winds, and sea level). Climate-derived risks to ports can be classified into two different typologies: high-probability but low-impact events and low-probability but high-impact, or so-called extreme, events. On the one hand, the former primarily affects the day-to-day operation of the port, which is generally related to the interruption of port services, or services' downtime: wave agitation and high wind speed episodes that affect the operations for a couple of hours are examples of these events. In this methodology, hourly time series of the relevant climate variables are used to determine high-probability low-impact hazards.

On the other hand, extreme or episodic events that directly affect critical infrastructures such as ports for a number of days, such as cyclones and harsh winter storms, cannot be modeled using a deterministic approach (Burcharth, 1993). Thus, infrastructure performance is evaluated under diverse return period-related synthetic compound events. Synthetic events, formed by a combination of concomitant extreme values for the evaluated climatic drivers, are emulated based on an extreme value analysis of the climate driver time series to conduct a probabilistic-based assessment. In the present methodology, synthetic multi-variate climate variables are used to determine low-probability high-impact hazards (Lucio et al., 2024). Henceforth, each set of concurrent hazard drivers, which contains either a time-series value or a synthetic event, is defined as a multihazard state.

Climate change is included by considering the diverse climate dynamic projections of met-ocean drivers, coupled with sea level rise projections, to accurately model their effects on nearshore wave propagation processes, including surface zone hydrodynamics variations and nonlinear interaction changes, among others. Precisely, climate change induced variability in the met-ocean variables is coherently accounted for utilizing the time series of the RCMs (Regional Climate Models) of the sea level, waves and winds for different future time horizons and Greenhouse Gas (GHG) emission scenarios, considering diverse model realizations to capture the distinct performance of the regional projections at local scale. Then, synthetic events are conformed based on this diversity of time horizons, scenarios and model realizations, independently for each of them (Lucio et al., 2024).

Finally, climate hazards should be coherently characterized at the necessary spatial and temporal levels of granularity by applying statistical numerical or hybrid downscaling techniques, if needed.

The outcome of this step is the probabilistic characterization of a number of multihazard states, at port locations, that represent the climatic conditions that cause stress to the subsystem throughout its lifetime, accounting for CC effects.

Step 2: Characterization of exposure: operational units (OU)

The second element of this methodology is exposure characterization, which includes the socioeconomic utility, physical features, functionalities and relationships within the infrastructure subsystem, which are all encompassed in the definition of operational units (OU, Lucio et al. submitted). According to the subsystem definition, OUs are shaped as heterogeneous, independent entities that engage all port operations, from the entrance of the ship into the channel to the exit of the goods through the hinterland connections. The units are heterogeneous due to the variety of structures (protection, berthing, storage structures, etc.), equipment (loading, transportation, etc.) and areas (navigation, berthing and hinterland) that they entail. Additionally, they are independent, as their definition specifies that impacts, even those propagated within the same unit, are not propagated between units. Hence, they shall encompass all assets and uses required to thoroughly perform the provided service while enabling the isolation of the risk sources for each evaluated unit, thus enabling the characterization of the system complexity and compound affection of multiple hazards with the highest level of granularity.

The outcome of this step is the spatial identification of port subsystems (OUs), accounting for structures and equipment, and the characterization of their physical and functional features and uses.

Step 3: Vulnerability characterization

After the inclusion of each use-related area and asset into the different OUs, the evaluation of their vulnerability starts with the characterization of each subsystem's element vulnerability. For each assessed asset and service, a number of impact modes are defined to link the hazards obtained to their derived consequences. Failure modes (FMs), which are generally caused by extreme events, are related to structural damage and evaluated through the use of ULS and/or SLS requirements, whereas stoppage modes (SMs) are related to operational downtimes and non-operable conditions and are therefore evaluated

through the use of OLS. Altogether, each impact mode (FM and SM) is related to a limit state, which, in practice, can be evaluated through a combination of numerical models and semiempirical equations meant to discern whether the evaluated element (e_i) is being disrupted by a multihazard state (h_j). The limit state analysis also necessitates setting its vulnerability threshold as determined by the geometrical and structural properties of the element ($\Psi_{k_{dw}}$). When this threshold is surpassed, structural failure (for ULS), asset damage (for SLS) or activity downtime (for OLS) are considered to occur.

$$\frac{\Psi_k(e_i, h_j)}{\Psi_{k_{thr}}} > 1 \rightarrow I_k \tag{1}$$

where $\Psi_k(e_i, h_i)$ is the output variable of the limit state analysis (i.e., overtopping volume, armor damage parameter, etc.) for a given impact mode I_k , which governs the occurrence of structural collapse (ULS), repairable damage (SLS) and downtime (OLS). To be mentioned, when evaluating ULS and SLS, the same synthetic multi-hazard state is considered to stress the full infrastructures' system, triggering collapse or damage if the limit state equations are not fulfilled (i.e., a synthetic extreme event with flooding and strong wind causing combined damage to cranes, treated as SLS or ULS depending on the degree of damage, linked with the functionality of the element posterior to event's occurrence). In parallel, downtime evaluation (OLS) relies on the cross-match of the climate variables time-series with the operability thresholds (i.e., a multihazard state causes disruption if any of the concomitant variables surpasses the threshold). Therefore, $\Psi_k(e_i,h_i)$ values are computed for each synthetic event for the ULS/SLS evaluation, and for each hour for the OLS evaluation.

In the present methodology, the vulnerability model is only based on the resilience of each element to the climate impacts. However, the adaptive capacity of the system (preparation of personnel, presence of Early Warning Systems, etc.) may as well play a major role in the definition of its vulnerability. The evaluation of these features is more related with the adaptation framework of ports, which would be the required next step after the risk assessment and has been accordingly treated by Fernandez-Perez et al. (2024).

The final outcome of this step is the characterization of the relationships between the identified hazards (Step 1) and the physical and socioeconomic consequences (failure or stoppage) for each identified exposed element (Step 2) via the set of limit states.

