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

Toimil, Alexandra; Losada, Iñigo J.; Nicholls, Robert J.; Dalrymple, Robert A.; Stive, Marcel J.F.

**DOI**
10.1016/j.coastaleng.2019.103611

**Publication date**
2020

**Document Version**
Accepted author manuscript

**Published in**
Coastal Engineering

**Citation (APA)**
Toimil, A., Losada, I. J., Nicholls, R. J., Dalrymple, R. A., & Stive, M. J. F. (2020). Addressing the challenges of climate change risks and adaptation in coastal areas: A review. *Coastal Engineering*, *156*, Article 103611. https://doi.org/10.1016/j.coastaleng.2019.103611

# ADDRESSING THE CHALLENGES OF CLIMATE CHANGE IN COASTAL AREAS: A REVIEW

**Alexandra Toimil[1], Iñigo J. Losada[1], Robert J. Nicholls[2], Robert A. Dalrymple[3], Marcel J.F. Stive[4]**

[1] Environmental Hydraulics Institute "IHCantabria", Universidad de Cantabria, Isabel Torres 15, 39011, Santander, Spain

[2] School of Engineering, University of Southampton, Highfield, Southampton SO17 1BJ, UK

[3] Civil and Environmental Engineering, Northwestern University; 2145 Sheridan Road, Evanston, Illinois, 60208, USA

[4] Department of Hydraulic Engineering, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Stevinweg 1, 2628 CN Delft, Netherlands

**Abstract**

Climate change is altering the world's coasts, which are the most densely populated and economically active areas on earth and home for highly value ecosystems. While there has been considerable research on this topic, in the author's experience this problem remains challenging for coastal engineering practice. The present paper reviews these challenges and identifies three key issues to address them: (a) a refocus of traditional engineering practice towards more climate-aware approaches; (b) the development of more integrated risk frameworks, including 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 it will take a significant effort to address these issues. Furthermore, given the complexity of the possible solutions more practical guidance is required.

**Keywords:** Climate change; coastal engineering; multi-risk; non-stationarity; uncertainty; adaptation.

## 1. Introduction

Climate change (CC) refers to natural or human-induced changes in the background climate state that persist for an extended period, typically decades or longer (IPCC, 2014). Since the 1950s, anthropogenic activity has led to unprecedented effects on the environment, 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 be increasingly manifest itself in the form of 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 widely 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 coastal locations less attractive, lowering property values and encouraging migration away from the coast (Sweet et al., 2018; McAlpine and Porter, 2018) or promoting adaptation, such as improved floodproofing, barriers or drainage.

The implications of CC for coastal engineering have been considered for more than 30 years (Dean et al., 1987); however, standard approaches have evolved little since then and may start falling short in various ways. First, traditional risk assessments do not consider the multiple dimensions of the risk problem in an integrated way, including changes to climate and environment, society (e.g., 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, would remain within a predictable range based on past observations is no longer valid (Milly et al., 2008; Hallegatte, 2009; Zscheischler et al., 2018). This, along with exposure and vulnerability that change in time, requires non-stationary risk approaches. Third, there is an increasing need for transitioning from deterministic methods that provide little or no uncertainty estimates to more robust frameworks that incorporate uncertainty, and hence support risk-informed decisions (Callaghan et al., 2008; Jongejan et al., 2012; Wainwright et al., 2016). Finally, the limited guidance on the application of conceptual CC risk frameworks (e.g., IPCC, 2012; IPCC, 2014) leaves it open to many questions when it comes to simulate coastal hazards and impacts, assess and integrate exposure and vulnerability, and define and implement adaptation goals.

This paper aims to review these challenges and identifies future steps required to address them. The work is organized as follows. In Section 2, we argue the need for traditional coastal engineering practices to be reshaped to face the threats of CC. In Section 3, we discuss the requirements for a new multi-dimensional risk framework. In sections from 4 to 7, we attempt to build 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 climate risks. The paper does not include explicit practical guidance, although we hope that its contents inspire such developments.

## 2. Coastal engineering and climate change

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 in terms of aesthetics/natural values and enhanced recreation (van Loon-Steensma et al., 2014). Over the last decades, our utilisation and understanding of the coast have grown significantly, and the maintenance of existing 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 (Delta Commissioner, 2010).

Besides this shift in coastal management, there has been a growing awareness about CC and its potential consequences. Rather than just a change in climate conditions, CC involves a large increase in uncertainty (Hallegatte, 2009). This has at least three implications for coastal engineering. First, CC needs to be incorporated into long-term planning. Many current coastal protection structures have been around for centuries. Thus, they should now be designed and maintained under a changing climate. Second, local action for CC adaptation has to be integrated into large-scale management schemes. Interventions cannot be looked at in isolation but need to consider the entire coastal system in which they are located (Hall et al., 2003; Nicholls et al., 2013). Third, adaptation should preferably be flexible and incremental, as SLR has a long timescale (Clark et al., 2016; Nicholls et al., 2018). Flexible adaptive approaches are being increasingly required as they allow coping with uncertainty, anticipating problems before they arise, committing to short-term actions, and maintaining options open to guarantee the most appropriate response (Ranger et al., 2013). Hallegatte (2009) provided a well-established classification of adaptation options especially suited to deal 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 possible 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, and some adaptation will still be essential far into the future (see **Fig. 1**).

Recently, particular emphasis has been given to the value of ecosystems in coastal protection (Duarte et al., 2013; Bridges et al., 2014), 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 scenarios, which can make it difficult to consider CC uncertainty. In contrast, NBS have the potential that they might self-adjust to incremental CC provided that the rate of SLR does not exceed their tolerance levels. A well-known example that integrates NBS into long-term planning and large-scale management is the mega-nourishment project at the Dutch coast (the Sand Engine pilot project). It comprises a large single sand placement designed multifunctionally to feed a long stretch of coastline over years to decades and enhance 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 speed 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., 2016; Bakker et al., 2017), which raises many questions. Would we have the capacity to adapt to such an accelerated rise? Would we be able to organize efficiently? What would we protect and where might we choose to retreat? How would potential solutions be funded? Can natural systems inherently adjust, or are there thresholds were change and breakdown occur? While unlikely, coastal engineering needs to consider these questions if robust and adaptable solutions are to be proposed. For rapid sea sea-level rise there are good analogues from subsiding coasts in deltas, especially in Asia (Takagi et al., 2017; Nicholls, 2018). Further, the knowledge base continues evolving as climate science advances, and specific training and the most solid grounding in the assessment of CC risks are essential to use this information optimally (Milly et al., 2008). In what follows, we review and examine major challenges in developing new comprehensive CC risk frameworks and assessing their components, as more appropriate approaches are increasingly being requested to address complex coastal issues such as 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 is influenced by adaptation and mitigation.

This framework is widely used 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., Purdi, 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 easily be drawn in the interpretation of risk, and between impacts and consequences, and hazards and events, the terms exposure and vulnerability are not recognised in ISO 31000 (2018) as stand-alone components, but to some extent are embedded in the consequences. Even though exposure and vulnerability are often conflated in the literature, they are distinct. Exposure is a necessary but not sufficient 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 essential 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 more comprehensive 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. Coastal engineers have long aspired to develop comprehensive risk assessments, and CC brings this issue into focus as it expands the uncertainty. Below we consider the requirements of such 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 the integrated risk frameworks is to be multi-impact (see **Table S1**). Some coastal impacts need to be studied in conjunction to model inter-dependencies, accumulation and cascade effects (IPCC, 2012; Gallina et al., 2016). Examples include morphodynamic changes affecting coastal flooding (Roelvink et al., 2009); physical, chemical, ecological, social, and economic impacts that cascade after sequential extreme events such as hurricanes (Paerl et al., 2001); and system failures triggered by the disruption of critical infrastructures (Chang et al., 2007). Coastal 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 the background climate state, hurricanes causing heavy wind and rain, and local storm surges and flood events (Zscheischler et al., 2018). This highlights the need for multi-hazard frameworks that aim to cover the full probability space of all possible future conditions (see **Table S1**). Modelling the statistical dependency between the relevant climate drivers needs knowledge of their joint probability of occurrence (Leonard et al., 2014), being essential not to limit the analysis to the upper tails of the distributions. The simulation of compound climate hazards may be further challenged by non-linear interactions (Moftakhari et al., 2017) and non-climate drivers (e.g., human activity and the movement of the tectonic plates), which may lead to inappropriate design levels or increased probabilities of structural failure if disregarded (Salvadori et al., 2015). For example, tsunamis and earthquakes should be considered in multi-hazard analysis for susceptible regions such as the Pacific coast. Subduction zone earthquakes can lead to large scale coastal subsidence, such as the sinking of Honshu post Tōhoku quake (2011) on the order of 1 m, and a similar land displacement expected to occur in Oregon and Washington after the next Cascadia earthquake.

Finally, integrated frameworks need to be multi-exposure and multi-vulnerability (see **Table S1**). Exposure is typically expressed through sectors (e.g., coastal ecosystems, socioeconomic settings, human activities, and governance contexts) and 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 whose available information is heterogeneous, since standardized downscaling methods are yet undeveloped (Toimil et al., 2017a). Vulnerability varies across impacts and exposure, and its integrated assessment requires the combination of quantitative and qualitative approaches to capture tangible and intangible aspects in its different dimensions (IPCC, 2012).

