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A review

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Addressing the challenges of climate change risks and adaptation in coastal areas: A review

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ABSTRACT

Climate change is and will continue altering the world's coasts, which are the most densely populated and economically active areas on earth and home for highly valuable ecosystems. While there is considerable relevant research, in the authors' experience this problem remains challenging for coastal engineering. This paper reviews important challenges in this respect and identifies three key actions to address them: (a) refocusing traditional practice towards more climate-aware approaches; (b) developing more comprehensive risk frameworks that include the multi-dimensionality and non-stationarity of their components and consideration of uncertainty; and (c) building bridges between risk assessment and adaptation theory and practice. We conclude that the way forward includes numerous activities including increased observations; the attribution of coastal impacts to their drivers; enhanced climate projections and their integration into impact models; more impact assessments at the local scale; dynamic projections of spatially-distributed exposure and vulnerability; and the exploration of inherently adaptive options. Given the complexity of the possible solutions, more practical guidance is required.

1. Introduction

Climate change (CC) refers to natural or human-induced changes in the climate state that persist for an extended period, typically decades or longer (IPCC, 2014). Since the 1950s, anthropogenic activity has led to unprecedented and ongoing effects on climate, such as increasing air and ocean temperature, declining ocean pH, and sea-level rise (SLR) (IPCC, 2013). While there is uncertainty about the rates of change that can be expected in the future, it is incontestable that this trend will continue and increasingly cause impacts. CC involves complex interplays between climate hazards, exposure, and vulnerability, resulting in growing risks. This issue is of major concern to the coastal zone (Nicholls et al., 2007; Wong et al., 2014), where impacts are apparent and growing and so are adaptation needs. For instance, the frequency of nuisance flooding, which is the flooding that occurs during high astronomical tides, has doubled along parts of the US coast over the last 30 years due to SLR, making many coastal locations less attractive, lowering property values and encouraging migration away from the coast (Sweet et al., 2018; McApline and Porter, 2018), or promoting adaptation, such as improved floodproofing, barriers or drainage.

While the important implications of CC for coastal engineering have been recognised for more than 30 years (Dean et al., 1987), standard approaches have evolved little and may be falling short in various ways. First, traditional risk assessments do not consider the multiple risk dimensions in a comprehensive way, including changes to climate, environment, society (demography, economy), and values (what people value and want), and their effects on hazards, impacts, exposure, and vulnerability. Second, the assumption that future extreme events, or design conditions, can be predicted solely based on observations is no longer valid (Milly et al., 2008; Hallegatte, 2009; Zscheischler et al., 2018). Hazard, exposure and vulnerability change in time and this requires non-stationary risk approaches. Third, there is a recognised need to transition from deterministic methods that provide little or no uncertainty estimates to more robust approaches that consider uncertainty and can better support risk-informed decisions (Callaghan et al., 2008; Jongejan et al., 2012; Wainwright et al., 2015). Finally, the limited

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guidance on the application of conceptual CC risk frameworks (e.g., IPCC, 2012; IPCC, 2014) leaves many questions open when it comes to simulate coastal hazards and impacts, assess and integrate exposure and vulnerability, and define and implement adaptation objectives.

This paper reviews these challenges and considers steps to address them. The work is organized as follows. In Section 2, we argue the need for traditional coastal engineering practices to be adjusted to face the threats of CC. In Section 3, we discuss the requirements for multi-dimensional and non-stationary risk frameworks. In sections 4 to 7, we explore bridges between risk and adaptation theory and practice. Finally, in Section 8, we provide a summary of avenues for future research and practice and consider the role that disciplines other than coastal engineering can play in the assessment of CC risks.

2. Climate change and coastal engineering

Although the academic discipline of coastal engineering within civil engineering has only emerged since World War II, coastal engineering works have been developed over thousands of years for port and harbour construction, reclamation of land from the sea, and coastal hazard protection (Kraus, 1996). Until the 1950s, coastal defence against flooding and erosion was mainly based on hard structural solutions (e.g., seawalls, levees and bulkheads), which were designed to be cost-effective for their entire lifetime (Sorensen et al., 1984). Since then, there has been a gradual change in engineering defence works on sandy shorelines from hard to soft (e.g., beach fills) and hybrid designs, such as the protection of seawalls and revetments against local scour through toe nourishment (Flemming, 1993; Hanson et al., 2002). This shift brought additional benefits such as aesthetics, natural values and enhanced recreation (Van Loon-Steensma et al., 2014). Over the last decades, our use and understanding of the coast have grown significantly, and the automatic maintenance of hard defences has been questioned (Nicholls et al., 2013). This reflects an appreciation of the benefits of less constrained and more dynamic coasts, the value of natural buffers and sedimentation, and increasing consideration of nature and landscape values in addition to providing safety, with good examples being Australia and the Netherlands (van Koningsveld et al., 2008; Harvey and Caton, 2010; Delta Commissioner, 2010).

In addition to this shift in coastal management, there has been a growing awareness of CC and its potential consequences. Rather than just a change in climate conditions, CC is increasing uncertainty in the future (Hallegatte, 2009), and this can have at least three implications for coastal engineering. First, the need to incorporate CC into mid- and long-term planning decisions. Existing coastal protection structures often have a life of many decades or even centuries. They therefore need to be designed and maintained under a changing climate. Second, the need to integrate local actions for adaptation into larger-scale management schemes. Interventions need to be treated as part as the coastal system to which they belong rather than in isolation (Hall et al., 2003; Nicholls et al., 2013). Third, flexible and incremental adaptation would be beneficial due to the long timescale of SLR (Clark et al., 2016; Nicholls et al., 2018). Flexible adaptive approaches to adaptation are gaining increasing attention (Lawrence et al., 2018; Losada et al., 2019) as they address uncertainty, allow anticipation of problems, and commit to short-term actions while maintaining long-term options open for the less certain future. Hallegatte (2009) provided a well-established classification of adaptation options especially suited to cope with CC uncertainty. These include low-regret solutions that bring benefits without CC although they can also entail losses (e.g., climate-proofing buildings); reversible solutions with the lowest cost of being wrong (e.g., limited urbanisation); safety margin solutions that reduce vulnerability at low costs (e.g., oversizing drainage infrastructures); and soft solutions based on institutional or financial mechanisms (e.g., regulations and insurance products). Note that even if the Paris Agreement mitigation goals are fully achieved, sea levels will still slowly rise for the foreseeable future, and some adaptation remains essential (Fig. 1).

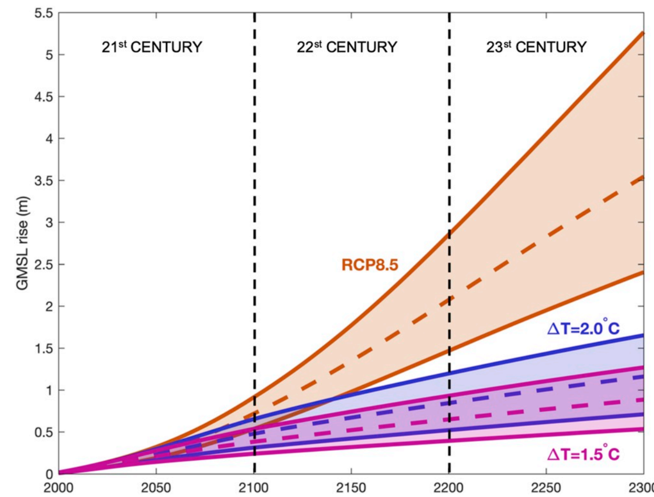

Fig. 1. An example of global mean sea-level (GMSL) rise projections to 2300 relative to 1986–2005 for a large (9×10^4) ensemble using the WASP Earth system model with parameter settings consistent with the models used by Church et al. (2013). Adapted from Nicholls et al. (2018). Dashed lines are the median ensemble projections over time and shaded areas represent the 90% confidence levels for RCP8.5 (orange) and 2.0 °C (purple) and 1.5 °C (magenta) stabilization scenarios.

