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Investigating the Effects of Climate Change on Structural Actions

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Abstract

The changing climate with resulting more extreme weather events will likely impact infrastructure assets and services. This phenomenon can present direct threats to the assets as well as significant indirect effects for those relying on the services those assets deliver. Such threats are path-dependent and place-specific, as they strongly depend on current and future climate variability, location, asset design life, function and condition. One key question is how climate change is likely to increase both the probability and magnitude of extreme weather events under different scenarios of climate change. To address this issue, this paper investigates selected effects of climate change and their consequences on structural performance, in the context of evolving loading scenarios in three different continental regions: Europe, North America, and Asia. The aim is to investigate some main place-specific changes of the exposure in terms of intensity/frequency of extreme events as well as the associated challenges, considering some recent activities of members of the IABSE TG6.1. Climate change can significantly affect built infrastructure and the society by increasing the occurrence and magnitude of extreme events and increasing potential losses. Therefore, specific relationships relating hazard levels and structural vulnerability to climate change effects should be determined.

Keywords: climate change; extreme weather events; flooding; scour; hurricanes; sea-level rise; tsunami

Introduction

The ageing and deterioration of civil engineering structures are likely to be exacerbated in the next decades by the effects of climate change. On the action side, one may observe an increase in both the probability and magnitude of extreme weather events, such as heavy rainfall, snow, sea-level rise and hurricanes. A decrease of the mean value (for example a reduction in the mean value of annual precipitation at a location) may not necessarily translate in a more favourable condition since if the variability (Coefficient of Variation, CoV) increases at the same time, the upper tail of the distribution may still increase, leading to more extreme magnitudes of actions.[1–2] Concerning frequency, climate change may have an influence on the return period of extreme events (floods, extreme storm events, drought) that may decrease, resulting in the same event having a higher likelihood in any given year.[1]

In this context, IABSE TG6.1 was established in 2017 to bring together a panel of international experts on the effects of climate change on buildings and civil engineering structures, with the aim to promote technical discussions and gather existing global knowledge. The strategy is to focus on a number of relevant case studies and to highlight common points between them when dealing with climate change (e.g. scale of the analysis, types of structures, methodology and objectives).[3] The goal of IABSE TG6.1 is to characterize not only the severity of impacts but also to give recommendations of adaptation strategies for management of structures in view of climate changes.[4]

Some of the aspects covered in this task group are presented in this paper to illustrate how different scenarios of climate change may produce changes of the exposure in terms of intensity/frequency of extreme events, with a focus on three different areas in the world: Europe, North America, and Asia.

The topic concerning Europe includes the potential changes in the intensity of load patterns. One part of this study investigates the effect of climate change on ground snow loads, river flooding, scouring effects, higher expected temperatures and consequences of sea-level rise. Flooding is one main reason that may affect the scour risk of bridges located in rivers. Flood-induced actions on infrastructures are influenced by climate change and present design practices need to be adapted to provide for reliable structures over the desired lifetime. The effect of the statistical characteristics of annual maximum flood event distributions (i.e. mean and standard deviations) and other types of asset and model uncertainties (such as foundation depth or scour model uncertainties) on scour risk are explored. The focus is on riverine bridges and the adverse impact due to scour and hydrodynamic loads. This study explores the relationship between flooding intensity measures (flow velocity, depth) and damage to bridges on the basis of past available data. The importance of these topics has been recognized by several reports providing background information for ongoing revisions of the Eurocodes.[5–7]

Focusing on North America, the presented study provides the assessment of hurricane surface wind, rain and surge hazards under a changing climate, which is achieved by performing advanced simulation components. Hurricane events are generated for both observed (historical) and projected climate conditions, and a systematical comparison between these two scenarios is investigated. In general, the simulation and comparison of results highlight the important effects of a global warming scenario on intensifying hurricane surface wind, rain and surge hazards, and hence impacting the performance of critical civil infrastructure in hurricane-prone areas (e.g. coastal structures).

In Asia, the rising sea levels could enhance negative impacts on coastal communities. A procedure for estimating the failure probabilities of bridges and embankment under tsunami hazard is thus established taking into consideration the sea-level rise. Monte Carlo-based tsunami propagation analysis is performed to obtain the tsunami hazard. Based on the comparison of risk and resilience with and without considering the climate change effect, whether the sea-level rise has to be considered in the risk assessment of coastal road networks under tsunami hazard is discussed in an illustrative example.

At present, the effects of climate change on the actions on structures are the subject of intensive research activities. Large uncertainties in the projections due to random physical processes evolving in time, lack of knowledge, and limited measurements make all results vague and any generalizations doubtful. This study focuses on selected regions and actions and aims to provide an overview of the existing knowledge. However, large uncertainties related to all projections should always be kept in mind.

Changes of Load Patterns in Europe

Effects on Ground Snow Loads

In respect of snow patterns, European regions belong to various climates such as maritime, continental, or cold, often with significant dependence on the altitude of the site. The climate in lowlands of Western-Central Europe and in the Mediterranean is characterized by an intermittent snow cover, that is, single or a few snowfalls followed by often complete melting. In contrast, the climate in mountains, such as in the Alps and in the cold Northern regions, is characterized by a sustained and accumulating snow cover.

The background documents providing the probabilistic basis of climatic actions modelling within the development of the Eurocodes[8–9] indicate that annual maxima of the ground snow loads can be well described by a Gumbel distribution (EVI) for the sites located at low altitudes (<1000 m a.s.l.) with intermittent and irregular snow covers. In contrast, a Weibull distribution (EVIII) seems to be appropriate for the sites at high altitudes (>1500 m a.s.l.) where snow accumulation is significant. A detailed analysis[10] focusing on the Carpathian region confirmed the Weibull distribution for mountains while arguing that a Fréchet (EVII) distribution provides the best fit for lowlands. The US experience advocates a lognormal distribution[11] that has also been considered in some countries in Europe.