Step 4: Calculating climate risks

Following the IPCC definition, risk assessment necessitates the joint evaluation of the consequences (impacts) of the hazards and their probability of occurrence. In the present framework, consequences are probabilistically characterized by inputting the multihazard states (output from Step 1) into the impact modes (output from Step 3) for each of the assessed elements (output from Step 2). Probability density functions (PDFs) are characterized for each impact mode (based on the synthetic extreme events emulator for the FM, and based on regular condition time series for the SM), to model the occurrence frequency of failures and stoppages for each evaluated asset/use.

The outcome of this step is the characterization of climate risks, which is achieved by obtaining the probability density functions of climate-associated damage and disruptions (consequences) in port subsystem elements.

Step 5: Determining the Acceptable Level of Risk

Once the risk analysis procedure is finalized, the resulting consequences are graded in terms of acceptability. Depending on the level of criticality of the infrastructure, or how essential is it to maintain the socio-economic functions of the region, the definition of the risk acceptability varies. For noncritical infrastructures, social (Lawrence and Haasnoot, 2017), environmental (Lantieri et al., 2017) and economic variables (European Commission, 2014) are taken into account. Conversely, when dealing with critical infrastructures, normative, administrative and legal conditions are considered (ISO/TC 98, 2015). Thus, in the present work, a predefined acceptable level (AL) of risk (IPCC et al., 2022) is defined as the minimum infrastructure condition necessary to be considered serviceable, which complies with ULS, SLS and OLS requirements. To set the acceptable levels of risk for each evaluated limit state, the technical requirements of the analyzed port infrastructure are evaluated ((PIANC, 2016; ROM 1.0–09, 2009)), which defines a maximum allowed value for each impact mode, depending on the infrastructure and protected socioeconomic service types.

2.2. Compound climate risk characterization

Compound climate risks are generally characterized as risks emerging from (1) the interaction of multiple coincident climate events (compound climate events), or (2) the sequential impacts (cascading effects) that affect exposed systems or sectors (Simpson et al., 2021). In the proposed methodology, both typologies are assessed.

2.2.1. Compound climate events

Compound climate events are modeled through correlation analysis of climate hazards. First, concurrent climate driver time series are evaluated to obtain the temporal correlations between variables, thus accounting for the CC-induced variations in future conditions. This procedure is based on Lucio et al. (2024), and it firstly evaluates the correlation of the extreme value distribution (GEV) from the time-series between all climate variables, for both present (baseline) and future (for different scenarios) time horizons. Extreme values are selected based on a monthly block maxima procedure to trace the seasonal variability. The assessment of the correlation between variables is performed using Spearman's rank correlation (to capture nonlinearities in the extremes). Then, this correlation parametrization is utilized in the synthetic event emulation to maintain coherent joint occurrences of compound extreme events, via Gaussian copula fitting of the climate extremes. The correlation analysis and compound event generation are available in the Supplementary Material.

2.2.2. Cascading effects

To model the systemic propagation of impacts in the established subsystems and that for the entire infrastructure system, a fault-tree framework (Burcharth, 1993) is utilized. First, the physical and operational relationships between elements (evaluated at Step 2 of the procedure) are mapped for each OU. Then, based on those relations, different propagation modes are defined based on temporal and logical links:

- Series propagation: TO gates in the fault trees represent how the failure/downtime occurrence of impacts can be triggered by the occurrence of other impacts

$$\frac{\Psi_A}{\Psi_{A_{thr}}} > 1 \to I_A \to I_B \tag{2}$$

- Parallel supplementary propagation: OR gates in the fault trees (\bigvee is the Boolean operator for OR) for a set of impacts, failure/downtime occurs when any of the vulnerability thresholds are surpassed. In Equation (3), if any Ψ_k/Ψ_{kdir} surpasses the unit, then I_A is assumed to occur.

$$\bigvee_{k=1}^{impact modes} \frac{\Psi_k}{\Psi_{k_{thr}}} \equiv \max_k \left\{ \frac{\Psi_k}{\Psi_{k_{thr}}} \right\} > 1 \rightarrow I_A$$
(3)

 Parallel complementary propagation: An AND gates in the fault trees (\(\lambda\) is the Boolean operator for AND) for a set of impacts, failure or downtime occurs when the interaction of hazards (linear summation) surpasses the vulnerability threshold, taking action as a complementary value.

$$\bigwedge_{k=1}^{npact modes} \frac{\Psi_k}{\Psi_{k_{thr}}} \equiv \sum_k \frac{\Psi_k}{\Psi_{k_{thr}}} > 1 \rightarrow I_A$$
(4)

Overall, the definition of the fault trees and propagation links for each operational unit enables us to characterize the vulnerability and exposure of the subsystems.

2.3. Infrastructure performance indicators

in

The aim of this step is to quantify the variations induced by CC in the occurrence and recurrence of failures and stoppages in system elements, subsystems and throughout the entire infrastructure system. In this way, we obtain the outputs of the CC risk assessment, defining a set of Infrastructure Performance Indicators (*IPIs*). To maintain the temporal coherence with traditional infrastructure assessment methodologies (limit states), the temporal unit of analysis is the design lifetime of the infrastructure. Thus, all indicators refer to the climate risk of the infrastructure over its entire lifetime under climate (hazard) conditions for the corresponding period of analysis. Uncertainty is bounded in the computation of the indicators by calculating them independently for each climate model realization (RCM).

2.3.1. Failure mode indicators

Failures are considered to occur due to extreme conditions; therefore, the computation of the failure mode indicators will be based on the evaluation of the limit states under the synthetic extreme multi-hazard states. Based on (Lucio et al., 2024), to characterize the frequency of structural collapse (ULS) and repairable damage (SLS), the main indicators used are the probability of failure of the asset and its expected lifespan, which are compared with the acceptable risk levels (output of Step 5). The probability of failure (p_f) features the number of synthetic lifetimes in which a failure derived from impact (I_k) occurs, as a ratio of the total number of evaluated lifetimes. A synthetic lifetime is considered as a cluster of extreme synthetic events in a number of years sufficient to be representative of the extreme conditions the infrastructure will suffer over its lifetime.

$$p_{f_k} = \sum_{N=1}^{\#_{lifetimes}} \left[\bigvee_{n=1}^{\#_{years}} \left\{ \frac{\Psi_{k_{N,n}}}{\Psi_{k_{dir}}} > 1 \right\} \right] / \#_{lifetimes}$$
(5)