Recently, particular emphasis has been given to the value of ecosystems in coastal protection (Duarte et al., 2013; Bridges et al., 2015), and the recognition of the significant natural defences we have lost (Beck et al., 2018). While there is no evidence suggesting that nature-based solutions (NBS) might work better than traditional coastal protection options, the design of hard structures has often been based on single values (e.g., associated with scenarios), making the consideration of CC uncertainty difficult. In contrast, NBS can have the potential to self-adjust to incremental CC provided that the rate of SLR does not exceed their tolerance levels. A well-known example integrating NBS into mid-term planning and system-scale management is the mega-nourishment project at the Dutch coast (the Sand Engine project), which is part of the dynamic preservation of the Dutch coast with ongoing shore nourishment where retreat is outlawed and has not been allowed since about 1990 (Roeland and Piet, 1995). It consists of a large single sand placement designed multi-functionally to feed a long stretch of coastline over years to decades and enhance its ecological, recreational and landscape values (Stive et al., 2013; De Schipper et al., 2016). However, at present, for most NBS neither design criteria nor even good scientific understanding of their evolution is established necessitating considerable further research.

A particular challenge with CC is the higher speed and scale at which changes will unfold in the future, making adaptation decisions more complicated (Hallegatte, 2009). For instance, consider the case of a low-probability, high-consequence scenario of rapid collapse of the West Antarctic ice sheet leading to SLR of more than 1 cm/yr (Tol et al., 2006; Bakker et al., 2017). We might easily protect one valuable coastal site, but these changes will be happening globally. What would we protect and where might we choose to retreat? How much would potential solutions cost and how might they be funded? While unlikely, this scenario is possible and worthy of consideration if robust and adaptable solutions are to be proposed (e.g., Lincke and Hinkel, 2018; Nicholls et al., 2019). For rapid sea sea-level rise there are good analogues from subsiding coasts in deltas, especially in Asia (Takagi et al., 2017; Nicholls et al., 2014). Furthermore, the knowledge base continues evolving as climate science advances, and specific training and the most solid background for assessing CC risks may be essential to use this information optimally (Milly et al., 2008). In what follows, we review major challenges in developing comprehensive risk frameworks and assessing their

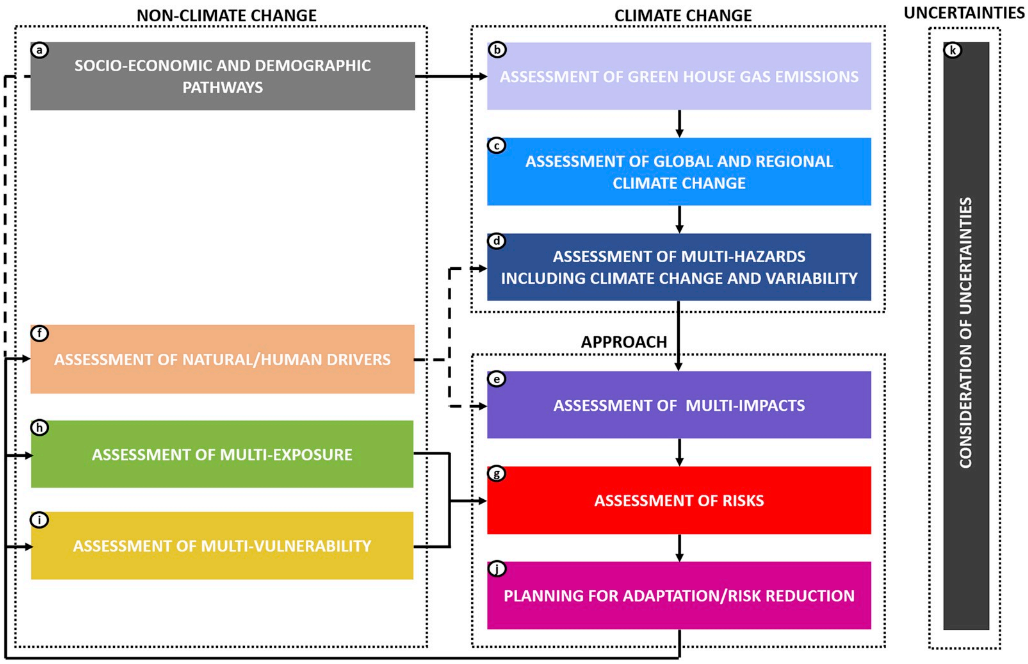

Fig. 2. Conceptual flowchart that illustrates the steps involved in the comprehensive assessment of climate change risks and adaptation. Dashed arrows represent that boxes may or may not be applicable.

components, as these can be key to address complex CC-related issues such as coastal adaptation.

3. Assessing the risks of climate change

The classical conceptual frame of reference applied to the analysis of extreme weather and disasters risks was adopted by the IPCC (2012; 2014), giving rise to a well-established framework in which risk results from the interaction of hazard, exposure, and vulnerability and it is influenced by adaptation and mitigation. This framework has been widely applied by many coastal engineers that work in the field of CC, but it is not the only one since a large part of the community adopts, for instance, the ISO 31000 standard for risk management (e.g., Purdy, 2010; Tonmoy et al., 2018). In order to harmonise understanding of risk concepts and show how risk assessments undertaken using both frameworks may be usefully compared leading to balanced decisions, Table S1 provides the definition of core terminology and possible analogues. While parallels can be drawn in the interpretation of risk, and between impacts and consequences, and hazards and events, ISO 31000 (2018) does not recognise exposure and vulnerability as stand-alone components but includes them in the consequences. Even though exposure and vulnerability are often conflated in the literature, they are distinct. Exposure is a necessary but insufficient determinant of risk, as it is possible to be exposed but not vulnerable, for example, by living in a floodplain but having means to modify a building or structure and mitigate potential losses (IPCC, 2012). However, to be vulnerable and have a propensity to suffer adverse impacts (e.g., flooding), it is indispensable to be exposed. In some high-populated coastal locations, changes in vulnerability may therefore become the main driver of risk.

Current literature on how hazard, exposure and vulnerability are combined in risk analysis is diverse. This ranges from index-based approaches that detect hotspots at large scales or where quantitative data is scarce (e.g., Thieler and Hammar-Klose, 1999; Calil et al., 2017) to further-reaching methodologies that consider multiple sectors (e.g., Toimil et al., 2017a), multiple impacts (e.g., Dawson et al., 2009; Stripling et al., 2017), multiple hazards and vulnerability attributes (e.g., Gallina et al., 2016), or the evolution of risk over time (e.g., Sarhadi et al., 2016; Toimil et al., 2018). All these types of risk analysis are robust in that they assess one or two risk attributes, but none of them are comprehensive. CC brings this issue into focus as it expands the uncertainty. Below we consider the requirements of comprehensive assessments that involve addressing the full risk from several impacts and hazards including exposure and vulnerability interplays, providing a robust quantification of uncertainty, and considering non-stationarity.