Estimated fractiles with return periods of 50 years and longer can be very sensitive to the chosen type of probabilistic distribution. This sensitivity further increases with the assessment methods to be used, namely the statistical framework (Generalized Extreme Value, Generalized Pareto Distribution, Point Processes, etc.), the parameter estimation methods (such as Method of Moment or Maximum of Likelihood), the cleaning of the data and choices within the statistical methods (for instance block length for GEV or threshold value for GPD).

Reference [12] investigated the predicted effects of climate change on the ground snow loads in Norway. They concluded that the expected global temperature increase would, in the majority of the country, lead to decreasing ground snow loads in 2070–2100. Yet, in some inner areas, an increase in ground snow loads is predicted with the expected impact on structural reliability.

Regarding milder snow climate regions, the statistical analysis of recorded ground snow loads in Central Europe has shown:

(1) Statistically significant decreasing trends in annual maxima for the Swiss Alps[13] and the Carpathian region,[10] confirming the substantial decrease in snow depth and snow coverage observed for Romania.[14] In the Carpathian region this decreasing trend has negligible or favourable effect on structural reliability.
(2) The effect of statistical uncertainties was substantial,[10] mainly because the observation periods were short in comparison with the return periods considered in structural reliability analyses. Consideration of time trends and extrapolation in time increases this uncertainty.
(3) An increase in the variability of the meteorological effects might result in more frequent heavy snowfalls especially in higher mountainous regions as for example demonstrated by some roof failures in Bavaria.[15]

Reference [16] recently analysed records of extreme ground snow loads in Europe from 1951 with projections until 2100. They showed that ground snow loads with a 50-year return period could mostly decrease as a result of the projected decrease of mean annual maxima, partly outweighed by increased variability. For some regions, increasing extreme ground snow loads were predicted, including Mediterranean, Iberian Peninsula, UK, Norway and Sweden. The study concluded that these climate change effects need to be combined with the inherent uncertainty of climate models and scenarios to assist decisions about adaptation measures.

It appears that unambiguous recommendations regarding the probabilistic modelling of ground snow load extremes affected by climate change cannot be made considering the state-of-the-art knowledge. This is why CEN/TC[17] requires that the recommendations regarding climatic loads should be continuously developed and periodically revised, at minimum every 15 years. Expected trends of significant time-dependent parameters should also be given.

Effects on River Flooding

Flooding is a major natural hazard in most of Europe.[18] Climate change in Europe is foreseen to increase risk of river flooding, particularly in North-Western and Northern Europe.[6] The JRC report[7] concluded that Western Europe exhibited increasing flood occurrence as current 100-year events might manifest every about 30 years in the 2080s. In other European regions, projections of river floods show higher spatial and temporal variability, with lower and less significant patterns of changes:

- In about 30% of Southern and Eastern Europe, a significant decrease in extreme flood discharges is expected (with an increase in 10% of this region),
- For 24% of Northern Europe, a significant increase in extreme flood discharges is projected while a significant decrease is estimated for 23% of this region,
- In Central Europe, areas with a significant increase (26%) dominate over those with a projected decrease (15%).

Numerous studies investigated trends and severity in floods due to heavy rainfalls or snowmelt.[18] It was estimated that in a +2°C world 25% of the people living in regions affected by fluvial floods would face increased flood risk compared with the situation of no global mean temperature increase (no climate change). This percentage rises to 50% in a +4°C world. Furthermore, the flood-affected population would increase to 211 and 544 million in the +2°C and +4°C world, respectively.[19] Observational data show increasing frequencies rather than the magnitudes of floods.[20]

A range of probabilistic distributions have been considered in modelling of extreme flood discharges. Examples of commonly applied models include a Pearson III distribution with log-normal transformation of data, Gumbel (EVI) distribution, or a two-parameter lognormal distribution.[21–23] When a peak-over-threshold method is applied, a generalized Pareto distribution can be used.[24] Note that an appropriate model should be selected on the basis of the statistical tests taking into account experience with distributions of flows at other localities.[22]

In some cases, climate change has been shown to induce more scattered events, meaning higher extreme events, but also more frequent extreme events.[25] Infrastructure managers concerned by the recent flood episodes in France, Belgium and Germany have noticed that 100-year return events happen every few years, which is in agreement with the observations in the JRC report.[7] Similarly, rain events have been noticed to be longer in time, which is an issue for floods and scour.

These insights imply that trends in occurrence rates and magnitudes of events need to be analysed before an appropriate distribution is selected to describe a flood level or discharge, given the occurrence of an extreme event.

Further, flood-induced risks will increase due to increasing population in the future, which can be seen as a key reason for increased flood losses in Europe and other densely populated regions with large areas of pavements, vanishing gardens and parks, poor drainage system maintenance etc. Based on the extensive review of recent studies, Ref. [26] concluded that the flood risk has increased over many areas in Europe due to a range of climatic and non-climatic effects whose relative importance is site-specific.

The 2013 flood of the Danube River is considered thereafter as an example of measures taken after a particular disastrous event. This flooding event brought the highest ever recorded discharge in Bratislava (Slovakia) and the highest ever recorded water level in Budapest (Hungary), along with other large floods in the neighbouring region. Researchers immediately called for analysing the effect of climate change on floods and on reconsideration of design parameters of flood defences. Reference [27] found out that in Germany - similarly as in other locations - considerable increase in flood-related losses could be expected due to climate change.