Jointly, the expected lifespan characterizes the expected time between failures arising from the same impact (I_k) . It assumes that the failure occurrence is governed by a Poisson process with an annual failure rate λ_{year_i} . The expected lifespan (LS) is computed as follows:

$$p_f = 1 - \prod_{i=1}^{LS} (1 - \lambda_{year_i}) = 1 - (1 - \bar{\lambda})^{LS}$$
(6)

$$\overline{\lambda} = \sum_{i=1}^{LS} \lambda_{year_{i/LS}}$$
⁽⁷⁾

$$LS_{k} = \log\left(1 - p_{f_{AL}}\right) / \log(1 - \overline{\lambda})$$
(8)

where $p_{f_{AL}}$ is the acceptable probability of failure and $\overline{\lambda}$ the average failure rate. LS_k represents the theoretical lifespan of the infrastructure, indicating how long it is expected to last while still meeting the safety standards specified by the technical requirements ($p_{f_{AL}}$).

The joint use of both indicators is recommended, since the former quantifies the probability of occurrence of any failure mode during the infrastructure's lifetime, while the latter indicator characterizes the



Fig. 1. Aggregation of assets and uses in operational units to evaluate coherently induced impacts to coastal structures (CS_v), port equipment (PE_w) and uses (U_x).

occurrence of more than one failure during the infrastructure's lifetime.

2.3.2. Stoppage mode indicators

In the present framework, stoppage, or downtime, is evaluated under regular conditions; therefore, the computation of the stoppage mode indicators will be based on the evaluation of the limit states under the time-series multi-hazard states. For operability analysis (OLS), the main indicator is the annual non-operability rate, which reflects the number of climate drivers' with downtime (non-operational hours) resulting from the impact (I_k) on the infrastructure lifetime.

$$r_{f_k} = \sum_{h=1}^{\#hours} \left[\left\{ \frac{\Psi_{k_{nh}}}{\Psi_{k_{thr}}} > 1 \right\} \right] / \#hours \text{ for any given } year_i \tag{9}$$

It is assumed that downtime occurs when non-operational conditions occur $\left(\Psi_{k_{n,h}}/\Psi_{k_{thr}}\right)$ and that the activity is recovered when climate conditions permit (i.e., when the threshold is no longer exceeded).

Failure and stoppage indicators will be computed for each



Fig. 2. Developed workflow for climate change derived compound risk for port infrastructures subsystems.



Fig. 3. Location of the climate database nodes and downscaling points for the study case ports.

Operational Unit, accounting for the propagation of failures and stoppages in the subsystem fault-tree scheme. Therefore, if an impact occurs for any asset or service, its systemic effects are accounted for through the tree gates, deriving failure, stoppage or both for the entire unit.

2.3.3. Aggregation of indicators

Finally, to assess the consequences of each subsystem of individual element failures and downtimes, impact aggregation is conducted. The impact and thus performance indicators aggregation is firstly conducted for each specific element in the port (compound impact analysis), then for each OU (propagation of impacts within each unit) and finally for the entire port (aggregation assuming operational units are independent). This allows to identify the critical elements (individual elements with higher risk), and then prioritize improvements (or adaptation) for those critical elements and units. The entire procedure is depicted in Fig. 1, where after the disaggregation of the port into independent subsystems and their elements, the impacts are assessed and propagated through the defined fault-tree connections. Then, the aggregation of consequences, which are coherent with those fault trees, allows us to (1) evaluate the effects of individual element failures and stoppages into each subsystem and (2) identify the critical elements that disrupt the whole OU and/or the entire infrastructure logistic chain.

Following the procedure illustrated in Fig. 1, the final step of the methodology is the aggregation of the indicators for the entire port. The objective of this aggregation is to define a performance rating for the port. Assuming independence between the OUs (no propagation of impacts between different OUs):

2.3.3.1. Reliability and functionality indicators

$$\begin{cases} p_{f_{TOT}} = 1 - \prod_{a} \left(1 - p_{f_{OUa}} \right) \\ \lambda_{TOT} = 1 - \prod_{a} (1 - \lambda_{OUa}) \end{cases}$$
(10)

2.3.3.2. Operability indicators

$$r_{f_{TOT}} = \min_{a} \left(r_{f_{OU_a}} \right) \tag{11}$$

Thus, the methodology is completed, as shown schematically in Fig. 2, along different modules. The characterization of compound climate hazards characterization begins with the analysis of climate variables under regular conditions by evaluating time-series and under extreme conditions through the generation of a number of synthetic compound episodic events, ultimately downscaling the so-called multi-hazard states to high-resolution analysis locations. Then, the exposure analysis begins with the physical, functional and socioeconomic features of each coastal structure, port equipment and use, and they are aggregated into independent and operationally homogeneous subsystems

(operational units). The assessment of the geometrical and physical characteristics of each asset allows the definition of many failure and downtime modes to characterize their vulnerability levels. A fault-tree approach is utilized to model the relationships between the characterized elements and to propagate the impacts for the subsystems (thus defining their systemic vulnerability and exposure). Finally, the evaluation of consequences through a probabilistic approach is used to define a set of indicators (IPIs) to monitor the CC risk for each element, subsystem and, when needed, port as a logistic infrastructure system.

3. Study case: the application of the methodology in two regional ports on the north coast of Spain

To demonstrate the application of the proposed methodology, two regional ports in the Cantabrian Sea (north coast of Spain) are selected: Llanes and Luanco. These ports are chosen due to their differences in location (which affects their exposure to northern and western storms), geometry, design procedures, stage of lifespan, (Llanes was constructed in 1994 and Luanco in 2008), asset types (structures or equipment) and activities involved.

The Port of Llanes $(43^{\circ}25'15''N, 4^{\circ} 44' 59''W)$ has an eastward entrance channel that is protected by a rubble mound breakwater (block units), which is crested at +13.8 m, an inner channel and a fishing area basin that is protected by a vertical wall. Additionally, a storm surge gate protects the marina basin. The port equipment includes a dry dock, jib cranes and a fish market building.