The first requirement of such comprehensive risk frameworks is to be multi-impact. Some coastal impacts need to be studied in conjunction in order to model their dependencies, accumulation and cascade effects (IPCC, 2012; Gallina et al., 2016). Examples include morphodynamic changes affecting coastal flooding (Roelvink et al., 2009); physical, ecological and socioeconomic impacts that accumulate after sequential extreme events (Paerl et al., 2001); and system failures triggered by the disruption of critical infrastructures (Chang et al., 2007). Some impacts can be pushed to extreme levels due to the co-occurrence of multiple dependent hazards interacting across different spatial and temporal scales. For instance, long-term changes in climate, hurricanes causing heavy wind and rain, and local storm surges and flood events (Zscheischler et al., 2018). Addressing this issue requires multi-hazard approaches aimed at covering the full probability space of all possible future conditions and reproducing the real complexity of the processes underlaying. The simulation of compound climate hazards can be challenged by limitations in the current multivariate approaches used to model their interdependencies, non-linear interactions (Moftakhari et al., 2017), and non-climate drivers (e.g., geological hazards and human activity), which may lead to inappropriate design levels or increased probabilities of structural failure if disregarded (Salvadori et al., 2015). For example, tsunamis and earthquakes need to be included in multi-hazard analysis for susceptible regions such as the Pacific coast. Subduction zone earthquakes can induce large-scale coastal subsidence, such as the sinking of Honshu post Tōhoku earthquake (2011) on the order of 1 m, and a similar land displacement expected to occur in Oregon and Washington after the next Cascadia earthquake. Possible human-induced changes that could be important are enhanced subsidence due to ground fluid withdrawal or falling/-failing sediment supplies to the coast due to upstream dam construction.

Additionally, comprehensive frameworks require to be multi-exposure and multi-vulnerability. Exposure is typically expressed

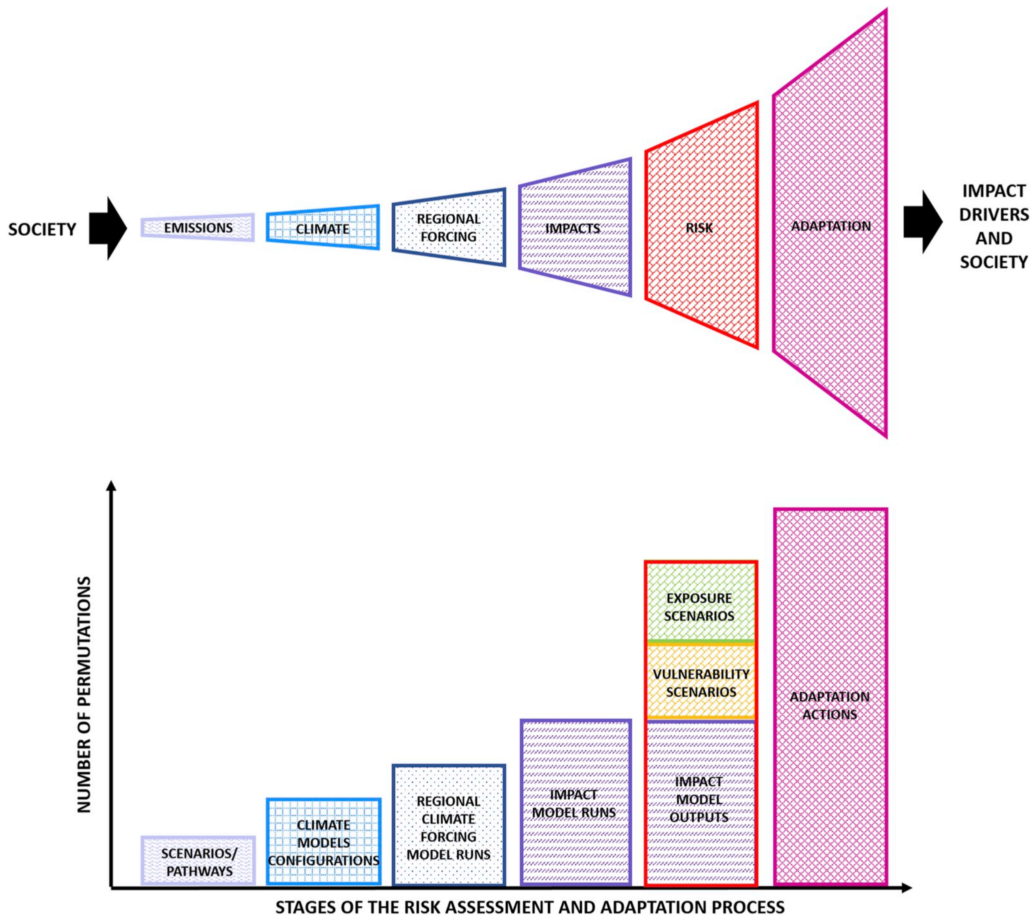

Fig. 3. Conceptual illustration of the cascade of uncertainty in which uncertainty is associated with the area of the shape (upper panel); and ways to consider as many likely futures as possible, and hence incorporate uncertainty, at each stage of the process (lower panel).

through sectors (e.g., coastal ecosystems, socioeconomic settings, human activities, governance contexts) and the associated socioeconomic and natural indicators, which need to be allocated geographically and at the appropriate resolution. This is especially challenging when dealing with multiple sectors where information is heterogeneous in terms of format, time and space (Toimil et al., 2017a). Vulnerability varies across impacts and exposed elements, and its integrated assessment requires combining quantitative and qualitative approaches to capture its multiple dimensions (IPCC, 2012).

Fig. 2 illustrates a conceptual scheme with the steps involved in a comprehensive, integrated assessment of CC risks and adaptation. As we consider further into the future and also larger spatial scales, this type of approach becomes more and more relevant. First, the assessment of greenhouse gas (GHG) emissions (b) resulting from socio-economic and demographic pathways (a), which may also lead to non-climate drivers (e.g., human-induced changes in land use) and influence exposure and vulnerability (f). Second, the assessment of CC through global and regional circulation models (GCMs and RCMs, respectively) (c). Third, the assessment of multi-hazards considering CC and variability (d) and incorporating relevant non-climate drivers if any (e.g., land subsidence/uplift) (f). Fourth, the assessment of multi-impacts, including additional natural/human factors if applicable (e.g., the effects of dams on sediment supply) (f). Fifth, the assessment of risks (g), combining the outcomes of the multi-impact assessment (e), multi-exposure (h), and multi-vulnerability attributes (i). Finally, adaptation (j) comes full circle as it can affect multi-vulnerability (i), multi-exposure (h) and non-climate drivers (f). There are uncertainties through the entire process that need to be considered (k).

The approaches used to assess the multi-risk components depend on the geographic scale, data availability and the models used, resulting in different levels of uncertainty, which spreads across the steps (Fig. 2) and accumulates in a cascade form (Wilby and Dessai, 2010; Ranasinghe, 2016) although not necessarily follows a linear sequence. Fig. 3 shows a conceptual representation of uncertainty cascade (upper panel). Uncertainty comes from socioeconomic development and demographic pathways, translates into GHG emissions, propagates through GCMs and RCMs, regional coastal forcing models (RCFMs) and local coastal impact and damage models, and reaches the adaptation response. Uncertainty in future risk also grows with timescale (Ranger et al., 2013), and hence needs to be considered in planning decisions. A robust quantification of uncertainty assessing across possible futures can be addressed differently across the steps (Fig. 3, lower panel). We propose uncertainty to be mainly but not exclusively considered using ensembles of GHG emissions scenarios or representative concentration pathways (RCPs, Moss et al., 2010), different RCM-GCM configurations, multiple simulations of impact models with different combinations of forcing variables, multiple exposure and vulnerability scenarios, and flexible adaptation.