Some researchers claim that the assumption of stationarity cannot be upheld and they call for non-stationary models in water management.[28] Others point out that observations are limited and statistical uncertainty still governs extreme predictions, thus there might be no practical gain in moving to non-stationary models.[29] This uncertainty could be reduced by incorporating predictions of global circulation models. By incorporating climate model predictions, uncertainty of large return period events (> 1000 years) can be considerably reduced,[30] though there are multiple caveats, for example a single relatively short measured realization of the Earth's climate is used for the validation of these models. It should be noted that flooding is affected by a wide range of factors other than changes in extreme precipitation, for example human land use, that is, urbanization can greatly increase the flood risk.[31] Therefore, climate change is likely to affect weather patterns and the hydrological cycle due to global warming, increasing the frequency and magnitude of rainfall and, as a consequence, of flooding events. In particular, climate change is expected to influence extreme (low-probability, high-impact) events.[32]

Results in literature show an intensification of extreme precipitation and flood events over all climate regions, with non-uniform rates according to the region (due to different interacting drivers of extreme precipitation changes).[33,34] Analysis of the effects of climate change and identifying statistically significant time trends are further complicated by many geographical and meteorological factors that affect extreme discharges during floods and may evolve themselves over time. Possible climate change effects may be overestimated by non-statistical influences that may have developed during the period covered by the measurements and may affect future extreme discharges. These influences include[22]:

- River management including maintenance and/or restoration of floodplains, modifications of depth, width, and roughness of a river channel, and removal of vegetation;
- Local paved areas affecting local flood conditions;
- Effects of deforestation, changes in land use, and other human-made interventions in the environment, etc.

The hydrological data always require critical hydrological review to faithfully represent best knowledge about the flooding conditions.[35]

Effects on Flow Velocity in Rivers and Risk of Scouring

There is established consensus that the increased risk of scour to bridge piers and abutments is one of the critical effects of climate change.[36,37] For example, according to Ref. [36], bridge scour may increase by between 5% and 50% by the 2080s in the UK, depending on the bridge conditions and location. However, a quantitative assessment of the potential consequences of climate change on bridge scour is missing[38] and the need to incorporate the effects of climate change (e.g. more intense, frequent rainfall) for assessing the associated risk of bridge failures due to scour action still remains.[39,40]

Scour depth is linked to the speed of the water flow. Indeed, regarding the parameter time, without sediment transport, scouring grows slowly and tends towards the asymptotic value, and the phenomenon is slow. But with sediment flow, the scour hole is dug very quickly and oscillates around a mean value. This threshold is an extreme depth, applicable for all cases of possible hydraulic flow.[41] Currently, alongside these long-term phenomena, rivers and their environment are exposed to short-term ones, for example, aggressive water flows or flash floods. The force of the water flow is similar to an impact force on everything which happens to be on its path, as for example bridge piers or bridge decks. These phenomena and their consequences cannot be predicted currently, and generally the engineering work consists in conducting some post-phenomenon remedial works and emergencies to describe and explain what happened.

Potential future increases in flooding due to climate change need to be taken into consideration when designing new structures or assessing existing ones. The challenge in accounting for climate change in scour assessments is that the sensitivity of peak river flows to climate change is likely to be different for various different types and locations of rivers. A framework for quantifying such sensitivities has been recently proposed by Ref. [42]. In scour design and assessment codes, the potential effects of climate change are usually captured by simply increasing the magnitude of the design flood, which is the river discharge for a given return period, that is 200 or 500 year, by a percentage, that is, 20–25%.[43,44] The new UK guidance on highway bridges have recently updated climate change allowances, which have become location-specific.[45] However, in other national codes (e.g. the Italian Guidelines on Risk Classification and Management of Bridges[46]); climate change is not detailed in the risk assessment of scour and hydraulic risk.[47] On the other hand, there are studies that have been carried out recently which attempt to model, in more detail, the effect of climate change on the flood-frequency distributions and their effect on scour risk.[38,48–50] For example, Ref. [51] modelled the effect of climate change as a variation in the parameters that underpin the annual flow distribution (mean value, standard deviation).

Structural Health Monitoring (SHM) provides a valuable tool for monitoring bridges affected by climate change-related flood damage,[52] to understand bridge management actions (e.g. bridge closure, reduce traffic) to be undertaken after a severe flood. The costs of bridge management actions are expected to increase as the intensity and frequency of flood events increase, since severe damage states are more likely to occur. On the other side, as climate change is leading to more extreme flood events, sensor monitoring could become more cost-effective in the future.

Effects of Higher Expected Temperatures

With higher expected temperatures in the future due to climate change, this may have an effect on the response of civil engineering structures. One potential effect may be the fatigue stress cycling of bridge structures. Reference [53] carried out a study in Denmark to understand the influence of temperature on the response of orthotropic bridge decks; the authors utilized long-term monitoring data collected on the Great Belt Bridge in terms of temperature and strains at various locations of the bridge deck. The study confirmed the temperature dependence of the stress ranges experienced at welded joints of the bridge deck, depending on their location with respect to the bridge's pavement. It was shown that a mean air temperature increase of 2.9°C by the year 2100 can reduce the remaining fatigue life of critical bridge details by approximately 25 years. A recent European study also showed that the design thermal actions on bridges are expected to be affected by climate change and the influence of higher extreme temperatures.[5]