**Fig 2** illustrates a conceptual scheme with the steps involved in a comprehensive, integrated assessment of CC risks and adaptation. 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, the design and implementation of adaptation (j), which comes full circle as may 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 strongly depend on the geographic scale, the data available and the models used, resulting in different levels of uncertainty, which spreads across the steps of the process (described in **Fig 2**) and accumulates in a cascade form (Wilby and Dessai, 2010; Ranasinghe, 2016). **Fig. 3** shows a conceptual representation of the cascade of uncertainty (upper panel). Uncertainty proceeds from socio-economic 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 finally comes down to the adaptation response. Uncertainty in future risk increases at longer prediction lead times (Ranger et al., 2013), which therefore needs to be incorporated in decision making. A robust quantification of uncertainty involves dealing with as many likely futures as possible, which can be addressed differently according to the various stages (see **Fig 3,** lower panel). We suggest uncertainty to be mainly considered by but not limited to using ensembles of GHG emissions scenarios or representative concentration pathways (RCPs, Moss et al., 2010) that allow spanning a range of projected changes, 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 can be addressed in a satisfactory way to date. For example, future socio-economic pathways is a key uncertainty, and this uncertainty goes far beyond climate change. Analysing multiple socio-economic pathways allows us to understand how sensitive our decision might be to different futures. This societal dimension becomes increasingly important as the spatial scale increases, playing a fundamental role in informing policies on issues such as budgets, prioritisation or strategic approaches. Hence, this is not so important at the local scale, although we need to consider climate change as the loadings in design.

Another critical issue is that multiple simulations of impacts may be possible with fast reduced-complexity models that encapsulate only the dominant physical descriptions. Alternatively, when using more sophisticated but computationally demanding models, two options could be considered. Importance or stratified sampling methods reduce the number of simulations to make them practicable (Ranasinghe, 2016); and hybrid downscaling techniques allow increasing computing efficiency without reducing accuracy (Camus et al., 2011). A third key aspect is that incorporating uncertainty associated with exposure and vulnerability would ideally require the damage model to operate as a structural function in a probabilistic approach (e.g., Monte Carlo), drawing thousands of samples from the range of impact model outcomes combined with multiple exposure and vulnerability scenarios. We encourage a deeper focus on developing and implementing increasingly fully probabilistic risk assessments that allow integrating all of the information sources involved so that a better understanding of change can be achieved. Ultimately, flexible adaptation and systematic monitoring may be essential to deal with uncertainty through the planning and adaptation process (Ranger et al., 2013).

Alternatives to probabilistic frameworks 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 through introducing expert judgement (e.g., Le Cozannet et al., 2017a). These methods have been used to characterise hazards, but their application within impact modelling and risk assessment remains rather unexplored.

The last need for the integrated risk frameworks is the consideration of non-stationarity. Traditional risk analysis have been carried out typically assuming that exposure and vulnerability would remain unchanged, and that hazard-related variables had time-invariant probability distribution functions (pdf) whose properties could come from instrument record or reanalysis, and limiting future risk estimates to past observations. However, CC effects are already observable (IPCC, 2013) and will continue, giving rise to greater impacts interacting with evolving exposure and vulnerability, and consequent grower 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 erroneously designed assuming that historical (compound) extreme events could adequately represent future conditions. By the 2050s, CC may have altered extreme river flows, SLR may have increased the likelihood of extreme events of 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 was ignored, by the 2100s, settlements may no longer be protected; instead, they may suffer chronic inundation due SLR compounded by land subsidence, many beaches may disappear, and saltwater intrusion may migrate upstream (e). However, theoretical frameworks and supporting tools to representing such complex dynamics quantitatively are so far underdeveloped. The non-stationarity of risk has at least four major implications for how multi-dimensional hazards and impacts, exposure, and vulnerability need to be addressed and modelled. First, when GCMs are to be coupled with impact models, downscaling procedures and bias correction producing a realistic tail behaviour are required, as impact models rely on unbiased model output for both drivers and their dependence structure (Maraun et al., 2017). Second, the quality of modelled future climate cannot be evaluated against observations, and calibration parameters based on current standardised relationships (e.g., flood-producing rainfall and catchment's antecedent conditions in a hydrological model) may be no longer appropriate (Zscheischler et al., 2018). Third, the model of economic development implemented over the last decades is increasing coastal urban pressure and ecosystem degradation. Since this trend is expected to continue, scenarios of changes in population, economic growth, built and natural capital, and land use, covering a broad range of possible futures need to be created for coastal areas at the geographic scale required by impact models (e.g., using economic models and cellular automates). Fourth, future hazards may alter vulnerability by, for instance, reducing resilience, and this may be rather different across exposed elements, and from one impact to another. While capturing the full spectrum of possible changes in vulnerability attributes is far from realistic, scenarios representing likely futures and including the possibility of enhancing resilience and adaptive capacity need to be developed. Efforts in these directions will allow us to work with the temporal evolution of risk probability (Toimil et al., 2018) 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 towards the latter part of this century and beyond, 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 global SLR projections to be downscaled, as mean sea level is not rising uniformly across the world, and many processes contribute to spatially varying patterns (Mitrovica et al., 2001; Willis and Church, 2012). In particular, land subsidence compounds local/regional SLR in densely populated, subsiding coastal cities and deltas, which already have significant areas below normal high tides and depend on defences and drainage to be habitable (Nicholls, 2018).

Since future emissions are not known, SLR is normally linked to specific emissions scenarios. The likely ranges presented in IPCC Fifth Assessment Report for each emissions scenario correspond to the 67% probability, and thus do not give information about the highest outcomes, which ultimately may be key for design purposes. For instance, combining full probability distributions of SLR projections with extreme value distributions may allow obtaining estimates of the expected number of years in which flooding exceeds a given elevation (Kopp et al., 2014). Uncertainty about ice-sheets melting might be addressed in the short-term through combining probabilistic SLR projections modelling outcomes with expert judgement (Oppenheimer et al., 2016; Le Cozannet et al., 2017a). Although the assessment of CC risks benefits from considering all the existing knowledge, we need to be careful about even more uncertain projections that are not fully agreed upon (e.g., from semi-empirical models). An authoritative assessment of all available SLR science (Hinkel et al., 2015) and a scientific consensus on the appropriate representation and interpretation of high-end changes needs to be achieved. Further, it is of increasingly importance to develop robust statistical methods that allow combining probabilistic SLR projections (e.g., Kopp et al., 2014) with other projected drivers (e.g., waves and storm surges) and eventually feeding impact models.

Another challenge is the reliability of, and the difficulties associated with developing and using scenarios (Nicholls et al., 2014). However, decisions cannot be postponed until ideal SLR scenarios are developed, and the improper 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 should include the full 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 understand the full effects to be expected, 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 twenty-second 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, and ongoing adaptation is required (Wong et al., 2014).

Recognising SLR as the main CC result in coastal areas has resulted in improved regional projections (e.g., Slangen et al., 2014; Carson et al., 2016), improved quantification of uncertainty (e.g., Perrette et al., 2013; Kopp et al., 2014) and improved communication with relevant stakeholders and decision makers (e.g., Nerlich et al., 2010; Wahl et al., 2018). However, waves, storm surge and river discharge 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 understanding of climate state 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 0.56º-3.75º and 0.11º-0.44º, respectively) have limitations and fail to provide information at the local scale, leading to the need to downscale their outputs. This can be achieved through statistical, dynamic, or hybrid modelling approaches, or using many assumptions that increase uncertainty (Camus et al., 2017; Camus et al., 2018). There are several pros and cons to be deemed when using dynamic or statistical downscaling methods. Dynamic downscaling provides data coherent spatially and temporally across global climate variables and it can be used in regions where no observations are available; however it can be considerably computationally demanding, especially where higher model resolutions are not available, thus hampering multiple realisations. The dynamic approach delivers future time series of waves and storm surges to which non-stationary statistical analysis can be applied to obtain extreme-value and regular-climate distributions. This offers important added value for design and operation of infrastructure, as capital expenditures (Capex) are obtained based on extreme values for different return periods, and operating expenses (Opex) require parameters of the long-term 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 yields site-specific estimates and it is computationally efficient, allowing long-term simulations at high spatial resolutions using GCM multi-model groups, diminishing the effects of individual realisations, and hence reducing the uncertainty (Camus et al., 2014). The downside of the statistical approach includes the unverifiable assumption that past statistical relations remains stationary in the future and its tendency to underestimate extremes.

Further research efforts are required towards understanding contemporary extreme sea levels, quantifying their associated uncertainty (Wahl et al., 2017), and developing enhanced projections of future regular and extreme climate, ideally including changes in extra-tropical storms and tropical cyclone activity (intensity, severity and tracks). Since the IPCC Fourth Assessment Report, intensive research has been placed into wave climate projections. An example is the Coordinated Ocean Wave CLImate Projections (COWCLIP) community working group, which emerged in 2011 aiming at summarising wave climate projection studies, documenting existing methods, establishing working protocols and developing technical frameworks. This encouraged the quantification of uncertainty in projected changes (e.g., using ensembles) and the development of multi-model wave climate projections using dynamical (e.g., Hemer et al., 2013; Mentashi et al., 2017; Casas-Prat et al., 2018) and statistical approaches (e.g. Wang et al., 2014; Camus et al., 2017). Among the works 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 suggests the latter demands a deeper focus, as it is key information, inter alia, to determine the accidental damage and ultimate limit state desig loads for coastal structures. Furthermore, only few works include information about wave period and direction, although these could have significant implications to coastal impacts such as dune erosion (van Gent et al., 2008). Likewise wave climate projections, future changes in storm surges and extreme sea levels have been obtained at the global (Wahl et al., 2017; Vousdoukas et al., 2018) and regional (Vousdoukas et al., 2016; Lee et al., 2017; Vousdoukas et al., 2017) scales, but not at the resolution required for coastal engeering applications.