However, not all these issues have been addressed in a satisfactory way to date. For example, future socio-economic pathways are a key uncertainty that goes far beyond CC. Considering multiple socioeconomic pathways allows us to understand how sensitive our decisions might be to different futures. This societal dimension becomes increasingly important as the spatial scale increases, informing policy analysis of budgets, prioritisation or strategic approaches. Hence, although it is not so important at the local scale, we need to include CC in design.

Another critical issue is that making the necessary runs of the impact model in a reasonable amount of time requires fast and relatively simple models that are also accurate enough to simulate the dominant physical

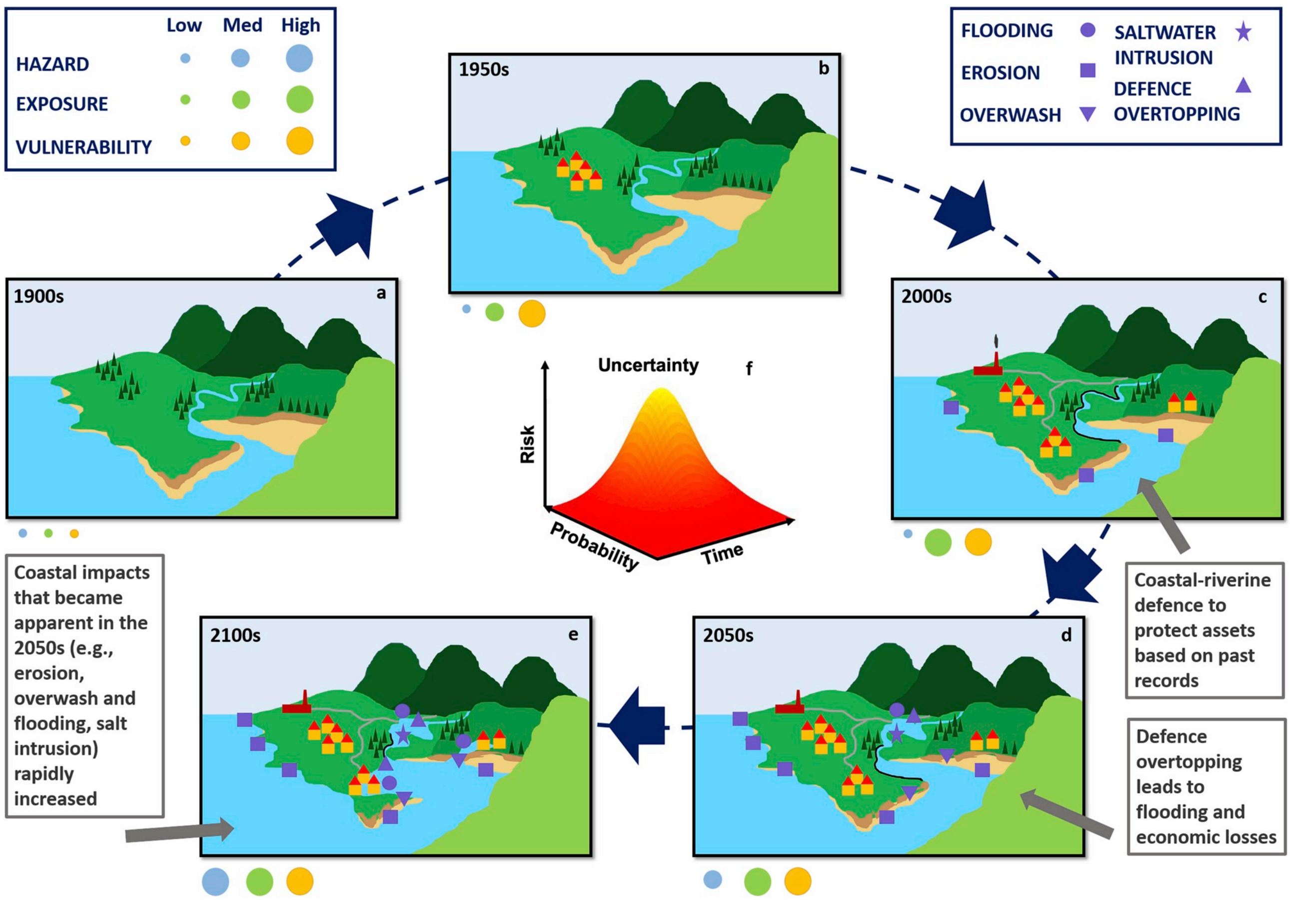

Fig. 4. Moving clockwise from the 1900s, a conceptual illustration of a hypothetical evolution over time of hazard, impacts, exposure, and vulnerability in a coastal system subjected to climate change. The temporal evolution of the risk components leads to the temporal evolution of risk itself (panel f, where non-stationary risk can be expressed e.g., in economic or accounting terms, as a percentage, or dimensionless). The amount of hazard, exposure and vulnerability is shown at the lower left corner of panels a–e.

processes (French et al., 2015). In the case of using computationally demanding models, stratified sampling methods (Ranasinghe, 2016) or hybrid downscaling techniques (Camus et al., 2011) can be used to increase efficiency, reducing the number of simulations required to quantify uncertainty. Additionally, incorporating uncertainty in exposure and vulnerability requires the damage model to operate as a structural function in a probabilistic approach (e.g., Monte Carlo), drawing thousands of samples that combine the impact model outcomes with multiple exposure and vulnerability scenarios. We encourage a deeper focus on developing and implementing fully probabilistic risk assessments aimed at integrating all of the information sources involved so that a better understanding of change can be achieved. This may entail processing very large amounts of data and heavy computational costs; hence advanced statistical analysis and super computers may be required. Ultimately, flexible adaptation and systematic monitoring can be essential features to deal with uncertainty through the planning and adaptation process (Ranger et al., 2013).

Alternatives to probabilistic approaches are conditional probabilities and extra-probabilistic theories. The first incorporates the relative importance of predictor classes in determining the probability of hazard (e.g., Keyser and Westerling, 2017); the second pursues to assign imprecision to probabilistic measures, which can be achieved by introducing expert judgement (e.g., Le Cozannet et al., 2017a). These methods have been used to characterise climate hazards, but their application within impact modelling and risk assessment remains unexplored.

The last need for comprehensive risk frameworks is the consideration of non-stationarity. Traditional risk analysis has typically assumed that exposure and vulnerability would remain unchanged, and that hazard variables had time-invariant probability distribution functions (pdf) whose properties could come from instrument record or reanalysis, hence limiting future risk estimates to observations. However, CC effects are already observable (IPCC, 2013; Letcher, 2015) and will continue, causing higher impacts, interacting with evolving exposure and vulnerability, and ultimately growing risk levels. Fig. 4 shows a hypothetical evolution of hazards, impacts, exposure, and vulnerability in a coastal system subject to CC over more than a century to represent the non-stationarity of risk. In the 2000s, a significant increase in exposure and vulnerability (a-b-c) led to the construction of a coastal-riverine defence (c), which failed some decades later as it was wrongly designed assuming that historical compound hazards could adequately represent future conditions. By the 2050s, CC may have altered extreme river flows, SLR may have increased the likelihood of extreme waves and storm surges, and their associated impacts may be apparent, including beach erosion, dune breaching, defence overtopping, and ultimately flooding (d). Defence failure may be produced by coastal-riverine dynamics acting jointly, causing flooding of the road and incurring in economic losses by interrupting the activity of the plant nearby. If adaptation were ignored, by the 2100s, settlements may no longer be protected and experience chronic inundation due SLR compounded by land subsidence, many beaches may disappear, and saltwater may migrate upstream (e). However, theoretical frameworks and supporting tools that allow representing such complex dynamics quantitatively are so far undeveloped.