Effects of Sea-Level Rise for Coastal Infrastructures

All models responsible for the projection of future sea-level rise are driven by regional characteristics, which makes local prediction important to identify potential impacts and to improve planning for safety measures needed. For example, in the Mediterranean region there are numerous coastal areas that are potentially vulnerable to flooding and erosion. These issues coupled with future sea-level rise should be explored thoroughly. Reference [54] suggested a model that shows a spatially-averaged projected sea-level rise by 2040–2050 will be 9.8 and 25.6 cm in the Mediterranean Sea in their minimum and maximum scenarios, respectively, values that are slightly smaller than the minimum and maximum likely ranges of variation assessed by the IPCC AR5 under the RCP6.0 scenario. The Bank of Greece[55] predicted sea-level rise in the Greek coastal areas by 2100 in a range from 0.2 to 0.59 m while conservative projections reach 1.5–2 m. Although there are large variations in these projections, the effect of sea-level rise on the frequency and intensity of natural hazard events is unquestionable. Flooding caused by the increased tidal or storm surge heights is one important hazard to structures that is affected by sea-level rise. The coupling of tsunami hazard, which is a cascading effect after strong earthquake events, with sea-level rise is also critical. Based on recent events and historic records the potential impact of tsunamis can be disastrous. However, the combination of tsunami actions with sea-level rise has not been yet sufficiently explored (see Section 3). Even the occurrence of mini tsunami events, as the one triggered by the Samos earthquake of magnitude 7.0 Mw on 30 October 2020 that could be set to worsen with sea-level rise, shows the significance of studying this coupling effect. There is an urgent need to determine these potential hazards based on regional characteristics and perform targeted vulnerability assessments on critical coastal infrastructure (e.g. transportation and electric power networks) located at the coastlines to identify those that are at high risk.

Besides, let us illustrate the effect on sheet piles in coastal infrastructures. In France,[56] 25% of harbors' infrastructures are built with sheet piles and this percentage reaches 50% for key economic or military infrastructures. Reference [57] illustrated with a case study that structural reliability is mainly sensitive to the loading from the soil, except if large corrosion occurs. Sea-level rise acts on this loading: first, on the position of the permanent loading and on the intensity of this loading in case of embankment (Archimede effect) and second on the position of cyclic loading due to waves and tide, thus on the level of stress in the fatigue assessment. Additionally, there is a coupling with corrosion as the sea-level rise changes the vertical profile of corrosion (Ref. [58]). For quantifying the relative impact of this effect, Table 1 presents the effects of corrosion and sea-level rise on the mean stress for the RCP8.5 scenario applied to the case study of Ref. [59]. It is interesting to observe in this case that the sea-level rise decreases the stress and compensates the effect of the corrosion.

Configuration	Zone	Stress (MPa)			
		After 50 years		After 100 years	
		Without sea-level rise	With sea-level rise	Without sea-level rise	With sea-level rise
Wharf exposed to tide change	At the tie rods	83.95	81.267	84.16	74.436
	In the maximum bending area (immersion area)	−160.47	−149.01	−163.71	−138.84

Table 1: Effect of sea level rise on a sheet-pile wharf

Tropical Cyclone Surface Wind, Rain and Surge Hazards in North America

There remains significant debate about how rising greenhouse gas concentrations affect tropical cyclones (TCs), however, the available global climate models and downscaling techniques generally support the premise that the frequency of destructive high-intensity storms under changing climate will increase (with large regional variations).[60] Current climate models project significant changes in several environmental factors, including sea surface temperature (SST), environmental vertical wind shear, and moisture content and temperature at the tropopause level.[61] Among them, the SST is usually considered as the dominant one, linking climate and tropical cyclone phenomena. Increases in sea surface temperatures (SSTs) are acknowledged to be a result of global climate change due to increased CO2 emissions.[62] WEF[63] suggests that global average SST may increase 4°C by 2060 based on the current trends. Reference [64] found that the peak wind speeds of tropical cyclones could increase by 5% for every 1°C increase in SST. Elsner[65] stated that climate change causes higher SST; warmer SST results in more energy which is converted to stronger TC winds.

There have been efforts in the engineering community to conveniently and efficiently consider the influence of the warming climate on TC activities by integrating the projected environmental conditions into a TC assessment framework (e.g. Refs. [66,67]), generally involving a TC track model (consisting of genesis, trajectory, and intensity modelling components) to generate the synthesized storms. While there are several important environmental factors contributing to TC dynamics and thermodynamics (e.g. SST, wind shear, convective instability, temperature at the top of atmospheric boundary layer, and outflow temperature), SST is usually the only consideration in these downscaling exercises. To address this issue, a nonlinear intensity model integrating not only the contribution of the SST but also other thermodynamic and dynamic variables (such as vertical wind shear and convective instability) has been developed.[68]

Due to its simulation efficiency and accuracy, the enhanced TC track model developed by Ref. [68] can be effectively used in the context of a changing climate. To accurately assess the TC hazard under changing climate, the probability of various emission scenarios, conditional probability distribution functions (PDF) of regional environmental factors given a climate change scenario (considering inherent uncertainties and climate model differences) and conditional PDF of each TC hazards (e.g. wind, rain or surge) given a set of environmental factors should be carefully examined. The first two uncertainties (involved in the emission scenario simulations and climate models) have been well presented in the Section of "sea-level rise" discussion. The emphasis in this section will be focused on coupling the enhanced TC track models and TC hazard models. The obtained assessment framework of TC surface wind, rain and surge hazards under a specific set of environmental factors of a future global warming scenario is used thereafter to highlight the significant implications of a changing climate to costal structures and infrastructure.