There are at least three challenges regarding the development of climate projections. First, compound events are extremely complex, and resolving them in projections may require a methodology focused on impacts rathen than on drivers, emphasising the need for improved GCMs resolution and downscaling techniques (Zscheischler et al., 2018). GCMs with enhanced resolution and physics may allow reproducing smaller-scale phenomena such as tropical cyclones, which so far are usually approached through dynamical downscaling, for instance, coupling climate and high-resolution regional or local models (Lin et al., 2012; Emanuel, 2013). Second, non-linear interactions among SLR components, tides, waves, and storm surges have shown to be very important locally and with likely profund design implications (Arns et al., 2017). Including these effects in probabilistic climate projections requires fully coupled modelling approaches that may be beyond current modelling and computational capabilities (Vousdoukas et al., 2018). Finally, since probabilistic climate projections (e.g., Vousdoukas et al., 2018) are fundamental to consider uncertainty in the climate state, we need to find ways to extend their development and subsequent combination with SLR's to assess coastal impacts.

## 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 protection given by coral bleaching, and the decline/loss of coastal wetlands due to higher water tables, increasing salinity and/or insufficient sediment supply to keep pace with SLR (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 the high-tide or nuisance flooding that will lead to the abandonment of the shoreline or to an accommodate or protect response, and this will occur long before inundation. However, comprehensive methodologies and studies that combine SLR and projected extreme sea levels and waves to produce flood maps providing a robust quantification of uncertainty remain very low (Arns et al., 2017; Sayol and Marcos, 2018). We also encourage a deeper focus on the probabilistic assessment of multivariate flood extreme events resulting from the joined action of waves, storm surges, tides, SLR and river discharge in estuarine areas, especially considering relevant conditions that have no precedent in observational records (Zscheischler et al., 2018). Significant progress has already been done in this direction, for example, considering the non-stationarity of climate-related events by incorporating co-variables to the distribution parameters (e.g., Serafin and Ruggiero, 2014), or using a climate emulator based on weather patterns (e.g., Rueda et al., 2016), but further methodological developments are needed to improve flood risk assessments.

Recently much has been achieved on improvement of the understanding and modelling of sediment fluxes and linkages governing coastal processes and shoreline evolution, 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) may be insufficient in the sediment budget (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,the capability to model non-linear processes interaction and multi-scale coupling on timescales of beyond a few years (De Vriend et al., 1993; Stive et al., 2002; Ranasinghe, 2016); or developing a satisfactory model that allows coupling hydrodynamics and morphodynamics, reproducing short- and long-term shoreline changes, and that is not too computationally expensive to incorporate uncertainty. Overall, the need to better quantify uncertainty in coastal erosion modelling is gaining urgency (Ranasinghe et al., 2012; Toimil et al., 2017b). Thousand 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 erosion models and make it possible to obtain probabilistic estimates. Different forcing variables with different chronologies lead to different number of extreme events at different times, of different magnitude, and with different durations. This does not play a major role in long-term shoreline change but highly influences short-term erosion and accretion patterns (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 Mullet, 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; Camus et al., 2018), more comprehensive methodologies that allow considering regular and extreme climate incorporating uncertainty are required. This focus reinforces the need for modelling the operability and stability of coastal structures over time, for example, through 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 the analysis could be carried out on both facilities and operations.

The study of CC impacts other than the above shows even more limitations. One example is that SLR and changes in aquifer recharge and evaporation are expected to exacerbate salt intrusion into groundwater (Oude Essink et al., 2010), which is already subject to severe human pressure and highly influenced by complex ocean-aquifer interactions (Werner et al., 2013). Shortfalls in this field include the incomplete understanding of processes and the lack of mapping of mixing zone changes. Efforts are required to develop appropriate models and calibrate them, as well as to quantify uncertainty (Werner et al., 2013). Another example are the waste releases from the thousands of historical landfill sites located along the world's coast (Brand et al., 2017), which are threaten by flooding and erosion. Major challenges encompass the lack of field data and reliable methods to assess the extent of legacy pollution in coastal sediments; and the need for an improved understanding of the potential impacts of flooding on contaminant release, and of the nature, behaviour and environmental effects of solid wastes in the coastal zone (Brand et al., 2017).

Observations are valuable supportive tools to constrain the impact models used to project future changes (Cazenave and Le Cozannet, 2013). A systematic monitoring programme specifically focused on coastal impacts, specially on which are less understood, is overdue and fundamental to improve risk assessments. Although non-stationarity implies that the absence of past impacts cannot constitute evidence against the possibility of future impacts, detection and attribution may offer a form of improving our understanding of impact drivers mechanisms and refining our future projections (Cramer et al., 2014). The challenges ahead include creating coastal observatories and establishing observing networks that allow the systematic collection of field data concerning the drivers (e.g., through tide gauges, global sea level observing systems (GLOSS) and buoy networks, reanalysis and satellite measures) and the associated impacts (e.g., flood depths and extents and shoreline changes using cameras and drones, and salt concentration and pollution using sensors). This would allow making high-resolution, continuous, long-term observations at some point available and developing methods and tools that help to make progress in disentangling the factors affecting coastal systems beyond CC, whose interplays may be non-linear, non-local, and hard to understand and quantify (Stone et al., 2013; Cramer et al., 2014). While strides have been made in this field over last years, improved 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 common practice usually reduces it to physical assets such as buildings and infrastructures, information associated with indirect effects (e.g., sectoral GPD, income) need to be considered (Toimil et al., 2017a).

For instance, when an industrial plant becomes flooded, repercussions are not limited to the consequential (physical) damages on structure and contents but may include loss of profits due to business interruption or delay. However, obtaining such detailed data geographically distributed is still a challenge in many regions, and many studies have no other option than describe exposure through land use data instead of socioeconomic indicators (e.g., Prime et al., 2015), with all the constraints that would entail. 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, income) to achieve more realistic representations of population, assets and associated activities on the ground (Thieken et al., 2006; Toimil et al., 2017a) have been developed over the last decade, but more standardised downscaling methods and calibration tools are required. This might be the very first step on the long road towards the attainment of dynamic 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), as they are key to achieve an efficient and sustainable management of coastal natural resources.

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). Methodologies to assess vulnerability are diverse, including participatory, model-based, agent-based, and index-based approaches (Hinkel, 2011), as well as the damage functions specifically developed for the analysis of episodic flood risk. Damage functions are sector-specific and differentiate between direct damage (consequential 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 localised nature of damages, empirical functions built upon data gathered in the aftermath of real events should prevail over 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 have a crucial 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 in the literature of rubble-mound structures stability focus on addressing the damage progression of the armour layers during sea states and storms (e.g., Kobayashi et al., 2010; Melby and Kobayashi, 2011). Some of these approaches allow reproducing damage accumulation stochastically and yield its statistical distribution (e.g., Castillo et al., 2012), but none of them provides the temporal evolution of this damage during the entire structure lifetime. The way forward should then include the development of reliability methods based on the full probabilistic distribution of basic variables (the so-called Level III approach, Burcharth, 1993) allowing fully 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.

Overall, there is a need for methodologies and metrics to properly evaluate vulnerability, both in terms of the sensitivity of the systems 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 require to capture the complex behavioural dynamics of individuals, business, and governance bodies (Aerts et al., 2018), and incorporate maintenance strategies that help systems to withstand impacts, and hence increase resilience, and planning schemes, as well as flexibility in management and operation, and lock-ins, which may allow enhancing their adaptive capacity. In addition, methods and supporting tools to integrate vulnerability information into risk assessments more easily need to be developed.

## 7. Adaptation in the context of uncertainty

CC is a real threat that will require adaptation. Classically adaptation includes (planned) retreat, accommodation, protection, and attack (build seaward) options. These all imply analysis, design, planning, and societal decisions. Unplanned retreat is the worst case, in which 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, 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 (nature-based solutions, 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 essential. In addition, NBS also have drawbacks. First, ecosystems require much space and are not suitable for highly urbanized coastal cities unless these cities are placed far inland in deltas or estuaries (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 hampers their application. Therefore, 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 about costs, time to become established and effective, seasonal variation of protection, evolution of residual risks, regenerative or adaptive capacity and resilience estimates, performance levels when restored by human intervention, failure modes, tipping points and operating thresholds. Guidelines for NBS are limited and their implementation is 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 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 measures to enhance coastal 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 may be the case that existing coastal protection structures no longer meet the design performance criteria, and neither NBS nor hybrid solutions are feasible, or they do not guarantee the safety standards required. That would involve the need for upgrading the structures (e.g., rubble mound) by, for instance, modifying the structure profile and/or adding structure elements (Burcharth et al., 2014).