The Port of Luanco $(43^{\circ}37'10''N, 5^{\circ}46'54''W)$ has a southward entrance channel protected by a rubble mound breakwater (concrete block units), which is crested at +12.5 m. The main basin lodges a number of mooring structures for fishing and recreational ships. Port equipment include a dry dock, jib cranes and several storage and service buildings. The plans and cross-sections for both cases are available in the Supplementary Material.

3.1. Hazard assessment

Climatic drivers are obtained at the closest port nodes (see Fig. 3) as hourly time series based on offshore climate change projections, and a number of regional climatic models (RCMs) from the CMIP5 (Lemos et al., 2019) are considered. To ensure compound effects are factored into the risk assessment, it's crucial that the downloaded climate variables adhere to temporal coherence, meaning they should be based on the same timeframes. This consistency allows for modeling extreme compound events that are aligned with climate projections. Climate driver databases include time-matched hourly time series for wave (significant wave height {Hs}, mean and peak wave period, {Tm, Tp} and mean direction { Dir_m }), sea level (astronomical tide {AT} and storm



a) Port of Llanes

b) Port of Luanco

Fig. 4. Distribution of coastal structures (red lines), port equipment (blue Lines) and uses (shaded areas) at study case ports.

surge {SS}), and wind (gust peak speed { V_{gust} } and gust direction { Dir_{gust} }) variables for the baseline (1985–2005, BL) and those for two short-term and long-term future periods (2027–2045, ST, & 2082–2100, LT). The climate projections account for a probable RCP4.5 scenario and a high-emissions RCP8.5 scenario based on the HadGEM2, IPSL-CM5A and CMCC-CM RCM realizations. Jointly, ten equally probable values (deciles, based on the SLR-probability density functions, Oppemheimer et al., 2019) are used for the consideration of the sea level rise at the end of each study period for each of the RCP scenarios. To be mentioned, each RCM realization-SLR decile combination is treated independently for the whole risk assessment, obtaining a set of indicators for each combination and thus bounding the uncertainty pertaining to the climate models, assuming equal probability between them (Christensen et al., 2010).

Extreme synthetic compound states are simulated to obtain 10,000 lifetimes' synthetic data on offshore wave, sea level and wind episodic events, with a design lifetime of 25 years and containing 12 values per year, one episode per month, to capture seasonal variability.

The inclusion of CC involves incorporating dynamic climate projections of met-ocean drivers along with sea level rise projections to simulate the interplay between sea level and waves. Subsequently, hazards are regionally downscaled to protected areas (solving transformation on a smaller domain with higher resolution) through a blend of numerical models (such as the MSP solver of the elliptic mild slope equation by Diaz-Hernandez et al. (2021) and SWASH by Zijlema et al. (2011)), coupled with hybrid downscaling techniques. These techniques rely on selecting a representative set of climate conditions and then propagating and reconstructing the complete dataset, following the approach outlined by Camus et al. (2011). Further information about the synthetic multihazard states generation and the downscaling process is available in the Supplementary Material. Hence, the hazard (e.g., windand wave-induced current velocities and total water level) variables to be considered in impact modeling are obtained from the vicinity of the assets and use areas.

Please note that, even if subsidence is not relevant in the case studies selected due to their geological conditions, vertical land motion can be a critical risk driver when compounding with sea level rise and should be treated with care in other ports (Esteban et al., 2019).

3.2. Exposure assessment

The next step of the methodology is the identification of coastal structures, port equipment, uses and activities, which are relevant to Table 1

Considered Coastal Structures (CS_{ν}), Port Equipment (PE_{w}) and Uses (U_{x}) for study case risk analysis.

Port	Coastal Structures (CS_{ν})	Port Equipment(<i>PE_w</i>)	Uses (U_x)
Llanes	$CS_1 \equiv$ Main Breakwater	$PE_1 \equiv \text{Crane}$ $PE_2 \equiv \text{Dry Dock}$ $PE_3 \equiv \text{Building}$	$U_1 \equiv \text{Access}$ $U_2 \equiv \text{Fishing}$ $U_3 \equiv \text{Marina}$
Luanco	$CS_1 \equiv$ Main Breakwater $CS_2 \equiv$ Pontoon 1	$PE_1 \equiv Crane$	$U_1 \equiv \text{Access}$
	$CS_3 \equiv Pontoon 2$ $CS_4 \equiv Pontoon 3$	$PE_2 \equiv \text{Dry Dock}$	$U_2 \equiv \text{Fishing}$
	$CS_5 \equiv Pontoon \ 4$ $CS_6 \equiv Pontoon \ 5$	$PE_3 \equiv Buildings$	$U_3 \equiv Marina$

port operation, on a high-resolution local scale. Fig. 4 shows the distribution of assets and uses for both study cases, with the land and seaside areas harboring key uses identified as either marina, fishing or access areas.

For both ports, two different operational units are defined, one per each activity held by each port, encompassing the coastal structures, equipment, buildings and areas on which the identified activities depend. Thus, the aggregation of elements in the so-called operational units is performed as follows:

3.2.1. Port of Llanes

 $OU_1 \hspace{-1mm}=\hspace{-1mm} CS_1 \cup PE_1 \cup PE_2 \cup PE_3 \cup U_1 \cup U_2$

 $OU_2 \!\!=\!\! U_1 \cup U_3$

3.2.2. Port of Luanco

 $OU_1 \hspace{-1mm}=\hspace{-1mm} CS_1 \cup CS_5 \cup PE_1 \cup PE_2 \cup PE_3 \cup U_1 \cup U_2$

 $OU_2 \hspace{-1mm}=\hspace{-1mm} CS_1 \cup CS_2 \cup CS_3 \cup CS_4 \cup CS_6 \cup U_1 \cup U_3$

The numbers of CS_v , PE_w and U_x can be found in Table 1.