Climate-dependent Stochastic Simulation Framework of Tropical Cyclone Hazards

To adequately resolve TCs for obtaining sustained wind speeds (or TC intensity) with high accuracy, a very high resolution of current global climate models (e.g. on the order of 1 km or less) is needed.[69,70] To reduce the computational costs of explicitly simulated storms, downscaling exercises are typically used. Although numerous environmental factors from the outputs of climate models have been identified as the factors that have an influence on TC activities, current engineering applications mainly consider the effects resulting from SST.

TC-related hazards, namely, strong wind speeds coupled with torrential rainfall and powerful storm surge, are expected to increase significantly in the coming years because of the effects of global warming.[71–73] TC surface wind, rain and surge hazards under a changing climate can be accessed, for example, by performing the climate-dependent stochastic simulation framework of TC hazards developed at the University at Buffalo (UB). The UB climate-dependent stochastic simulation framework of TC hazards essentially consists of three components, namely an enhanced TC track model to generate the synthesized storms (including a physics-based intensity model integrating SST, wind shear, and convective instability contributions),[68] a novel thermal wind balance-based model to simulate the gradient wind profiles (explicitly considering environmental conditions of SST, temperature at the top of atmospheric boundary layer, and outflow temperature),[74] and efficient hazard models for wind, rain and surge simulations. Specifically, a height-resolving boundary-layer model was developed to obtain the surface wind and rain fields (reducing inherent uncertainties associated with conventionally used gradient-to-surface wind speed conversion factors),[75–77] and an efficient, artificial neural network-based model (i.e. multi-layer feedforward backpropagation network) was developed to predict storm surge using the standard TC parameters as inputs, namely, central pressure, translational speed, radius of maximum winds, and storm track.[78] The machine learning-based model is constructed using the large database of synthetic tropical storms obtained from the U.S. Army Corp of Engineers through NACCS. The NACCS database is accessible through the Coastal Hazards System web tool (https://chs.erdc.dren.mil/default.aspx). The schematic of the UB climate-dependent stochastic simulation framework for TC wind and rain hazards is presented in *Fig. 1*. Although each component of the UB climate-dependent stochastic simulation framework for TC hazards will undoubtedly improve over time, currently it provides a guide on how to integrate atmospheric science and wind (and coastal) engineering for effective evaluating effects of climate change on TC surface hazards.

Impact of Climate Change on Storm Surge Using the Slosh Model

An alternative to the artificial neural network-based model discussed above for modelling storm surge hazard is the use of physics-based models such as the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model.[79] Here, a case study is presented to generate the projection of future storm surge hazards for selected locations across the Atlantic and Gulf Coast regions of the U.S., considering the impact of the rise in sea surface temperature (SST). To generate the surge hazard, 20,000 TC years are simulated using a validated TC simulation model based on the Empirical Track Model (ETM) first proposed by Ref. [80] Projected future SST is obtained from the Coupled Model Intercomparison Project Phase 5 (CMIP5) for use in the simulation. The SLOSH model is employed for the storm surge analysis.

Figure 2 shows the projected changes in surge height at the end of the twenty-first century in eight locations across the Gulf and Atlantic Coasts. Three RCPs (RCP 2.6, 6.0, and 8.5) are considered for the analysis. As expected, there is a rise in surge level observed across the studied locations due to increased TC intensity. An analysis of the impact of the changes in SST on surge return periods also indicated that significant changes would be expected. For example, the 100-year surge height for the present climate is expected to become a 25–50-year occurrence under RCP 8.5 for the studied locations. It is also expected that sea-level rise will compound the impact of climate change on future surge hazards. It should be noted, however, that surge heights are not only a function of TC intensity. Other factors such as topography, bathymetry, and geographic layout play a huge role and directly impact the resulting surge height. Furthermore, variations in other TC parameters such as heading angle, translational speed, and landfall location also play a crucial role in surge heights.

The scenario-based approach used here does not consider the likelihood of the various IPCC emission scenarios. The likelihood of the scenarios has been a subject of much discussion. Reference [81] assessed the effect of current Intended Nationally Determined Contributions (INDCs) of countries outlining their post-2020 climate action and concluded that a median surface temperature warming of 2.6–3.1°C is expected by 2100. Such an increase indicates that a scenario between RCP 6.0 and 8.5 is likely. Some researchers have argued that the RCP 8.5 scenario is more likely than originally thought because of factors such as the release of greenhouse gases from thawing permafrost, which are larger than currently estimated.[82,83] Other researchers have argued that the RCP 8.5 scenario is becoming increasingly implausible partly because it will require a fivefold increase in coal use, which is highly unlikely, and the cost of clean energy sources will continue its falling trend.[84] There is an increasing call for a risk-based or probabilistic approach to modelling future climate scenarios. However, there are several challenges to moving to such an approach. The main challenge is that probabilistic climate scenarios might underestimate the uncertainty because of an inadequate number of global climate model runs due to computational limitations and the use of improper probability distributions in models.[85] Also, the likelihood of the various scenarios will keep changing constantly and will need to be updated as new data is collected and climate models are being updated.[86]

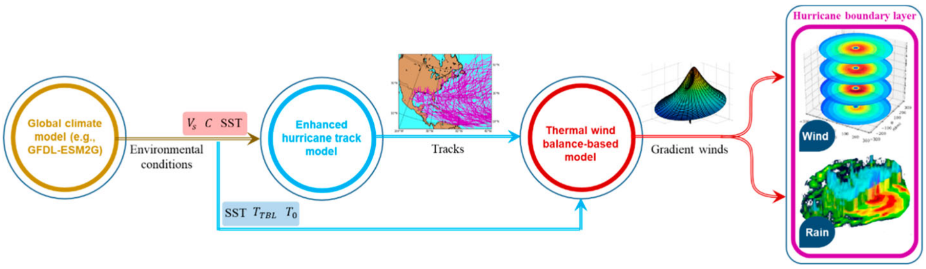

Fig. 1: UB climate-dependent stochastic simulation framework for TC wind and rain hazards[74] (Note: Vs is wind shear, C is convective instability, T_{TBL} is temperature at the top of the atmospheric boundary layer, and T_0 is outflow temperature)