The non-stationarity of risk has at least four implications for addressing and modelling multi-dimensional hazards and impacts, exposure, and vulnerability. First, GCM and RCM biases need to be corrected before using GCM and RCM output to produce projected forcing conditions for impact models. Otherwise, biases would be introduced in subsequent impact simulations (Maraun et al., 2017), reducing the capability of reproducing extreme events and statistics that depend on the temporal sequence of the original field (Dosio and Paruolo, 2011). Second, the quality of modelled future climate cannot be evaluated against observations, and calibration parameters based on current standardised relationships (e.g., rainfall and catchment's antecedent conditions in a hydrological model) may be no longer appropriate (Zscheischler et al., 2018). Third, the economic development model implemented over the last decades is increasing coastal urban pressure and ecosystem degradation. Since this trend is expected to continue but it is difficult to be predicted, generating scenarios of changes in population, economic growth, built and natural capital, and land us covering many possible futures (e.g., using spatial simulation models and cellular automates) would be highly beneficial. Fourth, future hazards may alter vulnerability by, for instance, reducing resilience, and this can be different across the exposed elements and from one impact to another. While capturing the full spectrum of possible changes in vulnerability attributes is not realistic, scenarios representing likely futures including the possibility of enhancing resilience and adaptive capacity could be developed where appropriate. Efforts in these directions would allow working with the temporal evolution of risk probability considering its multiple dimensions (f in Fig. 4).

4. Identifying and addressing climate hazards and drivers

Global-mean SLR is unequivocal, although its rate and magnitude are both increasingly uncertain beyond 2050, mainly due to the large unknowns in the melting of the Greenland and Antarctica ice sheets (Deconto and Pollard, 2016; Kopp et al., 2017). The assessment of coastal impacts and risks requires regional SLR values rather than global, as mean sea level is not rising uniformly across the world due to many processes that contribute to spatially varying patterns (Mitrovica et al., 2001; Willis and Church, 2012). In particular, land subsidence compounds regional/local SLR in densely populated, subsiding coastal cities and deltas, which often already have significant areas below normal high tides and depend on defences and drainage to be habitable (Nicholls et al., 2014). This is especially important in south, south-east and east Asia.

SLR is normally linked to specific emissions or concentrations scenarios. The likely ranges presented in IPCC Fifth Assessment Report for each scenario cover the 67% probability, and hence exclude the highest outcomes, which may be essential for design purposes (Hinkel et al., 2019). For instance, combining full probability distributions of SLR projections with extreme value distributions allow obtaining estimates of the expected number of years in which flooding exceeds a given elevation (Kopp et al., 2014). Uncertainty associated with the potential rapid disintegration of the Antarctic Ice Sheet has been included into updated probabilistic SLR projections (Le Bars et al., 2017; Kopp et al., 2017).

Many authors have proposed high-end scenarios to address uncertainty in SLR components (Bamber and Aspinall, 2013; Jevrejeva et al., 2016; Deconto and Pollard, 2016). However, although the assessment of CC risks benefits from considering the existing knowledge, we need to be careful about projections that are not fully agreed upon as they may be even more uncertain (e.g., from semi-empirical models). Thus, an authoritative assessment of all available SLR projections and a scientific consensus on the appropriate representation and interpretation of high-end changes would be beneficial (Stammer et al., 2019). Furthermore, developing robust statistical approaches that allow combining probabilistic SLR estimates with other impact drivers such as waves, storm surges and tides is of key importance to set appropriate boundary conditions for the impact models. An example is the dynamic approach proposed by Vousdoukas et al. (2018) in which the individual pdfs of all the projected extreme sea level components (i.e., regional SLR and water levels driven by waves, storm surges and tides) are obtained and combined using a Monte Carlo simulation.

However, decisions cannot be postponed until ideal or more certain SLR scenarios are produced, and the inadequate or no consideration of uncertainty may lead to misleading impact assessments, poorly-informed decisions or maladaptation with costly results (Ranger et al., 2013). For the timescale between 30 and 100 years into the future, scenarios need to include a wide range of SLR estimates, including low-probability high-consequence events, such as the rapid deglaciation in Greenland or Antarctica (Bakker et al., 2017), provided a consensus is reached. For longer timescales, two aspects need to be considered. The first is that SLR projections have to extend beyond 2100 to analyse the full effects and to make good decisions today on long-term planning and long-lived investments. For example, nuclear developers need to design new coastal plants (whose life cycle may extend well into the 20-s century) to be able to cope with SLR, higher ocean temperatures, and more frequent extreme events. The second implication is that, even with stringent climate mitigation, some impacts may be delayed rather than avoided (Wong et al., 2014).

Recognising SLR as the main CC driver in coastal areas has resulted in improved regional projections (e.g., Slangen et al., 2014; Carson et al., 2016), improved consideration of uncertainty (e.g., Perrette et al., 2013; Kopp et al., 2014; Stammer et al., 2019) and improved communication with stakeholders and decision makers (e.g., Nerlich et al., 2010; Wahl et al., 2018). However, the science of waves, storm surges and river discharge lags behind SLR's and their projections have not yet been fully incorporated into risk assessments, neglecting relevant coastal impacts drivers. Uncertainty in climate projections is deep, partly due to our lack of a complete knowledge of climate processes and our inability to represent them with computationally affordable models (Stainforth et al., 2007; Ranger et al., 2013). Further, GCMs and RCMs (that for the RCPs typically operate at resolutions of 0.56°-3.75° and 0.11°-0.44°, respectively) have limitations and do not provide the information required by impact models. Their outputs can be downscaled using statistical, dynamic, or hybrid modelling approaches. Using dynamic or statistical downscaling methods has several pros and cons. Dynamic downscaling provides data coherent spatially and temporally across global climate variables and can be used where no observations are available. However, it can be high computationally demanding, especially where higher model resolutions are not available, hampering multiple realisations. The dynamic approach delivers future time series of, for instance, waves and storm surges to which non-stationary statistical analysis can be applied to obtain extreme and mean climate distributions. This provides added value for infrastructure design and operation, as capital expenditures (Capex) are obtained using extreme values for different return periods, and operating expenses (Opex) require parameters of the mean distribution. Instead, statistical downscaling relates GCMs output to variables that are not simulated by climate models (e.g., waves, storm surges, sea surface temperature). It can deliver local estimates and it is computationally efficient, allowing long-term simulations at high spatial resolutions using multi-model groups, hence reducing uncertainty (Camus et al., 2014). The downside of the statistical approach includes the assumption that past statistical relations remain stationary in the future and its tendency to underestimate extremes.