The selection of the most appropriate adaptation options is of greater complexity due to the uncertainty in CC, particularly towards the last part of the century and beyond. Therefore, although ultimately we need to adopt specific values at the design stage, plausible higher changes are worth to be explored precisely 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 turning points that indicate the implemented measure is no longer effective and new or additional action is needed to meet certain pre-established (residual) risk goals (Ranger et al., 2013). Thus, APs are not triggered by time itself but by threshold levels (e.g., water levels) being exceeded. Flexibility is achieved by multiple interventions managed over time, as more is learned or uncertainty is reduced, introducing long-term objectives into short-term actions (Hassnoot et al., 2018). 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 remain at present limited, and there are good reasons to think that their expansion to other coastal systems is going to be long and gradual. First, the high technical capacity, strong financial and management resources, and high-order institutional commitment required (Barnett et al., 2014). Second, the need for clear and predetermined objectives, including pre-established acceptable or tolerable (residual) risk levels, which can be highly contested due to strong institutional and social values (Turner et al., 2016). Third, the identification of action triggers to monitor, their analysis to get timely and reliable signals for adaptation (e.g., threshold values), remain more at the formulation rather than implementation stage actions (Hassnoot et al., 2018), and monitoring systems to evaluate of their performance articulating sequential actions are under development. 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. An agenda for coastal engineering and climate change

This paper focuses on identifying grand challenges for coastal engineers concerning the assessment of climate change risks and adaptation. 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. Climate change effects need to be incorporated into long-term design and planning, and adaptation actions require to be part of large-scale management schemes. Coastal engineers need to consider the full range of possible future changes and require specific training and preparation on climate change risks-related issues. In some cases, current computational resources may be a constraint.

Risks. There is a necessity for more integrated and comprehensive risk frameworks able to determine the holistic risk due to several impacts and hazards, including vulnerability interactions and multiple sectors. This approach requires considering the non-stationarity of the risk components providing a robust quantification of the uncertainty cascade.

Hazards. Considerable efforts need to be directed towards an improved understanding of present climate, better climate models and downscaling methods, enhanced local projections of regular and extreme climate, a consensus on how to interpret high-end changes; and the combination and integration of (probabilistic) projections into impact models. This is especially relevant for coastal drivers (e.g., waves, sea levels).

Impacts. Methodologies and supportive tools are necessary, inter alia, to assess multivariate flood extreme events appropriately; model coastal erosion comprehensively; project changes in port structure operability and stability over time; model and calibrate salt intrusion; and predict potential flood and erosion impacts on solid wastes. More impact assessments, observations and monitoring, enhanced detection and 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. Challenges include dynamic projections of vulnerability; observations to derive empirical damage/loss functions; methodological developments to model probabilistically the evolution of structural damage; and improvements on the integration of vulnerability information into risk assessments.

Adaptation. The way forward entails developing and implementing flexible adaptation plans and associated monitoring systems, and exploring inherently adaptive solutions such as nature-based or hybrid, which require better understanding. Practical applications of the adaptation pathways approach in coastal engineering are also needed.

These challenges have been mapped in **Fig. 5** reflecting our perspectives on the issues. The horizontal axis represents their degree of priority (indicative), the vertical axis indicates their research-practice emphasis, and the colour intensity symbolises the spatial scale required. Finally, 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 the assessment of coastal risks, a problem which is growing in importance in their practice. However, dealing with climate change risks and planning for adaptation are complex issues that demand extensive collaboration and synergies across many fields of research. For example, atmospheric scientists and climate modellers develop future projections upon which risk assessments are based, oceanographers and hydrologists have a relevant role in understanding and modelling climate hazards and drivers (also known as climate services, Le Cozannet et al., 2017b), and impact modellers produce impact estimates that need to be combined 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 on infrastructure design or adaptation planning, and to develop policy instruments; but also, by private bodies such as (re)insurances that try to create new products to address climate change in coastal areas. Coastal engineers have specific knowledge from some of these disciplines (typically climate and impact modelling but not exclusively) but need to work closely with other professionals to provide multidisciplinary, integrative approaches to climate change risk assessment and adaptation processes.

**Acknowledgements**

Alexandra Toimil acknowledges the financial support from the Universidad de Cantabria through the 2018 Postdoctoral Fellowship Program. This work was also funded by the Spanish Government through the grant RISKCOADAPT (BIA2017-89401-R). The authors would like to thank Philip Goodwin for providing the data used in Fig 1.

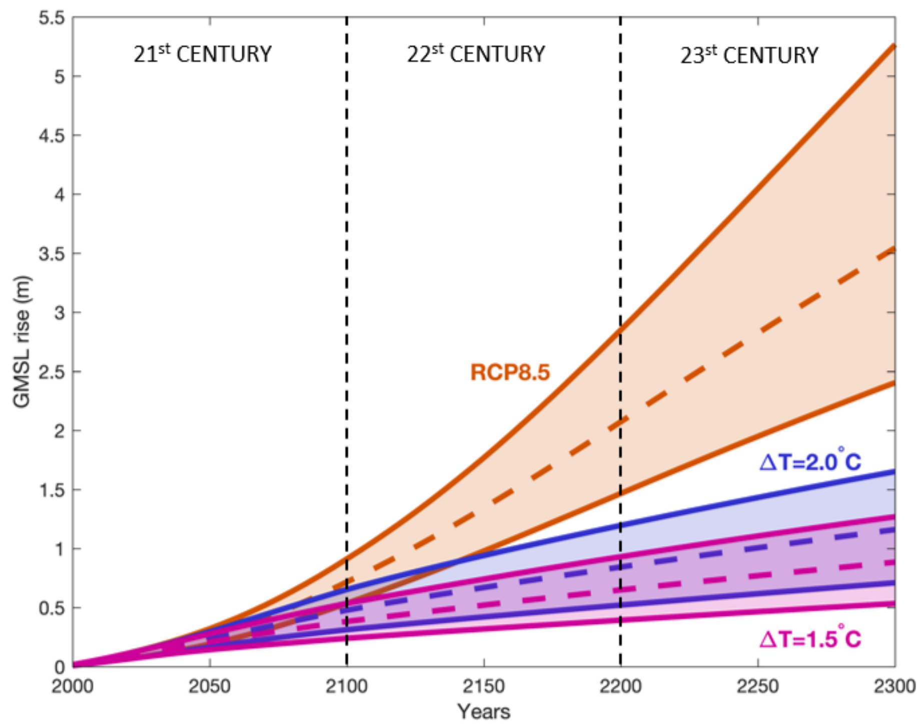


**Fig. 1** An example of global mean sea-level (GMSL) rise projections to 2300 relative to 1986-2005 for a large (9 x $10^4$) ensemble using the WASP Earth system model with parameter settings consistent with the models used by Church et al. (2013). Adapted from Nicholls et al., (2018). Dashed lines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

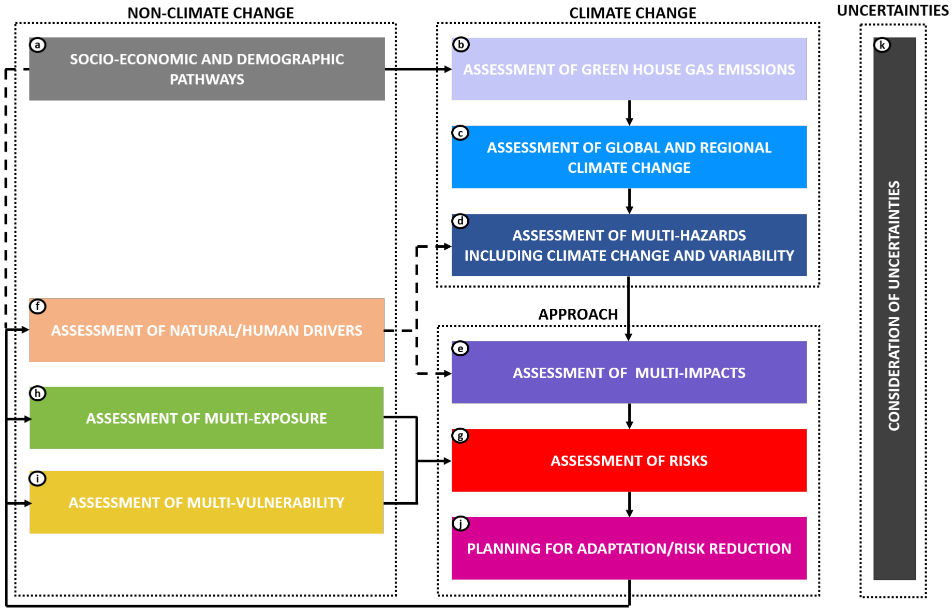


**Fig. 2** Conceptual flowchart that illustrates the steps involved in the comprehensive assessment of climate change risks and adaptation. Dashed arrows represent that boxes may or may not be applicable.