3.3. Vulnerability assessment

Beginning with the vulnerability evaluation, the impact mode characterization of the disaggregated port element portfolio is conducted following the definition of the main climate-induced impacts by

Table 2

Considered impact modes for each of the evaluated elements, including the evaluated semi-empirical equations, hazard drivers involved and consideration of uncerta	Considered impact modes for each of the evaluated elements, including the evalu	ated semi-empirical equations	hazard drivers involved and	d consideration of uncertaint
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ELEMENT	IMPACT MODES	Equation	Hazard Variables	VULNERABILITY THRESHOLD	Parameters Uncertainty ^{C}
Rubble-mound Breakwater	Detachment of slope's breakwater unit pieces (ULS)	$\frac{H_{\rm s}}{\Delta D_n} = \left(\frac{6.7N_{\rm od}}{N^{0.3}} + 1.0\right) \frac{2\pi}{g T_m^{-2}} (\text{van der Meer, 1988})$	$\{H_s, T_m, \eta\}$	$N_{od} = 0.5 (Beg. Damage)$ $N_{od} = 2 (Collapse)$	$ ho_{concrete} \sim N(2.35, 0.047)$ tan $lpha \sim N(**, 1/30)$
	Sliding of Crown-wall (ULS)	$SF_{Sliding} = \frac{(W - F_s) * \phi}{F_{h1} + F_{h2} + F_{d1} + F_{d2}}$ (Martin et al., 1999)	$\{H_s, T_m, \eta\}$	<i>SF</i> = 1.2	$\begin{array}{l} \rho_{concrete} \sim N(2.35, 0.047) \\ \tan \alpha \sim N(**, 1 \ /30) \\ Porosity \sim N(0.4, 0.02) \\ \varphi \sim N(0.6, 0.03) \end{array}$
	Overturning of Crown- wall (ULS)	$SF_{Sliding} = \frac{(W * x_w - F_s * x_s)}{F_{h1} * y_{h1} + F_{h2} * y_{h2} + F_{d1} * y_{d1} + F_{d2} * y_{d2}} $ (Martin et al., 1999)	$\{H_s, T_m, \eta\}$	SF = 1.2	$\begin{array}{l} \rho_{concrete} \sim N(2.35, 0.047) \\ \tan \alpha \sim N(**, 1 \ /30) \\ Porosity \sim N(0.4, 0.02) \\ \varphi \sim N(0.6, 0.03) \end{array}$
Mooring Structure (Pontoon)	Anchoring Failure (ULS)	$SF = \frac{F_N}{\sqrt{(F_{trans})^2 + (F_{long})^2}}$ $F_{long} = F_{wind_l} + F_{currl_p} + F_{currl_f} + F_{wavel}$	$\{H_s, Dir_m, V_{flow}, Dir_{flow}, V_{wind}, Dir_{flow}, Dir_{flow}, V_{wind}, Dir_{flow}, Dir_{flow}, V_{wind}, Dir_{flow}, Dir$	SF = 1.2	$F_N \sim N(600, 60)$ $L_{ship} \sim N(9, 0.45)$ $B_{ship} \sim N(2.7, 0.135)$
		$F_{trans} = F_{wind_t} + F_{currt_p} + F_{currt_f} + F_{wavet} $ (ROM 2.0–11, 2012)	Dur_{wind}		$D_{ship} \sim N(1.5, 0.075)$
Crane/Dry Dock/ Building	Flooding (SLS)	$q = \sqrt{m{g}\left(h+\eta ight)}*\etarac{\left(\eta-h_c ight)}{\left(h+\eta ight)}$	$\{\eta\}$	$q \sim N\left(rac{1l/s}{ml}, 0.1 ight)$	$q \sim N\left(1, 0.1 ight)$
	Overtopping (SLS)	$\frac{q}{\sqrt{g H_s^3}} = C_r \left(c_1 \exp\left[- \left(c_2 \frac{R_c}{H_s \gamma_f \gamma_\beta \gamma_{berm}} \right)^{1.3} \right] \right)$ $C_r = 3.06 \exp\left(-1.5 \frac{N^o Cubes D_n}{H_s} \right) \text{ (Eurotop, 2018)}$	$\{H_s, T_m, \eta\}$	$q \sim N\left(\frac{1l/s}{ml}, 0.1\right)$	$\begin{array}{l} \rho_{concrete} \sim N(2.35, 0.047) \ c_1 \sim \\ N(0.09, 0.0012) \\ c_2 \sim N(1.5, 0.225) \\ \tan \alpha \sim N(**, 1/30) \\ q \sim N \ (1, 0.1) \end{array}$
	Equipment Failure due to wind forces (SLS)	$SF = rac{V_N}{V_{wind}}$	$\{V_{wind}\}$	SF = 1.2	$V_N \sim N~(^{ m b})$
Fishing/Marina Use	Operability disruption (OLS)	$SM = [H_s \ge H_{sth}] \cap [V_{flow} \ge V_{flow}_{th}] \cap [[h_c - \eta] \ge [h_c - \eta]_{th}] \cap [V_{wind} \ge V_{windth}] \cap [q_{OT} \le q_{OT}_{th}] $ (ROM 2.0–11, 2012)	$\{H_s, V_{flow}, \eta, V_{wind}\}$	$ \begin{split} H_{sth} &= 2.5 \; m \mid 0.4 \; m^{\rm a} \\ V_{flow_{th}} &= 2 \; m/s \mid 1.5 \; m/s^{\rm a} \\ V_{wind_{th}} &= 17 \; m/s \mid 22 \; m/s^{\rm a} \\ [h_c - \eta]_{th} &= 0.5 \; m \\ q_{OT_{th}} &= 0.3 \; l/s/ml \end{split} $	-

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Notes.

 Δ =Relative density of cubes ($\rho_{\textit{concrete}}/\rho_{\textit{water}}$).

 $D_n = Cubes diameter.$

N= Number of waves.

W=Crown-wall height.

 x_w = Weight vector of force location.

- F_s = Uplift force.
- x_s = Uplift vector of force location.

F_h Hydrostatic force.

- y_h = Hydrostatic vector of force location.
- F_d = Dynamic force.
- y_d = Dynamic vector of force location.
- $R_{c} = Breakwater \ crest \ height.$
- $h_c = \text{Dock crest height.} \\$
- $\{c_1,c_2\}=$ Eurotop formula constants.

h = Water depth.

 $F_{windl} =$ Quasi-static long. force induced by wind pressures in the ship (equivalent w/transverse forces).