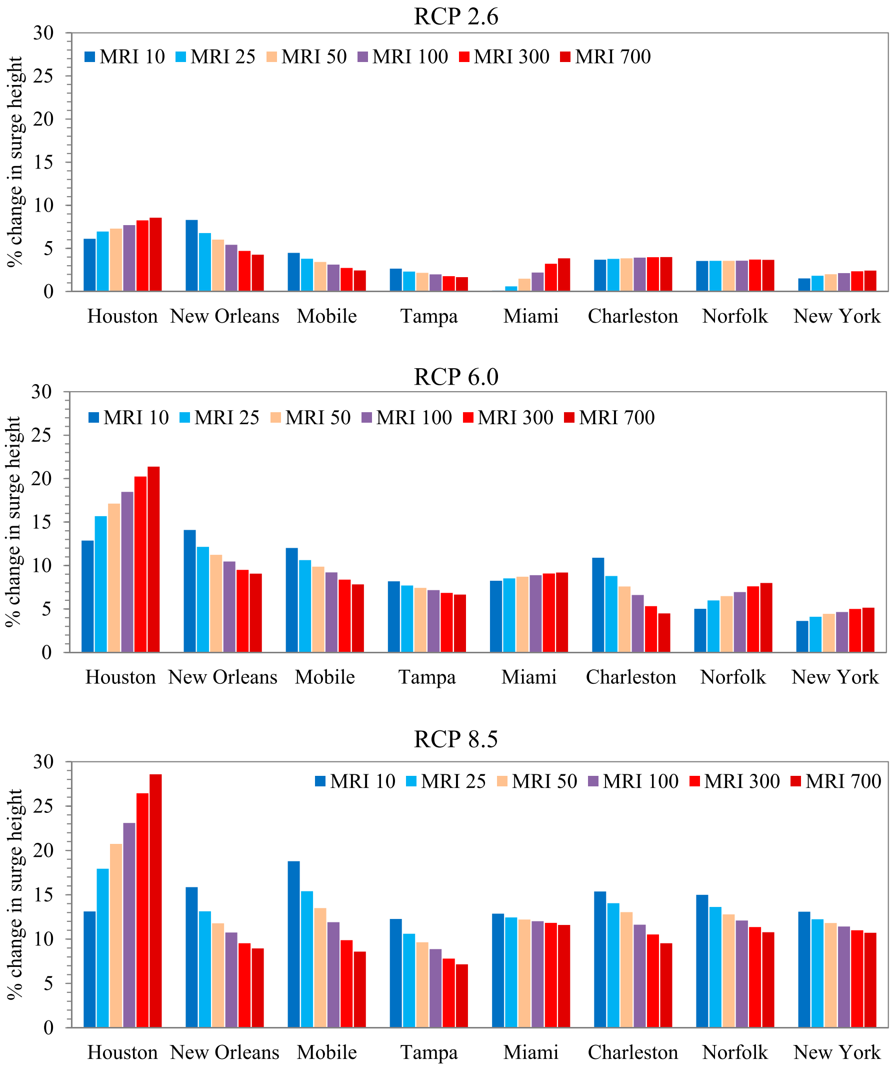

Fig. 2: Changes in storm surge hazard from 2020 to 2100 for different Mean Recurrence Intervals (MRI) under RCP 8.5

Implications for Coastal Structures and Infrastructures

Direct and indirect economic losses associated with TC wind, rain and surge hazards are expected to increase with growing coastal populations and associated structures and infrastructures in coastal regions.[87] Such losses are expected to increase because of a changing climate. Hence, TC risk-assessment models must be able to account for the non-stationary aspects of TCs, to account for the potential effects of climate change on TC damage costs. However, many existing models that estimate TC damage costs as a function of wind speed assume that the wind speed is stationary. Reference [88] developed a framework for TC risk assessment in Queensland, Australia. The framework assessed the impacts the changing global climate may have on damage costs, and found that increasing TC wind speeds could increase damage costs. Reference [89] assessed damage risks and the cost-effectiveness of designing new housing to be less vulnerable to TCs. References [90–91] proposed a conceptual framework for estimating TC damage risks to residential construction in Florida considering the change in wind speed as a result of climate change, as well as TC-induced surge considering climate variability in Miami-Dade County, Florida, New Hanover County, North Carolina and Galveston County, Texas in the USA.

Among TC hazards, wind and rain hazards are of great significance since a substantial part of economic and life losses resulting from TC events are directly or indirectly related to them (e.g. wind-induced structural damage, wind-driven rain penetration, and inland flooding). A systematical comparison of the simulation results between the historical climate scenario (1991–2010) and future climate scenario (2081–2100) subjected to the RCP 8.5 was carried out in Ref. [68] based on UB climate-dependent stochastic simulation framework of TC hazards for the northeast United States coastline. A total of 10,000 years of TC events were generated for both historical and projected climate conditions. TC surface wind speed and rain rate were characterized in terms of the MRI (mean recurrence interval). In general, higher TC surface wind speeds and rain rates were obtained for all levels of MRIs, with changing climate, based on the selected global climate model. For example, the wind speed corresponding to a 50-year MRI was projected under the RCP 8.5 climate scenario to increase by approximately 14% at a location of Monmouth County, New Jersey and an increase of 27% in the rain rate corresponding to a 100-year MRI was projected at a location of Nantucket County, Massachusetts. The obtained simulation results indicate that TC surface wind and rain risk mitigation and adaption for civil structures and infrastructures in coastal regions are necessary in light of a changing climate scenario.