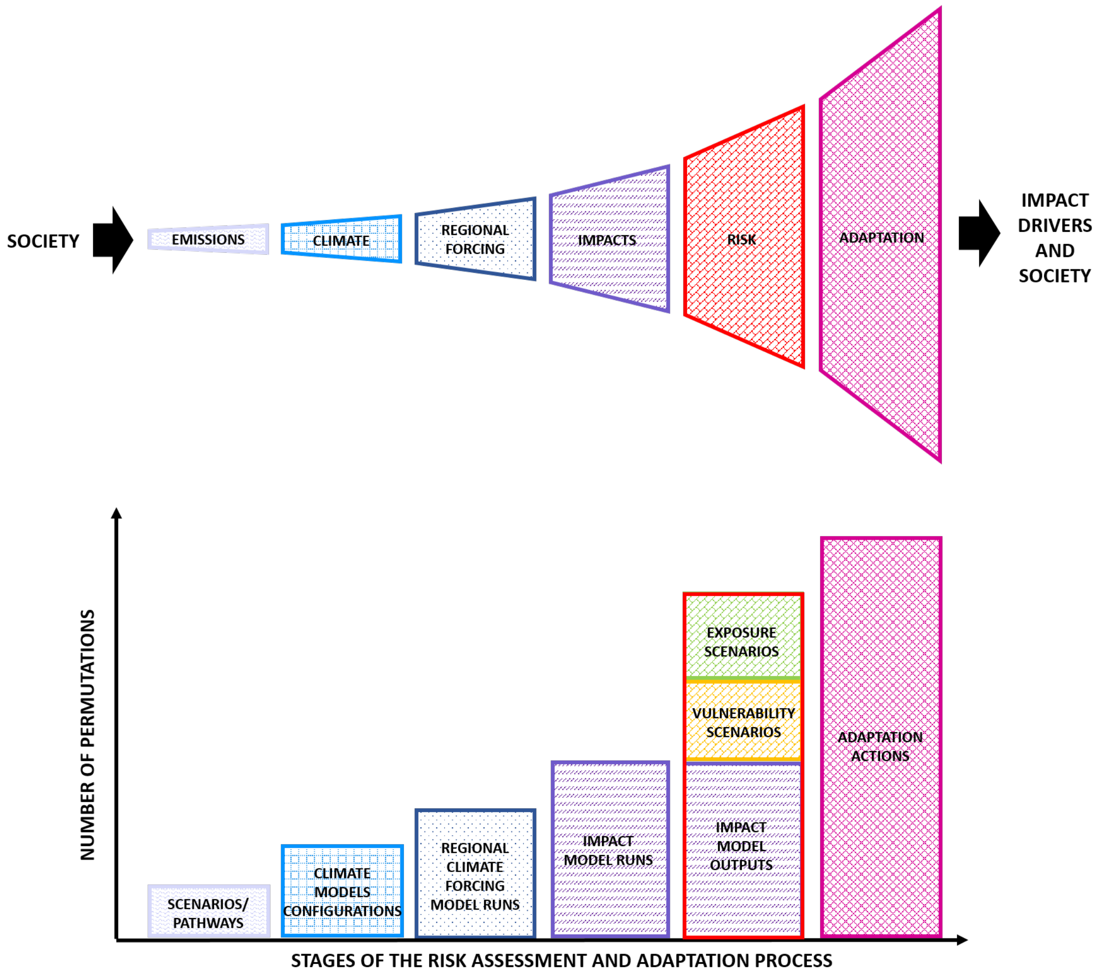


**Fig. 3** Conceptual illustration of the cascade of uncertainty in which uncertainty is associated with the area of the shape (upper panel); and ways to consider as many likely futures as possible, and hence incorporate uncertainty, at each stage of the process (lower panel).

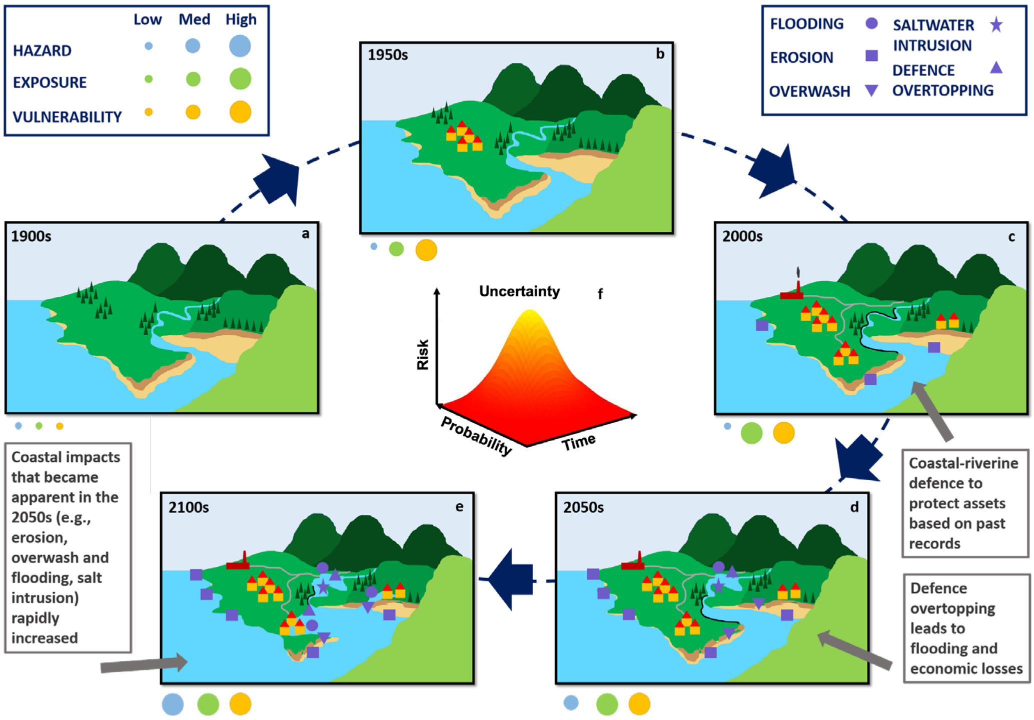


**Fig. 4** Moving clockwise from 9 o'clock, a conceptual illustration of a hypothetical evolution over time of hazard, impacts, exposure, and vulnerability in a coastal system subjected to climate change. The temporal evolution of the risk components leads to the temporal evolution of risk itself (panel 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.

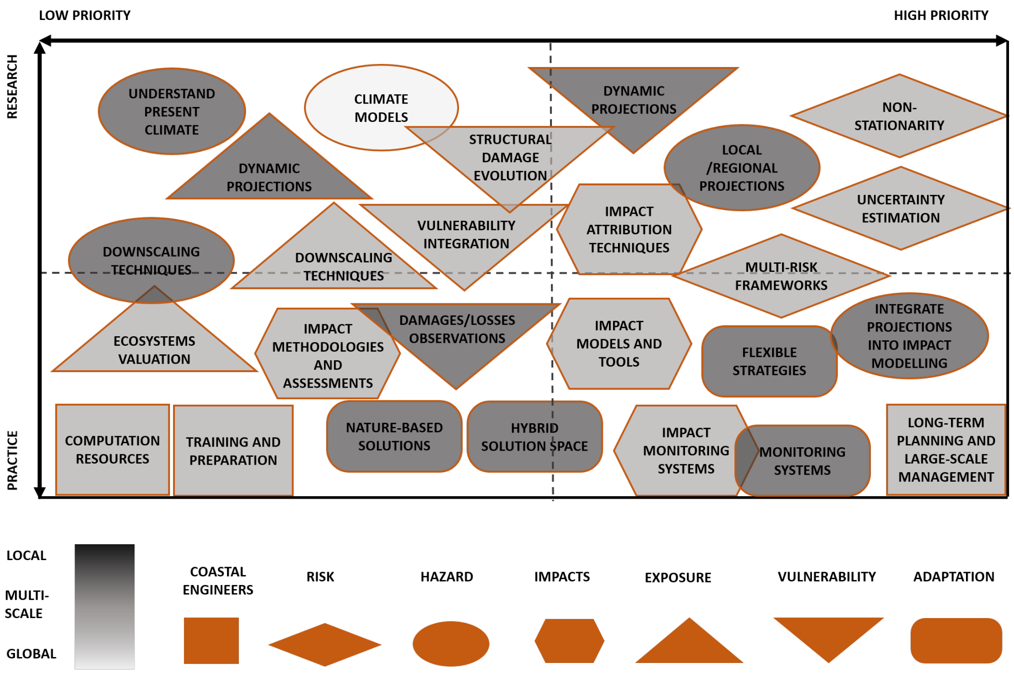


**Fig. 5** Illustration of the main challenges identified for coastal engineering. Subjectively, they are mapped by degree of priority, research-practice emphasis, and spatial scale (colour intensity). Shape represents the area or stage to which they belong according to the structure of the paper.

## References


Aerts JCJH, Botzen WJ, Clarke KC, Cutter SL, Hall JW, Merz B, Michael-Kerjan E, Mysiak J, Surminski S, Kunreuther H (2018) Integrating human behaviour dynamics into flood disaster risk assessment. Nat. Clim. Change 8:193-199.

Arns A, Dangendorf S, Jensen J, Talke S, Bender J, Pattiaratchi C (2017) Sea-level rise induced amplification of coastal protection design heights. Scientific Reports, 7 40171.

Bakker AMR, Wong TE, Ruckert KL, Keller K (2017) Sea-level projections representing the deeply uncertain contribution of the West Antarctic ice sheet. Scientific Reports 7 3880.

Barnett J, Graham S, Mortreux C, Fincher R, Waters E, Hurlimann A (2014) A local coastal adaptation pathway. Nat. Clim. Change doi:10.1038/nclimate2383.