 $F_{flow_{lp}} =$ Quasi-static longitudinal force induced by pressure flow forces in the ship (equivalent w/transverse).

 $F_{flow_{lf}} =$ Quasi-static long. force induced by friction flow forces in the ship (equivalent w/transverse forces).

 F_{wavet} = Quasi-static longitudinal force induced by wave forces in the ship (equivalent w/transverse forces).

 F_N = Nominal max. force for the mooring system.

 $V_{N}=\operatorname{Nominal}$ max. wind velocity for the equipment (3 s gust at 10 m height.

^a Access area threshold | Area threshold.

 $^{\rm b}$ Depending on evaluated element. (36,3.6) m/s for crane/dry dock and (40,4) m/s for buildings.

^c Parameter's uncertainty (standard deviation) is considered based on the state of the art, for a detailed analysis, please see (Lara et al., 2019; Lucio et al., 2019)



Fig. 5. Fault trees for risk assessment of Llanes and Luanco ports, considering defined operational units to aggregate consequences. Square boxes represent failure modes, round boxes, downtime modes. Dashed lines bound operational units.

design requirements for ports (PIANC, 2016; ROM, 2009). Detailed information on the considered limit state equations, vulnerability thresholds and how uncertainty is parametrized for each impact mode is provided in Table 2. The provided list of models enclosures the most representative climate derived impacts for the study case, but the vulnerability assessment methodology guarantees enough replicability to include a wider variety, if required.

Finally, fault trees are characterized for each of the defined OUs by analyzing the physical and operational relationships between defined elements and then exploring the propagation types for the impact modes needed. Fig. 5 shows fault trees for the study case ports. Overtopping, wind and flooding failure modes are considered to be causes of activity stoppage (TO gate); a number of impact modes can cause independent breakwater damage and activity downtime (OR gate); and overtopping, wind and flooding can impact the conjunction of the evaluated port equipment (AND gate). After the definition of these fault trees, the exposure and vulnerability assessment of the port infrastructure subsystem is considered to be complete.

3.4. Impact and risk assessment

3.4.1. Acceptable levels of risk

To obtain the acceptable impact levels for the evaluated infrastructures, the technical standards of the Spanish ports were analyzed. Based on economic, social and environmental importance, ROM (2009) defines a series of impact-related requirements. For fishing and marinas, the minimum required lifespan of its elements is $LS_{AL} = 25$ years, and when assessing the ULS and SLS, the maximum allowed probability of failure for reliability and functionality design is $p_{fAL} = 0.1$. For the OLS assessment, the maximum allowed non-operability is $r_{fAL} = 0.01$.

3.4.2. Compound impact assessment

First, a reliability analysis is performed (ULS) to evaluate the displacement occurrence of the armor pieces and crown-wall failure. In Figs. 6 and 7 (a to c), the empirical bivariate PDF plots reveal a significant correlation in the crown-wall failure modes (overturning and sliding), but no correlation occurs between the crown-wall and armor unit displacement. Additionally, variation analysis of the probability of failure (d) confirms the absence of correlation. For the Port of Llanes (Fig. 6d), the displacement of the main armor plays a larger role in breakwater failure, and a significant increase is found due to the CC for future time horizons, which can reach unacceptable values (p_{fAL}). For the Port of Luanco (Fig. 7d), a decrease in the probability of failure is observed for the displacement of main armor, which exhibits the greatest p_{f_2} although it maintains acceptable values. This difference in results might be driven by the fact that the Llanes breakwater is more exposed to extreme waves in the Cantabrian Sea, most of which break when the breakwater is reached during the BL period; however, the waves impact the breakwater with greater energy when the SLR increases the available water depth. Several ports worldwide are located at water depths that make the waves reaching their infrastructures to be



Fig. 6. Breakwater reliability (ULS) compound impact and risk analysis for Port of Llanes. For each limit state, impact bivariate PDFs are on a), b) and c)- d) bars show IPI variation for the analyzed periods and scenarios, accounting for compound effects (intersection) as part of the total impact (e). SF indicates the safety factor of the impact mode (SF < 1 indicates failure). NoD indicates the breakwater level of damage.

depth limited. Therefore, SLR will have a widespread affection on wave induced impacts even if wave conditions at deep water are not abruptly affected, highlighting the importance of considering compounding effects of sea level and wave variations due to CC.

When analyzing the functionality (SLS) of port equipment, the compound effects of wind, wave overtopping and flooding events are analyzed. As shown in Fig. 8 (a to c) and Fig. 9 (a), the interaction between wind and wave overtopping episodes plays a greater role in crane failure at the Port of Llanes than at the Port of Luanco, causing even the p_f to increase from acceptable to unacceptable values during some periods, which highlights the importance of integrating compound effects on climate impacts. In terms of CC (Fig. 8d), wind and wave overtopping failures follow complementary paths in future periods, as wind failure increases under RCP4.5 and decreases under RCP8.5, and wave overtopping events decrease under RCP4.5 and increase under RCP8.5. This results in a slight decrease in crane impacts while maintaining unacceptable values of p_{f} . These outputs are coherent with climate models that show a wave reduction due to CC, especially for RCP 8.5, due to a decrease of winds in the northern hemisphere (Lobeto et al., 2021). As Llanes is a port where waves are depth limited, SLR shall play a major role in overtopping impacts, with increasing overtopping volumes mainly for scenarios with high sea level rise. For the Port of Luanco (Figure 8b9), compound impacts do not have such a marked effect, as wave overtopping above coastal structures does not affect port equipment in this study. Wind failure plays a major role (Fig. 9b), however, increasing the RCP4.5 above acceptable levels in the short term but decreasing it in the remaining periods. Similar results are obtained for buildings and dry dock impacts (diagrams are available in the Supplementary Material).

Finally, operability (OLS) is analyzed in both study cases. The strongest correlations are found when analyzing wave heights and current velocities (bivariate PDFs in Figs. 10 and 11), which makes this interaction the only remarkable compound effect, although wave agitation has a greater independent influence on the non-operability of the Port of Llanes (Fig. 10g), showing unacceptable levels for all analyzed time horizons (including the present BL period). For the Port of Luanco (Fig. 11g), wind-induced downtimes play a major role in operability analysis, and they maintain acceptable values. Similar results are obtained for access and marina areas (diagrams are available in the Supplementary Material).