Studies are suggesting that TC hazard patterns may change due to a changing global climate. In addition to changes in TC wind and rain, TC-induced storm surge may also change as a result of climate change. Low-lying coastal areas are particularly susceptible to storm surge and the effects on communities can be catastrophic. Reference [78] coupled the UB climate-dependent stochastic simulation framework of TC with a newly developed machine learning-based surge model to assess storm surge hazard risks to coastal bridges under changing climate conditions. Their simulation results (at a control point of 41.05° Latitude and –71.96° Longitude) suggested that changing climate will have a significant, negative effect on the annualized rate of bridge closures, with the attendant direct and indirect economic losses. For example, the annual probability of exceedance increases from 2.6% under the historical climate to approximately 15% under RCP 8.5 for a 2 m storm surge threshold (a criterion that triggers bridge closure). This situation becomes even worse if sea-level rise under changing climate is considered. IPCC[92] stated that the global mean sea level (GMSL) is projected to rise by 0.28–1.02 m (likely range) under the new Shared Socioeconomic Pathways (SSP) scenarios, and has estimated that GMSL has already increased by 0.2 m between 1901 and 2018. Some regions in the U.S., are identified as extremely sensitive to sea-level rise. For example, regarding the New York Metropolitan Area, Ref. [93] states that sea level is projected to rise along the tidal Hudson by 0.05–0.254 m (2–10 in.) by the 2020s, 0.20–0.76 m (8-–30 in.) by the 2050s, 0.33–1.47 m (13–58 in.) by the 2080s and 0.48–1.75 m (15–75 in.) by the 2100s, while the need for the adaptation of coastal infrastructure to sea-level rise has been identified in numerous studies (e.g. [94,95]). Sea level rise affects directly the height of storm surge, since it is directly added upon it.[96] The combination of rising static water levels and the increase in the severity and frequency of TC events will lead to increasing submergence and flooding of coastal areas and even accelerated rates of coastal erosion. Increasing storm intensity means that the risk of severe storm surge flooding for coastal communities will rise, as well. Reference [97] presented a risk assessment methodology for coastal bridges that accounts both for TC-induced storm surge and sea-level rise and shows how climate change affects risk values.

Notes on Wind Actions in Other Regions and Associated Uncertainties

In general, it is recognized that wind pressures are a major climatic action for many structures all around the Globe. Besides hurricanes, (1) synoptic storms and (2) thunder storms cause frequently damage to built infrastructures. However, available knowledge is often inconclusive and significantly region-dependent. For Europe, the report focused on the climate change effects in Europe by CEN/TC[17] indicates that regarding (1), the lack of consensus on the significance of observed trends in tropical cyclone statistics poses a challenge to the interpretation of projections for tropical cyclones. Climate model-based simulations are expected to be extensively employed and generate larger sample sizes than those currently available from observations. To model extratropical cyclones, the current global climate models may still have insufficient resolution and thus it may still be the case that resolution is a factor limiting analyses of storm intensity; improvements in resolution are expected to be beneficial for future studies. Regarding (2), an increase in the frequency and magnitude of severe convective storms will influence the statistical properties of wind pressures. However, it seems that the explicit simulation in global or regional model studies is unfeasible in the near future. CEN/TC[17] concludes that the indications of a certain increase of wind extremes in Northern Europe and Northern parts of Central Europe may be expected while Southern Europe may expect fewer extreme wind storms. However, the results significantly depend on the climatic model used.

Apparently, the projections of severe wind events are associated with large uncertainties. For instance, Ref. [98] observes some consistency amongst the projections by different models for extreme wind pressures over Canada but underline that these are subject to considerable uncertainty due to the general inability of coarse resolution climate models to resolve many of the physical processes that drive extreme winds. They conclude that confidence in these projections is very low. According to CEN/TC,[17] presently broadly accepted methods to assess the non-stationary behaviour of extremes in time and space are missing and further research is needed to adequately capture uncertainties in projections (including statistical and model uncertainties).

Sea-level Rise Multi-hazards in Asia

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) suggested that the potential climate change impact might considerably exacerbate coastal hazards at a regional scale.[99] One noteworthy aspect highlighted in the IPCC AR5 is the global and regional scale sea-level rise, which could aggravate the coastal hazards to a greater extent, such as typhoon-induced storm surges[100] and flooding due to the precipitation level increase.[34] In addition, a study has revealed that 0.5 m of sea-level rise is sufficient to double the local tsunami hazard.[101] Therefore, sea-level rise assessment serves as a crucial task to enhance the resilience of coastal communities under future disasters.

Significant research efforts have been made to develop a model to project the future sea-level rise. These models are developed mainly based on two approaches: process-based and semi-empirical approaches. The process-based approach employs a grid-based numerical ocean and atmosphere circulation using climate-related prognostic equations, namely the General Circulation Model (GCM).[99] Conversely, despite the inadequate representation of the physical process, the semi-empirical approach evaluates the future sea-level rise statistically based on the past data by developing the relationship between the observed temperature and sea-level rises (e.g. [102]). However, though many previous studies have been devoted to investigating the future sea-level rise trends, its projection remains highly uncertain.