Beck MW, Losada IJ, Menéndez P, Reguero BG, Diaz-Simal P, Fernandez F (2018) The global flood protection savings provided by coral reefs. Nat Commun 9:2186.

Brand JH, Spencer KL, O'Shea FT, Lindsay JE (2017) Potential pollution risks of historic landfills on low-lying coasts and estuaries. WIREs Water e1264, doi:10.1002/wat2.1264.

Bridges TS, Wagner PW, Burks-Copes K, Bates MA, Collier ZA, Fischenich CJ, Galiani JZ, Leuck LD, Piercy CD, Rosati JD, Russo EJ, Shafer DJ, Suedel BC, Vuxton EA, Wamsley TV (2015) Use of natural and nature-based features (NNBF) for coastal resilience. ERDC SR-15-1. Vicksburg, MS: U.S. Army Engineer Research and Development Center.

Burcharth HF (1993) Reliability Evaluation and Probabilistic Design of Coastal Structures. In International Seminar on Hydro-Technical Engineering for Futute Development of Ports and Harbors Tokyo: Unyusho Kowan Gijutsu Kenkyujo.

Burcharth HF, Andersen TL, Lara JL (2014) Upgrade of coastal defence structures against increased loadings caused by climate change: A first methodological approach. Coast. Eng. 87:112-121.

Calil J, Reguero BG, Rueda AC, Losada IJ, Méndez FJ (2017) Comparative Coastal Risk Index (CCRI): A multidisciplinary risk index for Latin America and the Caribbean. PLoS ONE 12 (11): e0187011.

Callaghan, D. P., Nielsen, P., Short, A., and Ranasinghe, R. (2008). Statistical simulation of wave climate and extreme beach erosion. Coast. Eng. 55(5):375-390.

Camus P, Méndez FJ, Medina R (2011) A hybrid efficient method to downscale wave climate to coastal areas. Coast Eng 58(9):851-862.

Camus P, Menéndez M, Méndez FJ, Izaguirre C, Espejo A, Canovas V, Pérez J, Rueda A, Losada IJ, Medina R (2014) A weather-type statistical downscaling framework for ocean wave climate. J of Geophys Res: Oceans 119(11):7389-7405.

Camus P, Losada IJ, Izaguirre C, Espejo A, Menéndez M, Pérez J (2017). Statistical wave climate projections for coastal impact assessments, Earth's Future 5:918-933.

Camus P, Tomás A, Díaz-Hernández G, Rodríguez B, Izaguirre C, Losada IJ (2018) Probabilistic Assessment of Port Operation Downtimes Under Climate Change. Coast Eng (accepted).

Carson M, Köhl A, Stammer D, Slangen ABA, Katsman CA, van de Wal RSW, Church J, White N (2016) Coastal sea level changes, observed and projected during the 20th and 21st century. Clim Change, 134:269.

Casas-Prat M, Wang XL, Swart N (2018) CMIP5-based global wave climate projections including the entire Arctic Ocean. Ocean Modelling, 123:66-85.

Castillo C, Castillo E, Fernández-Canteli A, Molina R and Gómez R (2012) Stochastic model for damage accumulation in rubble-mound breakwaters based on compatibility and the central limit theorem. Journal of Waterway, Port, Coastal and Ocean Engineering, 138(6), pp 451-463.

Cazenave A, Le Cozannet G (2013) Sea level rise and its coastal impacts. Earth-s Future 2:15-34.

Chang SE, McDaniels TL, Mikawoz J, Peterson K (2007) Infrastructure failure interdependencies in extreme events: power outage consequences in the 1998 storm. Natural Hazards, 42(2):337-358.

Church J, Clark P, Cazenave A, Gregory J, Jevrejeva S, Merrifield M, Milne G, Nerem R, Nunn P, Payne A, Pfeffer W, Stammer D, Unnikrishnan AS (2013) Sea Level Change, pages 1137–1216. Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the

Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Clark PU, Shakun JD, Marcott SA, Mix AC, Eby M, Kulp S, Levermann A, Milne GA, Pfister PL, Santer BD, Schrag DP, Solomon S, Stocker TF, Strauss BH, Weaver AJ, Winkelmann R, Archer D, Bard E, Goldner A, Lambeck K, Pierrehumbert RT, Plattner G-K (2016) Consequences of twenty-first-century policy for multi-millennial climate and sea-level change. Nat Clim Change, doi:10.1038/nclimate2923.

Cramer, W., G.W. Yohe, M. Auffhammer, C. Huggel, U. Molau, M.A.F. da Silva Dias, A. Solow, D.A. Stone, and L. Tibig, 2014: Detection and attribution of observed impacts. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [eds CB Field et al.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 979-1037.

Dawson RJ, Dickson ME, Nicholls RJ et al (2009) Integrated analysis of risks of coastal flooding and cliff erosion under scenarios of long term change. Clim Change. doi:10.1007/s10584-008-9532-8.

De Schipper MA, de Vries S, Ruessink G, de Zeeuw RC, Rutten J, van Gelder-Maas C, Stive MJF (2016) Initial spreading of a mega feeder nourishment: Observations of the San Engine pilot project. Coast. Eng. 111:23-38.

Dean RG, Dalrymple RA, Fairbridge RW, Leatherman SP, Nummedal D, O'Brien MP, Pilkey OH, Sturges W, Wieger RL (1987) Responding to changes in sea level. Engineering implications. Committee on Engineering Implicatioms of Changes in Relative Mean Sea Level. Marine Board Commission on Engineering and Technical Systems. National Research Council. National Academy Press, Washington, D.C. ISBN 0-309-03781-6.

Dean RG, Houston JR (2016) Determining shoreline response to sea level rise. Coast. Eng. 114:1-8.

Deconto RM, Pollard D (2016) Contribution of Antartica to past and future sea-level rise. Nature 531:591-597.

Delta Commissioner, 2010. The 2011 Delta Programme Working on the Delta; Investing in a Safe and Attractive Netherlands, Now and in the Future (English version). Ministry of Transport Public Works and Water Management, Ministry of Agriculture, Nature and Food Quality, Ministry of Housing, Spatial Planning and the Environment, Dutch National Government.

De Vriend HJ, Zyseman J, Nicholson J, Roelvink JA, Pechon P, Southgate HN (1993) Medium term 2DH coastal area modelling. Coast Eng 21:193-224.

Do, AT, de Vries, S, Stive, MJF (2017) Beach Evolution Adjacent to a Seasonally Varying Tidal Inlet in Central Vietnam. Journal of Coastal Research, 34(1), 6-25.

Duarte CM, Losada IJ, Hendriks IE, Mazarrasa I, Marba N (2013) The role of coastal plant communities for climate change mitigation and adaptation. Nat Clim Change, doi:10.1038/nclimate1970.

Ecoshape (2018) Building with Nature programme. Web page: www.ecoshape.org

Emanuel KA (2013) Downscaling CMIP5 climate models shows increased tropical cyclone activity over the 21st century. PNAS 110(30):12219-12224.

Flemming CA (1993) Shoreline management in response to climate change: Roger White (Eds.) Engineering for climatic change: proceedings of the symposium on engineering in the uncertainty of climatic change, organized by the Institution of Civil Engineers and held in London on 28 October 1992. Tomas Telford, London. ISBN 0-7277-1925-4.

Gallina V, Torresan S, Critto A, Sperotto A, Glade T, Marcomini A (2016) A review of multi-risk methodologies for natural hazards: Consequences and challenges for a climate change impact assessment. Journal of Environmental Management 168:123-132.

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. Global Environmental Change 19:240-247.

Haasnoot M, Kwakkel JH, Walker WE, ter Maat J (2013) Dynamic adaptive policy pathways: A method for crafting robust decisions for a deeply uncertain world. Global Environmental Change 23:485-498.

Haasnoot M, van't Klooster S, van Alphen J (2018) Designing a monitoring system to detect signals to adapt to uncertain climate change. Global Environmental Change 52:273-285.

Hall JW, Dawson RJ, Sayers PB, Rosu C, Chatterton JB, Deakin R (2003) A methodology for national-scale flood risk assessment. Proceedings of the Institution of Civil Engineers-Water Maritime and Engineering. Volume 156(3): 235-248.

Hallegatte S (2009) Strategies to adapt to an uncertain climate change. Global Environmental Change 19:240-247.

Hanson, H., Brampton, A., Capobianco, M., Dette, H.H., Hamm, L., Laustrup, C., Lechuga, A., Spanhoff, R., 2002. Beach nourishment projects, practices and objectives—a European overview. Coastal Eng. 47, 81–111.

Hemer MA, Fan Y, Mori N, Semedo A, Wang XL (2013) Projected change in wave climate from a multi-model ensemble. Nat Clim Change 3:471-476.

Hinkel J (2011) "Indicators of vulnerability and adaptive capacity": Towards a clarification of the science-policy interface. Global Environmental Change 21:198-208.

Hinkel J, Jaeger C, Nicholls RJ, Lowe J, Renn O, Peijun S (2015) Sea-level rise scenarios and coastal risk management. Nat Clim Change 5:188-190.

IPCC (2012) Managing the risks of extreme events and disasters to Advance climate change adaptation. A special report of working groups I and II of the intergovernmental Panel on climate change [eds CB Field et al.]. Cambridge University Press, Cambridge, UK, and New York, USA, 582 pp.