Key aspects of making accurate projections include understanding contemporary extreme waves and water levels and quantifying their associated uncertainty (e.g., Wahl et al., 2017), and analysing recent changes and their driving mechanisms (e.g., Reguero et al., 2019; Young and Ribal, 2019). Further research efforts are needed to produce enhanced projections of mean and extreme climate conditions with higher resolutions and a robust quantification of the uncertainty cascade (Morim et al., 2018). The IPCC Fourth Assessment Report motivated an increase in research on wave climate projections as they were recognised as major drivers for coastal impacts (Hemer et al., 2010). In 2011, the

Coordinated Ocean Wave CLImate Projections (COWCLIP) working group was created to compile wave climate projections studies, revise methods, establish working protocols and develop technical frameworks. This encouraged considering uncertainty in projected changes (e.g., using ensembles) and developing multi-model wave climate projections using dynamical (Hemer et al., 2013; Mentashi et al., 2017; Casas-Prat et al., 2018) and statistical approaches (Wang et al., 2014; Camus et al., 2017). Among the studies developed, consensus in the projected signal of change in mean wind-wave height over the 21st century was found stronger than in extremes (Morim et al., 2018). This indicates that the latter demands a deeper focus, as it is essential information, for example, to determine the accidental damage and ultimate limit state design loads for coastal structures. Further, few works include information on wave period and direction, although these could have significant implications for coastal impacts such as dune erosion (Van Gent et al., 2008). As for wave climate projections, future changes in storm surges and extreme sea levels have been obtained at global (Wahl et al., 2017; Vousdoukas et al., 2018) and regional (Vousdoukas et al., 2016, 2017; Lee et al., 2017) scales, but not at the resolution needed for coastal engineering applications. The assessment of coastal risks, the implementation of adaptation measures or the design of coastal structures need projected impact drivers to be transferred to the coast to incorporate local effects.

There are at least three challenges for the development of climate projections. First, compound events are complex, and resolving them in projections may require approaches focused on impacts rather than on drivers, and improved GCMs and downscaling techniques (Zscheischler et al., 2018). GCMs with better resolution and physics may allow reproducing smaller-scale phenomena such as tropical cyclones, which are so far approached by dynamical downscaling, for instance, coupling climate and high-resolution regional or local models (Lin et al., 2012; Emanuel, 2013). Second, non-linear interactions between SLR components, tides, waves, and storm surges have shown to be relevant locally and with important design implications (Arns et al., 2017). Including these effects in probabilistic climate projections requires fully coupled modelling approaches that are at present highly computationally demanding (Vousdoukas et al., 2018). Finally, transferring climate uncertainty to impact estimates needs probabilistic projections of all climate drivers (not only SLR) to be combined appropriately to feed into impact models.

5. Evaluating the escalating impacts of climate change

Coastal areas will undergo different CC physical impacts, the most relevant being inundation and erosion, which can occur at different time scales (episodic or chronic) (Ranasinghe, 2016). Other expected impacts include salt intrusion of surface and ground waters, increased downtime and operational delays in ports and harbours, loss of coastal natural protection due to coral bleaching, and the decline/loss of coastal wetlands (Nicholls et al., 2007; Wong et al., 2014).

Coastal flooding is probably the most well understood and widely modelled impact. It is known that it is not the chronic inundation, but rather the storm-induced, high-tide or nuisance flooding that will lead to the abandonment of the shoreline or to an accommodate or protect adaptation response, and this will occur long before inundation. However, comprehensive methodologies and cases study that combine mean SLR and projected extreme sea levels and waves probabilistically to produce flood maps remain very low (Arns et al., 2017; Sayol and Marcos, 2018). We also encourage a deeper focus on the multivariate assessment of flood extreme events that result from the combined action of waves, storm surges, tides, SLR, and river discharge in estuarine and deltaic areas, especially considering relevant conditions that have no precedent in observational records (Zscheischler et al., 2018). There are different multivariate approaches to consider interdependencies among climate drivers in this field. They all have pros and cons, including Archimedan and extreme-value copulas (Masina et al., 2015), elliptical copulas (Wahl et al., 2016; Sayol and Marcos, 2018), multivariate logistics models (Serafin and Ruggiero, 2014), and conditional approaches (Heffernan and Tawn, 2004). Copulas are widely used since they can be easily constructed and the joint return period is defined by the copula itself (Salvadori et al., 2007). However, they can have limitations in modelling tail dependence or allowing multiple dimensions (Wahl et al., 2016). Enhancing the simulation of the statistical dependency between correlated drivers and applications that incorporate climate projections are required to improve the assessment of CC flood risks.

Recently much has been achieved to improve understanding and modelling of sediment fluxes and linkages governing coastal processes and shoreline change, including CC, whose implications seem to go far beyond setting the conditions for the upward and landward displacement of the coast. For instance, the recognition that the Bruun effect (Bruun, 1962) can be insufficient to describe the sediment budgets (Rosati et al., 2013; Dean and Houston, 2016; Toimil et al., 2017b), especially in inlet-interrupted coasts (Stive and Wang, 2003; Ranasinghe et al., 2013). However, much more remains to be done. For example, modelling non-linear interactions and coupling processes occurring at different scales on timescales of beyond a few years (De Vriend et al., 1993; Stive et al., 2002; Ranasinghe, 2016); or developing a fully satisfactory model that couples hydrodynamics and morphodynamics, reproduces short- and long-term shoreline changes, and that it is not too computationally expensive to consider uncertainty. Overall, there is a recognised need to better quantify uncertainty in shoreline change modelling (Ranasinghe et al., 2012). Thousands of sequences of multivariate design storms (Callaghan et al., 2008) or synthetic multivariate time-series of waves and storm surges (Toimil et al., 2017b) can feed into erosion models to produce probabilistic coastal erosion estimates. Different forcing variables with different chronologies can lead to extreme events that are different in their timing, number, magnitude, and duration. This does not play a fundamental role in long-term recession but can highly influence short-term shoreline change (Toimil et al., 2017b).

The assessment of CC impacts in ports, harbours and coastal structures also requires additional research efforts. Priority needs encompass the development of appropriate design standards and specified decision criteria to help to integrate climate information into port and harbour planning and management (McEvoy and Mullett, 2013). Since CC is expected to alter the operability and stability of coastal structures beyond the baseline conditions assumed for design (Camus et al., 2017, 2018), more comprehensive methodologies that allow considering mean and extreme climate conditions and including the associated uncertainty are required. This focus reinforces the need for modelling the operability and stability of coastal structures over time, for example, by considering non-stationary reliability and resilience, and analysing potential influencing factors such as changes in load intensity, and the contribution of the quality of periodic maintenance to their conservation and degradation (Li et al., 2015). The same approach may apply to port and harbour infrastructure, where a similar analysis could be carried out on both facilities and operations.

Observations are valuable supportive tools to constrain impact models (Cazenave and Le Cozannet, 2013). Systematic monitoring programmes focusing on coastal impacts are essential to enhance risk assessments. Although non-stationarity implies that the absence of past impacts cannot constitute evidence against the possibility of future impacts, detection and attribution can provide a form of improving our understanding of impact drivers and refining future projections (Cramer et al., 2014). Challenges include creating coastal observatories and establishing observing networks that allow collecting field data on the drivers (e.g., tide gauges, global sea level observing systems (GLOSS) and buoy networks, reanalysis and satellite measures) and on the associated impacts (e.g., flood depths/extents and shoreline changes using cameras and drones, and salt concentration and pollution using sensors). This systematic data collection would enable producing high-resolution, continuous, long-term observations available and developing methods and tools that help make progress in disentangling the factors affecting coastal systems beyond CC, whose interplays are non-linear, non-local, and hard to understand and quantify (Stone et al., 2013; Cramer et al., 2014). While strides have been made over last years, techniques (e.g., based on advanced statistical analysis and remote sensing) that allow attribution with high confidence remain low.