Taken together, the impact and risk analysis of the study cases reveal the importance of considering compound events when assessing



Fig. 7. Breakwater reliability (ULS) compound impact and risk analysis for Port of Luanco. For each limit state, impact bivariate PDFs are on a), b) and c). d) bars show IPI variation for the analyzed periods and scenarios, accounting for compound effects (intersection) as part of the total impact (e). SF indicates the safety factor of the impact mode (SF < 1 indicates failure). NoD indicates the breakwater level of damage.

multihazard-induced impacts. The great variance in the obtained results (with 90% confidence intervals displayed in brackets), induced by the variability of the CC hazard projections for different model realizations, should be mentioned. This variance highlights the significance of treating each model independently and avoiding performing ensembles when assessing climate-derived impacts, especially when dealing with extreme events.

3.4.3. Tracing the CC risk through infrastructure performance indicators

Finally, infrastructure performance indicators are computed for each future period and scenario. The aggregation of impact probabilities within the fault tree-OU framework is performed for both case studies following Equations (2)–(4) and (10) and (11).

Disaggregated results are mapped as *IPI* variation in Fig. 11: red values spot risks with values above the *AL* thresholds, yellow values indicate risk increase, and the green values indicate risk decreases resulting from CC. Jointly, the aggregated *IPIs* are shown in Table 3 by OU and for the whole port, using the same color codes. Tables including disaggregated values of the indicators can be found in the Supplementary Material.

For the Port of Llanes, when assessing reliability (ULS), a significant increase in the probability of the failure of displacement of main armor is found, with values increasing above the *AL* for all future periods.

Jointly, port equipment (SLS) impact indicators increase in the p_f , reaching values above the *AL* for long-term periods. The lifespan values are consistent with the results depicted by the p_f , indicating that the expected values are below the minimum acceptable value (25 years). The minimum required lifespan value is not fulfilled in the BL scenario, meaning that the present performance of the infrastructure is not at its optimum, while future CC-derived conditions may worsen present performance. In terms of OLS assessment, the highest non-operability values are shown for OU_1 (fishing use), and they are mainly driven by wave agitation in future periods (as shown in Fig. 10g); these values are far above those of the *AL* and increase slightly due to the CC over all study periods. IPIs trace the impact evolution of downtime due to CC, showing red values (nonacceptable) for fishing use for all future periods and for marina use (OU_2) in the RCP4.5 scenario.

For the Port of Luanco, the impacts of coastal structures (the ULS, main breakwater and pontoons) exhibit negligible variations with respect to those in the BL period, with values remaining far below the AL threshold for all analyzed periods (see Fig. 12, green and yellow values overall). Only for OU_1 do port equipment impacts (crane and dry dock) increase above the AL threshold for future periods (especially for RCP 4.5). In terms of non-operability, access areas show the highest non-operability values, slightly decreasing their magnitude for future periods below AL. Thus, the results show that operations within the Port of



Fig. 8. Crane functionality (SLS) compound impact and risk analysis for Port of Llanes. For each limit state, impact bivariate PDFs are on a), b) and c). d) and e) show IPI variation for the analyzed periods and scenarios. SF indicates the safety factor of the impact mode (SF < 1 indicates failure). *q* indicates the water flow.



Fig. 9. Crane functionality (SLS) compound impact and risk analysis for Port of Luanco. For each limit state, impact bivariate PDFs are on a). b) shows IPI variation for the analyzed periods and scenarios. SF indicates the safety factor of the impact mode (SF < 1 indicates failure). *q* indicates the water flow.

Luanco may not be affected by CC or may even result in reducing the effects of met-ocean hazards in day-to-day operations.

4. Discussion

Past studies have shown that both CC and SLR can affect coastal infrastructure reliability (Galiatsatou et al., 2018) and port service performance (Jebbad et al., 2022), thus increasing the need for resource



Fig. 10. Downtime (OLS) compound impact and risk analysis for Port of Llanes' fishing area. For each limit state, impact bivariate PDFs are a) to f). g) shows IPI variation for the analyzed periods and scenarios; h) compound effects (intersection) as part of the total impact.



Fig. 11. Downtime compound impact and risk analysis for Port of Luanco's fishing area. For each limit state, impact bivariate PDFs are a) to f). g) shows IPI variation for the analyzed periods and scenarios; h) compound effects (intersection) as part of the total impact.

allocation and repair and maintenance and reducing the productivity of certain protected areas. Lucio et al. (2024) showed that for a seaside railway, the reliance of services provided by the coastal transportation system is closely related to the reliability and functionality of the protecting coastal structure. For ports, given the number of elements (equipment, structures, etc.) involved in the uses and activities protected, the degree of complexity of assessing the effects of CC and SLR on performance requires the consideration of these elements as part of a complex system (Verschuur et al., 2022), where physical and operational relationships can be accounted for and compound effects are not neglected.

For that matter, the present work accounts for both system complexity (through fault tree analysis) and compound effects (keeping climate driver's dependency) in its climate change risk assessment methodology. A granular evaluation of impacts is performed, followed by an aggregation of impact proxies by means of exposure and vulnerability system-defining tools to trace the evolution of the infrastructure's reliability, functionality and operability. Thus, a set of indicators is used to encapsulate all the analyzed information in terms of the CC-induced consequences and the recurrence variation on each asset, subsystem or even the port as a whole. The usefulness of these indicators for decisionmaking is shown, as they allow us to promptly assess the response of a given infrastructure to CC effects. Based on those climate change risk proxies, port planners may allocate financial resources in advance to renew or upgrade equipment and relocate or switch uses. Thus, the proposed framework sets a baseline for a coherent adaptation

Table 3

Aggregated infrastructure performance indicators LS (top row) and p_f (mid-row) and r_f (bottom row) for study case ports. Median of model-SLR decile combinations shown, coefficient of variance in parenthesis.