IPCC (2013) Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [ eds. TF Stocker et al.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

IPCC (2014) Summary for policymakers. In Climate Change 2014: Impacts, Adaptation and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [eds CB Field et al.]. Cambridge University Press, Cambridge, UK, and New York, NY, USA, 2014, pp. 1-32.

ISO 31000 (2018) Risk management – Guidelines. www.iso.org/obp/ui#iso:std:iso:31000:ed-2:v1:en.

Jongejan, R.B., Ranasinghe, R., Vrijling, J.K., Callaghan, D., 2012. A risk-informed approach to coastal zone management. Australian Journal of Civil Engineering 9.

Kobayashi N, Farhadzadeh A, Melby JA (2010) Overtopping and damage progression of stone armor layer. J. Waterway, Port, Coastal, Ocean Eng. 136(5):257-265.

Keyser A, Westerling AL (2017) Climate drives inter-annual variability in probability of high severity fire occurrence in the western United States. Environ. Res. Lett. 12 065003.

Kopp RE, Horton RM, Little CM, Mitrovica JX, Oppenheimer M, Rasmussen DJ, Strauss BH, Tebaldi C (2014) Probabilistic 21$^{st}$ and 22$^{nd}$ century sea-level projections at a global network of tide-gauge sites. Earth's Future, 2:383-406.

Kopp RE, DeConto RM, Bader DA, Hay CC, Horton RM, Kulp S, Oppenheimer M, Pollard D, Strauss BH (2017) Evolving understanding of Antartic ice-sheet physics and ambiguity in probabilistic sea-level projections. Earth's Future 5:1217-1233.

Kraus NC (1996) History and Heritage of Coastal Engineering. American Society of Civil Engineering, New York, NY. Doi:10.1061/9780784401965.

Le Cozannet G, Manceau J-C, Rohmer J (2017a) Bounding probabilistic sea-level projections within the framework of the possibility theory. Environ. Res. Lett. 12 014012.

Le Cozannet G, Nicholls RJ, Hinkel J, Sweet WV, McInnes KL, van de Wal RSW, Slangen ABA, Lowe JA, While KD (2017b) Sea level change and coastal climate services: The way forward. Journal of Marine Science and Engineering 5, 49.

Lee BS, Haran M, Keller K (2017) Multidecadal scale detection time for potentially increasing Atlantic storm surges in a warming climate. Geophysical Research Letters, 44, 10617-10623.

Leonard M, Westra S, Phatak A, Lambert M, can der Hurk B, McInnes K, Risbey J, Schuster S, Jakob D, Stafford-Smith M (2014) A compound event framework for understanding extreme impacts. WIREs Clim Change, 5:113-128.

Li Q, Wang C, Ellingwood BR (2015) Time-dependent reliability of aging structures in the presence of non-stationary loads and degradation. Structural Safety 52 Part A, 132-141.

Lin N, Emanuel K, Oppenheimer M, Vanmarcke E (2012) Physically based assessment of hurricane surge threat under climate change. Nature Climate Change 2 (6), 462.

Maraun D et al. (2017) Towards process-informed bias correction of climate change simulations. Nat Clim Change 7, 764-773.

McApline, S.A. and Porter, J.R. (2018) Estimating Recent Local Impacts of Sea-Level Rise on Current Real-Estate Losses: A Housing Market Case Study in Miami-Dade, Florida. Population Research and Policy Review https://doi.org/10.1007/s11113-018-9473-5

McEvoy D, Mullett J (2013) Enhancing the resilience of seaports to a changing climate: Research synthesis and implications for policy and practice. Work Package 4 of Enhancing the resilience of seaports to a changing climate report series, National Climate Change Adaptation Research Facility, Gold Coast, 49 pp.

Mehvar S, Filatova T, Syukri I, Dastgheib, Ranasinghe R (2018) Developing a framework to quantify potential sea level rise-driven environmental losses: a case study in Semarang coastal area, Indonesia. Environ Sci Policy 89:216-230.

Melby JA, Jobayashi N (2011) Stone armor damage initiation and progression based on the maximum wave momentum flux. Journal of Coastal Research 27(1):110-119.

Mentashi L, Vousdoukas MI, Voukouvalas E, Dosio A, Feyen L (2017) Global changes of extreme coastal wave energy fluxes triggered by intensified teleconnection patterns, Geophys. Res. Lett., 44, 2416–2426.

Merz, B., Kreibich, H., Schwarze, R., and Thieken, A. (2010). Review article "assessment of economic flood damage". Natural Hazards and Earth System Science, 10(8):1697– 1724.

Milly PCD, Betancourt J, Falkenmark M, Hirsch RM, Kundzewicz WK, Lettenmaier DP, Stouffer RJ (2008) Stationarity is dead: whither water management? Science 319 (5863), 573-574.

Mitrovica, J.X., M.E. Tamisiea, J.L. Davis, and G.A. Milne, 2001, Polar ice mass variations and the geometry of global sea level change, Nature, 409, 1026-1029.

Moftakhari HR, Salvadori G, AghaKouchack A, Sanders BF, Matthew RA (2017) Compounding effects of sea level rise and fluvial flooding. Proc Natl Acad Sci USA 114 (37) 9785-9790.

Morim, J, Hemer M, Cartwright N, Strauss D, Andutta F (2018) On the concordance of 21st century wind-wave climate projections. Global and planetary change. 167:160-171.

Moss RH, Edmonds JA, Hibbard KA, Manning MR, Rose SK, van Vuuren DP et al. (2010) The next generation of scenarios for climate change research and assessment. Nature 463:747-756.

Nerlich B, Koteyko N, Brown B (2010) Theory and language of climate change communication. WIREs Clim Change 1:97-110.

Nicholls, R.J., P.P. Wong, V.R. Burkett, J.O. Codignotto, J.E. Hay, R.F. McLean, S. Ragoonaden and C.D. Woodroffe (2007) Coastal systems and low-lying areas. Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [eds. ML Parry et al.]. Cambridge University Press, Cambridge, UK, 315-356.

Nicholls RJ, Townend IH, Bardbury AP, Ramsbottom D, Day SA (2013) Planning for long-term coastal change: Experiences from England and Wales. Ocean Eng. Doi:10.1016/j.oceaneng.2013.01.025.

Nicholls RJ, Hanson SE, Lowe JA, Warrick RA, Lu Xianfu, Long AJ (2014) Sea-level scenarios for evaluating coastal impacts. WIREs Clim Change, 5:129-150.

Nicholls RJ, Marinova N, Lowe JA, Brown S, Vellinga P, de Gusmao D, Hinkel J, Tol RSJ (2011) Sea-level rise and its possible impacts given a 'beyond 4C world' in the twenty-first century. Phil. Trans. R. Soc., 369:161-181.

Oppenheimer M, Little CM, Cooke RM (2016) Expert judgement and uncertainty quantification for climate change. Nat. Clim. Change 6:445-51.

Oude Essink GHP, van Baaren ES, de Louw PGB (2010) Effects of climate change on coastal groundwater systems: a modeling study in the Netherlands. Water Resour Res 46:W00F04.

Paerl HW, Bales JD, Ausley LW, Buzzelli CP, Crowder LB, Eby LA, Fear JM, Go M, Peierls BL, Richardson TL, Ramus JS (2001) Ecosystem impacts of three sequential hurricanes (Dennis, Floyd, and Irene) on the United States' largest lagoonal estuary, Pamlico Sound , NC. PNAS 98(10) 5655-5660.

Penning-Rowsell, E., Johnson, C., Tunstall, S., Tapsell, S., Morris, J., Chatterton, J., and Green, C. (2005). The benefits of flood and coastal risk management: a handbook of assessment techniques. Flood Hazard Research Centre. Middlesex University Press, North London Business Park, Oakleigh Road South, London.

Perrette M, Landerer F, Riva R, Frieler K, Meinshausen M (2013) A scaling approach to project regional sea level rise and its uncertainties. Earth Syst. Dyn, 4:11-29.

Pontee N, Narayan S, Beck MW, Hosking AH (2016) Nature-based solutions: lessons from around the world. Maritime Eng. 129:29-36.

Prime, T., Brown, J. M., and Plater, A. J. (2015). Physical and economic impacts of sea-level rise and low probability flooding events on coastal communities. PLoS ONE, 10(2):1–28.

Ranasinghe R, Callaghan D, Stive MJF (2012) Estimating coastal recession due to sea level rise: beyond the Bruun rule, Clim Change 110 (2012) 561-574, doi:10.1007/s10584-011-0107-8.

Ranasinghe R, Duong TM, Uhlenbrook S, Roelvink D, Stive MJF (2013) Climate-change impact assessment for inlet-interrupted coastlines. Nat Clim Change. Doi: 10.1038/nclimate1664.

Ranasinghe R (2016) Assessing climate change impacts on open sandy coasts: A review. Earth-Science Reviews 160:320-332.

Ranger N, Reeder T, Lowe J (2013) Addressing 'deep' uncertainty over long-term climate in major infrastructure projects: four innovations of the Thames Estuary 2100 Project. EURO J Decis Process 1:233-262.

Reguero BG, Losada IJ, Méndez IJ (2019) A recent increase in global wave power as a consequence of oceanic warming. Nature Communications 10:205.

Roelvink D, Reniers A, van Dongeren A, de Vries JvT, McCall R, Lescinski J (2009) Modelling storm impacts on beaches, dunes and barrier islands. Costal Engineering 56:1133-1152.