6. Considering dynamic exposure and vulnerability

Exposure includes the whole inventory of elements that can be adversely affected by an impact. Although reducing exposure to physical assets such as buildings and infrastructures is common practice, information associated with indirect effects (e.g., sectoral GPD, income) cannot be disregarded. For instance, when an industrial plant becomes flooded, consequences are not limited to damages to structure and contents but can include loss of profits due to business interruption or delay. However, obtaining such detailed data geographically distributed is a challenge in many regions, and many studies have no other option than describe exposure using land use data instead of socioeconomic indicators (e.g., Prime et al., 2015). Another usual simplifying assumption is considering an equal distribution of elements over a whole administrative area (Merz et al., 2010), provided that an aggregated value is available. Disaggregation methods that rely on ancillary data (e.g. topographic maps, traffic and telecom networks, per capita income) to achieve better representations of population, assets and associated activities on the ground have already been developed (Thieken et al., 2006; Toimil et al., 2017a), but more standardised downscaling approaches and calibration tools are required. In fact, this would be essential to achieve robust projections of future spatially-distributed exposure. Finally, there is a widely recognised need to improve the economic valuation of tangible and intangible ecosystem services some of which are difficult to value (Toimil et al., 2018; Mehvar et al., 2018; Beck et al., 2018).

Since the ability of the systems to cope with change varies with time and across physical space and social frames, vulnerability has many facets (e.g., economic, social, demographic, geographic, environmental, cultural, institutional, and governance) (IPCC, 2012). Methods to assess vulnerability are diverse, including participatory, model-based, agent-based, and index-based approaches (Hinkel, 2011), as well as the damage functions used in the analysis of episodic flood risk. Damage functions are sector-specific and differentiate between direct damage (damage subject to restoration or rebuilding) and indirect loss of profit, and between business delay (reversible but with cost overburden) and disruption (irreversible). Given the local nature of damages, empirical functions built upon data gathered in the aftermath of real events are preferred than the synthetic or theoretical ones. Historical data on damages and losses are however scarce. Further, although flood depth may be the parameter that most affects damage to assets (Penning-Rowsell et al., 2005), flow velocity and event duration may play a key role in agriculture production and ecosystems, whose integrity also depends on the type, living conditions, and coping capacity.

Another challenging issue concerns the assessment of the vulnerability of coastal structures. Many studies have focused on the stability of rubble-mound structures address the damage progression of armour layers during sea states and storms (e.g., Kobayashi et al., 2010; Melby and Jobayashi, 2011). Some of these approaches allow reproducing damage accumulation stochastically and yield its statistical distribution (e.g., Castillo et al., 2012), but none provides the temporal evolution of the damage during the entire structure lifetime. The way forward includes the development of reliability methods based on the full probabilistic distribution of basic variables (the so-called Level III approach, Burcharth, 1993) allowing comprehensive understanding of structural reliability and resilience over time, including the influence of CC in damage, and its connection with the different failure modes. This will contribute to incorporating uncertainty in failure probabilities.

There is an overall need for methodologies and metrics to evaluate the vulnerability of coastal system, both in terms of their sensitivity to impacts, and their ability to adjust to harm (adaptive capacity), especially for impacts other than flooding (e.g., Toimil et al., 2018). Vulnerability projections need to capture the complex and dynamic behaviour of individuals, business, and governance bodies (Aerts et al., 2018). For instance, they need to consider maintenance strategies that help systems to withstand impacts and increase resilience, and flexibility in management and operation, which may allow them to enhance their adaptive capacity. In addition, methods and supporting tools to integrate vulnerability information into risk assessments easily would be beneficial.

7. Adaptation in the context of uncertainty

CC is a real threat that requires adaptation. Classical adaptation options include planned or un-planned retreat, accommodation, protection, and attack (build seaward). These imply analysis, design, planning, and societal decisions. Unplanned retreat is the worst case as relocation and abandonment are forced. While we acknowledge these different alternatives, we focus on protection here.

Traditional hard solutions for coastal protection involve structural features, in which continual and costly maintenance (e.g., raising and widening to keep pace with increasing risks) and undesirable ecological side-effects such as coastal squeeze raise concerns (Temmerman et al., 2013). Although much less understood and presently more speculative, there is growing interest in NBS (Duarte et al., 2013; Temmerman et al., 2013; Bridges et al., 2015). It is argued in the literature that they might have notable advantages over hard structures, for example, being more cost-effective and self-sustaining in the long-term, including CC, due to their dynamism and self-capacity to recover and regenerate following damage (Spalding et al., 2013). This may be valid in many cases, although stronger evidence is needed. NBS also have drawbacks. First, ecosystems require significant space and are not suitable for highly urbanized coastal cities unless these cities are placed far inland in estuaries/deltas (Temmerman et al., 2013). Second, NBS are not as well understood as traditional systems and may not reach the standards of protection required (Van der Nat et al., 2016). Finally, the uncertainty in their future state and function hinders their application. Thus, while ecosystems subject to CC potentially remain in place for longer periods of time than hard defences, this is beyond our present understanding, and the expected service life of NBS requires further research. For instance, we need information on costs, time to become established and effective, seasonal variation of protection, evolution of residual risks, regenerative or adaptive capacity and resilience, performance levels when restored by human intervention, failure modes, tipping points and operating thresholds. Guidelines for NBS are limited and their implementation is still small-scale (Pontee et al., 2016). Experimental practice and systematic monitoring programmes are fundamental to improve our understanding of NBS, informing on appropriate designs that offer high protection levels. We argue that strong claims about the success of NBS in coastal engineering terms have to be treated with great caution, reflecting the limited experience.

Hybrid approaches that combine NBS with traditional engineered options might be in the interim in terms of effectiveness and affordability. Recent studies supported the identification, evaluation and integration of NBS within structural and non-structural solutions to enhance resilience (Bridges et al., 2015; Ecoshape, 2018). Marsh-levee and dune-dyke systems are two examples in which NBS may contribute to downsizing structural defences and reducing residual risks. Vuik et al. (2018) demonstrated that vegetated foreshores can lead to a reduction in dyke failure probability against wave impact and overtopping, which has long been appreciated (Rupp-Armstrong and Nicholls, 2007). The evidence to support hybrid options varies but is generally stronger than for NBS (The Royal Society, 2014). It might be the case that an existing coastal protection structure no longer meets the design performance criteria, and neither NBS nor hybrid solutions are