			Study Period			
Element	BL ·	RCP 4.5		RCP 8.5		
		\mathbf{ST}	LT	\mathbf{ST}	LT	
Port of Llanes						
OU1	4.830 (1.26)	$0.071 \ (0.56)$	$0.053\ (0.57)$	$0.050 \ (0.46)$	$0.043 \ (0.73)$	
	0.21(0.88)	0.94(0.42)	$0.95\ (0.81)$	0.93 (0.5)	0.96(0.48)	
	0.05(0.58)	$0.16 \ (0.20)$	$0.14\ (0.18)$	$0.15\ (0.17)$	$0.15\ (0.19)$	
	-	-	-	-	-	
OU2	-	-	-	-	-	
	0.01 (0.25)	$0.01 \ (0.37)$	$0.01 \ (0.35)$	0.00(0.19)	$0.00 \ (0.22)$	
	4.830 (1.26)	$0.071 \ (0.56)$	$0.053\ (0.57)$	$0.050 \ (0.46)$	$0.043 \ (0.73)$	
TOT	0.21(0.88)	0.94(0.42)	$0.95\ (0.81)$	0.93 (0.5)	0.96(0.48)	
	0.05(0.58)	$0.16\ (0.20)$	$0.14\ (0.18)$	$0.15\ (0.17)$	$0.15\ (0.19)$	
Port of Luanco						
	30.648 (0.81)	5.788(0.47)	5.63(1.13)	26.99(0.58)	26.919 (0.55)	
OU1	0.11 (0.40)	0.32(0.71)	$0.23\ (0.79)$	0.06(0.28)	$0.10\ (0.57)$	
	0.03(0.12)	$0.01 \ (0.31)$	0.00(0.34)	0.01 (0.24)	$0.00 \ (0.07)$	
	$581.514 \ (0.57)$	$630.545 \ (0.23)$	$263.977 \ (0.715)$	579.885(0.60)	425.862(0.28)	
OU2	0.00(0.51)	0.00(0.31)	$0.00 \ (0.46)$	0.00(0.39)	0.00(0.41)	
	0.03(0.12)	0.01 (0.31)	0.00 (0.34)	0.01 (0.24)	$0.00 \ (0.07)$	
TOT	29.0732 (0.80)	5.747(0.47)	5.415 (1.12)	26.681 (0.58)	26.235 (0.53)	
	0.11(0.40)	0.32(0.71)	$0.23\ (0.79)$	0.06(0.28)	$0.10\ (0.57)$	
	0.03(0.12)	$0.01 \ (0.31)$	0.00(0.34)	0.01 (0.24)	$0.00 \ (0.07)$	

assessment for marine climate hazards, including compound events, enabling the development of robust measure portfolios that can capture the synergic effects of sets of measures for complex infrastructure subsystems.

The proposed framework aims to comprehensively address the varying physical and environmental conditions that port infrastructures may encounter throughout their lifespan. While it is designed to be modular and adaptable, allowing for the inclusion of key variables like the port's business model, investment cycles, and infrastructure aging, such enhancements would inevitably increase the complexity of the problem and introduce additional uncertainties. Therefore, in order to focus primarily on analyzing the effects of compound hazards and impacts on port infrastructure systems, the decision has been made not to vary risk acceptability, exposure, and vulnerability over time. However, it is acknowledged that future research could delve into these aspects, albeit with careful consideration of the increased dimensionality and complexity that would entail.

Furthermore, the present methodology lacks the capacity to capture the cascading effects of different failure modes between diverse types of infrastructure systems (i.e., roads, power, water systems, etc.) in a highresolution scheme; this approach can be taken in future work.

5. Conclusions

This study presents a methodology that combines traditional critical infrastructure analysis (limited state-based) with the climate change risk IPCC framework to account for climate compound and cascading risks. This methodology can serve as a first approach to the introduction of compound climate change risk assessment methodologies into the evaluation and design of coastal and port infrastructures. Moreover, a modular framework is composed of the three pillars of risk, namely, hazard, exposure and vulnerability. Then it is assessed (quasi)independently, enabling us to (1) update any of the assessment modules with new databases or numerical or empirical models when needed, (2) scale the analysis for ports of different sizes and typologies (when information and resources permit) and (3) replicate it for different types of infrastructure systems to account for the increasing complexity.

In terms of the former, the authors acknowledge that more recent databases are available for several hazard variables (CMPI6). However, the absence of regional met-ocean databases (for waves and storm surges) requires the use of the CMPI5 in order to maintain temporal coherence between hazards, which is required for a consistent climate compound assessment.

Overall, the applicability of the proposed methods is demonstrated in two study cases conducted on the north coast of Spain. First, the results show the importance of accounting for compound impacts when assessing climate change effects on coastal infrastructures, as interactions between sea level, wind and waves can lead to the neglect of damage and downtime when evaluating those impacts independently (as seen in Llanes and Luanco's equipment failure mode analysis). In terms of impact and risk variation, the study results are consistent with those of previous research, as they show an increase in the extreme wave impacts of protection structures that is mainly driven by SLR (Lucio et al., 2024); a decrease in wind effects; an increase in extreme sea levels affecting equipment and berthing activities (Jebbad et al., 2022); and a decrease in operability due to wave agitation, which is mainly driven by an increase in larger waves entering the basin due to SLR (Camus et al., 2019). Considering each CC model realization independently also



a) Port of Llanes



b) Port of Luanco

Fig. 12. Risk variation analysis via infrastructure performance indicators. Green color indicates risk decrease; yellow indicates risk increase, with acceptable values, red indicates unacceptable values.

reveals the high variability of the results when evaluating extreme event-related impacts, which discourages the use of multimodel ensembles for the extreme condition assessment of infrastructures.

Finally, the inclusion of a set of performance indicators for each element, subsystem and port as a whole provides a powerful tool for port planners and decision-makers to first map the evolution of CC and SLR-induced conditions at coastal locations and their effects on analyzed infrastructures at high spatial and temporal resolutions and then to develop and present adaptation plans.

CRediT authorship contribution statement

Alberto Fernandez-Perez: Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. Javier L. Lara: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization. David Lucio: Supervision, Methodology, Investigation. Iñigo J. Losada: Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Fernandez-Perez, A. reports financial support was provided by Spain Ministry of Science and Innovation. Lara, J.L. reports financial support was provided by Spain Ministry of Science and Innovation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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