Rosati JD, Dean RG, Walton TL (2013) The modified Bruun Rule extended for landward transport. Marine Geology 340:71-81.

Rueda A, Camus P, Tomas A, Vitousek S, Mendez FJ (2016) A multivariate extreme wave and storm surge climate emulator based on weather patterns. Ocean Modelling 104:242-251.

Rupp-Armstrong, S., Nicholls, R. J. (2007). Coastal and estuarine retreat: a comparison of the application of managed realignment in England And Germany. Journal of Coastal Research, 23(6), 1418-1430. DOI: 10.2112/04-0426.1

Salvadori G, Durante F, Tomasicchio GR, D'Alessandro F (2015) Practical guidelines for the multivariate assessment of the structural risk in coastal and off-shore engineering. Coast. Eng. 95:77-83.

Sarhadi A, Ausin MC, Wiper MP (2016) A new time-varying concept risk in a changing climate. Scientific Reports 6:35755.

Sayol JM, Marcos M (2018) Assessing flood risk under sea level rise and extreme sea levels scenarios: application to the Ebro Delta (Spain). J of Geophys Res: Oceans 123:794-811.

Serafin, K. A. and Ruggiero, P. (2014). Simulating extreme total water levels using a time-dependent, extreme value approach. Journal of Geophysical Research: Oceans, 119:6305-6329.

Slangen ABA, Carson M, Katsman CA, van de Wal RSW, Köhl A, Vermeersen LLA, Stammer D (2014) Projecting twenty-first century regional sea level changes. Clim Change, 124:317-332.

Sorensen RM, Weisman RN, Lennon GP (1984) Control of erosion, inundation, and salinity intrusion caused by sea level rise. In: Greenhouse effect and sea level rise. A challenge for this generation. Edited by Barth MC and Titus JG. Published by Van Nostrand Reinhold Company Inc. New York. ISBN 0-442-20992-6.

Spalding MD, McIvor AL, Beck MW, Koch EW, Moller I, Reed DJ, Rubinoff P, Spencer T, Tolhurst TJ, Wamsley TV, van Wesenbeeck BK, Wolanski E, Woodroffe CD (2013) Conservation Letters, doi:10.1111/conl.12074.

Stainforth D, Downing TE, Washington R, Lopez A, New M (2007) Issues in the interpretation of climate model ensembles to inform decisions. Philos Trans R SocA 365:2163-2177.

Stive MJF, Aarninkhof SGJ, Hamm L, Hanson H, Larson M, Wijnberg KM, Nicholls RJ, Capobianco M (2002) Variability of shore and shoreline evolution. Coast Eng 47:211-235.

Stive MJF, Wang ZB (2003) Morphodynamic modeling of tidal basins and coastal inlets. In Elsevier oceanography series 67, 367-392.

Stive MJF, de Schipper MA, Luijendijk AP, Aarninkhof SGJ, van Gelder-Maas C, van Thiel de Vries JSM, de Vries S, Henriquez M, Marx S, Ranasinghe R (2013) A new alternative to saving our beaches from sea-level rise: the sand engine. J of Coast Res 29(5):1001-1008.

Stone D, Auffhammer M, Carey M, Hansen G, Huggel C, Cramer W, Lobell D, Molau U, Solow A, Tibig L, Yohe G (2013) The challenge to detect and attribute effects of climate change on human and natural systems. Clim Change 121(2):381-395.

Stripling S, Panzeri M, Blanco B, Rossington K, Sayers P, Borthwick (2017) Regional-scale probabilistic shoreline evolution modelling for flood-risk assessment. Coast. Eng. 121, 129-144.

Sweet WV, Dusek G, Obeysekera J, Marra JJ (2018) Patterns and Projections of High Tide Flooding Along the U.S. Coastline using a Common Impact Threshold, National Oceanic and Atmospheric Administration, Silver Spring, MD.

Takagi, H., Fujii, D., Esteban, M., Yi, X. (2017) Effectiveness and Limitation of Coastal Dykes in Jakarta: The Need for Prioritizing Actions against Land Subsidence. Sustainability 9 (4), 619

Tarrant, O and Sayers, P.B. (2012) Managing flood risk in the Thames Estuary – the development of a long-term robust and flexible strategy. In Sayers, P.B. (ed.) Flood Risk, Institution of Civil Engineers

Temmerman S, Meire P, Bouma TJ, Herman PM, Ysebaert T, De Vriend HJ (2013) Ecosystem-based coastal defence in the face of global change. Nature Perspective 504:79-83.

The Royal Society (2014) Resilience to extreme weather events. The Royal Society Science Policy Centre Report 02/14. Issued: November 2014 DES3400. ISBN:978-1-78252-113-6.

Thieken, A., Merz, B., Kreibich, H., and Apel, H. (2006). Methods for flood risk as- sessment: concepts and challenges. International Workshop on Flash Floods in Urban Areas, September:1–12.

Thieler, ER, Hammar-Klose, ES (1999) National assessment of coastal vulnerability to sea-level rise; US Atlantic Coast (No. 99-593).

Toimil, A., Losada, I. J., Diaz-Simal, P., Izaguirre C, Camus P (2017a) Multi-sectoral, high-resolution assessment of climate change consequences of coastal flooding. Clim Change, 145:431-444.

Toimil, A., Losada, I. J., Camus, P., Diaz-Simal, P. (2017b). Managing coastal erosion under climate change at the regional scale. Coastal Eng, 128, 106–122.

Toimil A. Diaz-Simal P, Losada IJ, Camus P (2018) Estimating gthe risk of loss of beach recreation value under climate change. Tourism Management 68:387-400.

Tol RSJ, Bohn M, Downing TE et al. (2006) Adaptation to five metres od sea level rise. Journal of Risk Research 9:467-482.

Turner RK, Palmieri MG, Luisetti T (2016) Lessons from the construction of a climate change adaptation plan: A broad wetland case study. Integrated Environmental Assessment and Management 12(4):719-725.

Van der Nat A, Vellinga P, Leemans R, van Slobbe E (2016) Ranking coastal flood protection designs from engineered to nature-based. Ecol. Eng. 87:80-90.

Van Gent MRA, van Thiel de Vries JSM, Coeveld EM, de Vroeg JH, van de Graaff J (2008) Large-scale dune erosion tests to study the influence of wave periods. Coast Eng 55(12):1041-1051.

Van Loon-Steensma JM, Schelfhout HA, Vellinga P (2014) Green adaptation by innovative dike concepts along the Dutch Wadden Sea coast. Environ. Sci. Policy 44:108-125.

Vousdoukas MI, Voukouvalas E, Annunziato A, Giardino A, Feyen L (2016) Projections of extreme storm surge levels along Europe. Clim Dyn 47(9-10):3171-3190.

Vousdoukas MI, Mentashi L, Voukouvalas E, Verlaan M, Feyen L (2017) Extreme sea levels on the rise along Europe's coasts. Earth's Future 5:304-323.

Vousdoukas MI, Mentashi L, Evangelos Voukouvalas, Verlaan M, Jevrejeva S, Jackson LP, Feyen L (2018) Global probabilistic projections of extreme sea levels show intensification of coastal flood hazard. Nat Communications 9:2360.

Vuik V, van Vuren S, Borsje BW, van Wesenbeeck BK, Jonkman SN (2018) Assessing safety of nature-based flood defences: Dealing with extremes and uncertainties. Coast. Eng. 139:47-64.

Werner AD, Bakker M, Post VEA, Vandenbohede A, Lu C, Ataie-Ashtiani B, Simmons CT, Barry DA (2013) Seawater intrusion processes, investigation and management: Recent advances and future challenges. Advances in Water Resources 51:3-26.

Wahl, T., Plant, N. G., and Long, J. W. (2016). Probabilistic assessment of erosion and flooding risk in the northern Gulf of Mexico. Journal of Geophysical Research: Oceans, 121(5):3029-3043.

Wahl T, Haigh ID, Nicholls RJ, Arns A, Dangerdorf S, Hinkel J, Slangen ABA (2017) Understanding extreme sea levels for broad-scale coastal impact and adaptation analysis. Nat Commun 8:16075.

Wahl T, Brown S, Haigh ID, Nielsel JEØ (2018) Coastal sea levels, impacts, and adaptation. J. Mar. Sci. Eng. 6, 19.

Wainwright, D.J., Ranasinghe, R., Callaghan, D.P., Woodroffe, C.D., Jongejan, R., Dougherty, A.J., Rogers, K., Cowell, P.J., 2015. Moving from deterministic towards probabilistic coastal hazard and risk assessment: Development of a modelling framework and application to Narrabeen Beach, New South Wales, Australia. Coastal Engineering 96, 92–99.

Wang XL, Feng Y, Swail VR (2014) Changes in global ocean wave heights as projected using multimodel CMIP5 simulations, Geophys. Res. Lett., 41, 1026–1034.

Wilby RL and Dessai S (2010) Robust adaptation to climate change. Weather 65(7):180-185.

Willis JK, Church JA (2012) Regional sea-level projection. Science 336(6081):550–551.

Wong PP, Losada IJ, Gattuso J-P, Hinkel J, Khattabi A, McInnes KL, Saito Y, Sallenger A, Coastal systems and low-lying areas. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [eds CB Field et al.]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2014, pp. 361-409.