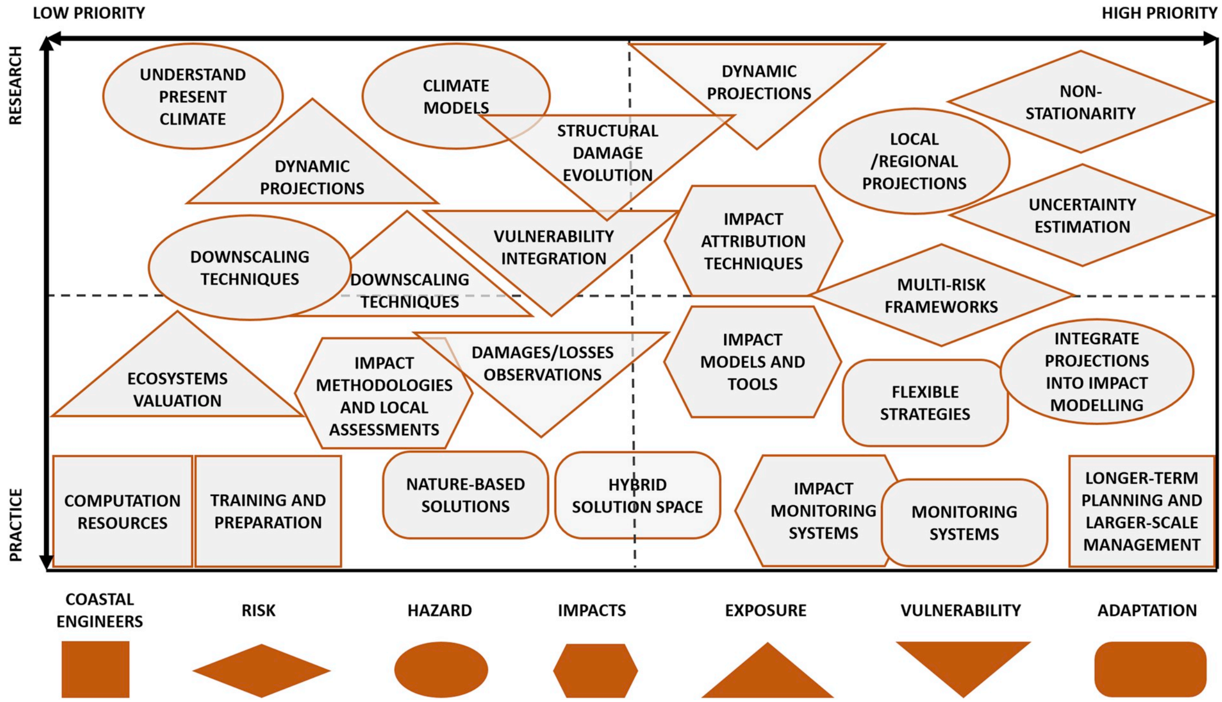

Fig. 5. Illustration of the main challenges identified for coastal engineering. Subjectively, they are mapped by degree of priority and research-practice emphasis. Shape shows the area to which they belong according to the structure of the paper.

feasible, or they do not guarantee the safety standards required. Alternatives may include the progressive raising of ports (only part of the port is raised at one time, allowing port operations to continue elsewhere as experienced in Indonesia, Esteban et al., 2019) and the upgrading of structures (e.g., rubble mound) by, for instance, modifying the profile and/or adding structure elements (Burcharth et al., 2014).

The selection of the most suitable adaptation options is complex due to the uncertainty in CC, particularly beyond 2050. Therefore, although we ultimately need to adopt specific values for design, plausible higher changes are worth exploring to inform long-term performance under such design and encourage flexibility. Dynamic adaptive plans such as the adaptation pathways (AP) (Haasnoot et al., 2013) allow identifying when, how and how much to adapt keeping pace with changing conditions, provided they are supported by systematic monitoring. The AP consist of sequences of actions linked through adaptation tipping points, which indicate that a new action is needed to meet certain adaptation objectives (Ranger et al., 2013). Thus, the AP are not triggered by time itself, but by threshold levels (e.g., water levels) being exceeded. A well-known example is the Thames Estuary 2100 Project, which identified a range of adaptation options for up to a 5-m rise in sea level, allowing the development of adaptive planning to manage London's coastal flood risk far into the future (Tarrant and Sayers, 2012). However, real-world applications of the AP approach remain at present limited, and there are good reasons to think that their expansion to other coastal systems is going to be gradual. The first reason is that high technical capacity, strong financial and management resources, and high-order institutional commitment are required (Barnett et al., 2014). The second reason is the need for clear and predetermined adaptation objectives, including acceptable or tolerable risk levels that can be highly contested due to strong institutional and social values (Turner et al., 2016). The third reason is the difficulty in identifying, monitoring and analysing signposts and triggers to get timely signals for adaptation, which remain more at the formulation rather than at implementation phase (Haasnoot et al., 2018). Finally, understanding and enhancing the adaptive capacity of structural, ecological or human systems, and measuring the effectiveness of adaptation options at every level, their appropriate timing and their possible combination to build resilience, are fields still full of uncertainties in coastal engineering.

8. Recommendations on addressing climate change in coastal engineering

This paper focuses on identifying the main challenges for coastal engineers on the assessment of climate change risks and adaptation approaches for coastal areas. Below, we present an overall summary of avenues for future research and practice, which have been organised in seven blocks following the paper structure:

Coastal engineering. While climate change is considered by coastal engineers, this needs to be strengthened, especially regarding mid- and long-term planning, and adaptation actions require to be part of system-scale management schemes. Coastal engineers would benefit from specific training and preparation on climate change risks and adaptation issues. For structure design and planning for adaptation, they need to consider the widest range of possible futures changes. In some cases, current computational resources may be a constraint.

Risks. More comprehensive risk frameworks are needed to determine the holistic risk due to several impacts and hazards, including vulnerability interactions and multiple sectors. Such approaches require considering the non-stationarity of the risk components and allowing to quantify uncertainty.

Hazards. Efforts need to be directed towards a better understanding of present climate and recent changes, improved climate models and downscaling methods, enhanced local projections of mean and extreme climate conditions that provide uncertainty estimates, a consensus on how to represent and interpret high-end changes, and the combination and integration of probabilistic projections into impact models. This is particularly relevant for coastal drivers (e.g., waves and sea levels).

Impacts. Methodologies and supportive tools are needed to assess future multivariate flood extreme events appropriately, model coastal erosion comprehensively, and project changes in coastal structure operability and stability over time. Increased observations and monitoring, more impact assessments at the local scale, enhanced attribution techniques, and consideration of uncertainty are required.

Exposure. Research needs encompass dynamic projections of spatially-distributed exposure, standardized downscaling methods and calibration tools, and enhanced methodologies to assess the value of ecosystem services.

Vulnerability. The way forward includes dynamic projections of vulnerability, field data to derive empirical damage/loss functions, methodologies to assess the probabilistic evolution of the structural damage, and improvements on the integration of vulnerability information into risk assessments.

Adaptation. Major challenges involve developing and implementing flexible adaptation approaches and the associated monitoring systems and exploring inherently adaptive solutions such as nature-based or hybrid, whose behaviour requires better understanding. Practical applications of the adaptation pathways approach would be beneficial for coastal engineering.

These challenges have been mapped in Fig. 5 reflecting our perspectives on the issues. The horizontal axis represents the degree of priority (indicative) and the vertical axis indicates the research-practice emphasis. Shapes allow classifying the challenges according to the aforementioned blocks.

Coastal engineers bring an overarching knowledge that places them in a strong position for leading coastal risk and adaptation assessments, which are growing in importance in their practice. However, dealing with such complex issues requires extensive collaboration and synergies across many fields of research. For example, atmospheric scientists and climate modellers develop future climate projections upon which risk assessments are based, oceanographers and hydrologists play a key role in understanding and modelling climate hazards and impact drivers (also known as climate services, Le Cozannet et al., 2017b), and impact modellers produce impact estimates that combine with socioeconomics, which requires collaboration with economists and social scientists. Risk-related outcomes are used by coastal managers and policy makers to make risk-informed decisions (e.g., on infrastructure design or adaptation planning) and to develop policy instruments; and by private bodies such as (re)insurances to create new products (e.g., insurance premiums). Coastal engineers have specific knowledge from some of these disciplines (typically climate and impact modelling but not exclusively) but need to work with other professionals to provide multidisciplinary and comprehensive approaches to climate change risk assessment and adaptation processes.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.coastaleng.2019.103611.

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