The uncertainties associated with sea-level rise arises from several aspects, including the amount of emitted greenhouse gas concentration (i.e. climate change scenario),[103] ocean and geophysical processes such as ocean circulation and ocean bottom pressure change, and the spatial variability of sea-level rise due to the distributed location of the glacier and ice sheet mass. An extensive summary of sea-level rise uncertainties has been provided by Ref. [104] ranging from global to regional scale. One of the highlighted uncertainties includes the sea-level rise projections among GCMs. Sea-level rise projections among GCMs are considerably varied since each climate model group employed different prognostic formulas and approaches during the modelling process.

Therefore, the probabilistic approach of sea-level rise assessment is deemed appropriate to consider all of the uncertainties mentioned above.[105] An appropriate framework for probabilistic sea-level rise hazard assessments can be developed by utilizing the sea-level rise projections from the process-based approach to perform a statistical analysis of GCMs and other sea-level rise models. Finally, the sea-level rise uncertainties can be integrated with future coastal disasters to promote better climate change adaptation strategies for coastal communities.

Framework for Probabilistic Sea-level Rise Hazard Assessments

Several studies have carried out the probabilistic projections of sea-level rise by analysing each component according to their uncertainty source and including their local variability. For instance, Ref. [106] suggested that on a modest climate change scenario (i.e. RCP 4.5), the sea-level rise due to the oceanographic process from GCM projections could be 0.13–0.4 m on a global scale in 2100. In terms of total sea-level rise (i.e. combination of oceanographic process, ice sheets, glaciers, and ice caps), the global sea level is expected to rise in the range of 0.36–0.96 m in 2100. Nevertheless, these uncertainties associated with the ice sheet sea-level rise from previous studies were justified according to the expert elicitation and were carried out by disregarding the dependencies between sea-level rise components. The complete framework for probabilistic sea-level rise hazard assessments as complementary from previous research has been presented by Ref. [107] and discussed briefly herein.

The complete framework for probabilistic sea-level rise hazard assessments has been presented by Ref. [107] First, the regional sea-level rise, defined as the sea-level rise in a particular location in the ocean, is estimated by multiplying each global mean sea-level rise component (i.e. the average value of sea-level rise over the ocean) with its corresponding spatial variability (hereafter referred to as sea-level fingerprint).[105] Three sea-level rise components are considered herein: (1) sterodynamic sea-level rise due to thermal expansion and dynamical ocean currents; (2) glacier sea-level rise due to surface mass balance; and (3) ice sheet sea-level rise due to dynamical ice shelf basal melting. The surface mass balance represents the net loss of snow accumulation and ice mass melting of the glacier and ice sheet, while the dynamical ice shelf basal melting is caused by the detachment of the ice shelf from the bedrock due to ocean warming, which accelerates the ice sheet flow into the ocean. To generate a more representative outcome, further study is needed to consider other non-climatic sea-level rise components including tectonics and glacial isostatic adjustment.

Figure 3 shows the flowchart for estimating the regional total sea-level rise hazard.[107] Each regional sea-level rise component's probability density function (PDF) is estimated differently by utilizing their corresponding uncertainties. Based on statistical analysis, the sterodynamic sea-level rise PDF S is assessed using the available GCMs from the Coupled Model Intercomparison Project 5 (CMIP5) based on statistical analysis.[108] It should be emphasized that before utilizing these models, several preprocessing steps should be carried out, such as model drift correction due to the dynamical imbalance of the GCM initial condition and grid interpolation due to the difference in ocean grid resolution.[105] In terms of the global mean glacier sea-level rise PDF G, the glacier models involved in the Glacier Model Intercomparison Project (GlacierMIP)[109] can be employed. Finally, the global mean ice sheet sea-level rise PDF I is evaluated based on the surface mass balance component using the volume above floatation (VAF) change data[110] and the ice sheet dynamics assessment following the method proposed by Ref. [111] The details for each component's assessment can be found in Ref. [107]

The sea-level rise fingerprints for each sea-level rise component are also estimated differently depending on each source location. The glacier and ice sheet sea-level fingerprint can be estimated using the land-water mass change data from the Gravity and Recovery Climate Experiment (GRACE).[112] The land-water mass changes in the corresponding glacier and ice sheet locations are converted into sea-level rise fingerprints by applying the sea-level equation solver provided by Ref. [113]. On the other hand, the sterodynamic sea-level rise FGSTR is estimated using the ocean bottom pressure (OBP) change data from the Norwegian Earth System Model (i.e. NorESM1-M) as suggested by Ref. [114]. The OBP change data is assumed as static loading and converted into a regional sea-level rise associated with self-attraction and loading (SAL) effects by employing the sea-level equation solver from Ref. [113] and normalized with its associated global mean value. Finally, each global mean sea-level rise PDF is multiplied by its corresponding sea-level fingerprint using Monte Carlo simulation (MCS) to obtain regional sea-level rise PDF for each component, as shown in *Fig. 3*.

Each sea-level rise component is assumed perfectly correlated with each other since they increase simultaneously with respect to global warming over time. By applying the convolution of probability distributions concept and incorporating the occurrence probability of climate change scenario defined as representative concentration pathway (RCP), the cumulative distribution function (CDF) of regional sea-level rise hazard can be evaluated according to Ref. [107]. There has been no established consensus associated with the likelihood of each future climate change scenario, considering that they are dependent on energy and land-use trends. For simplicity, the likelihood between RCP scenarios is assumed to be the same herein.[107] Future studies should be further developed to consider the likelihood of RCP scenarios.

Figure 4 illustrates the regional total sea-level rise hazard map and the sea-level rise hazard evaluated over the Macau Special Administrative Region for the year 2100 with respect to the

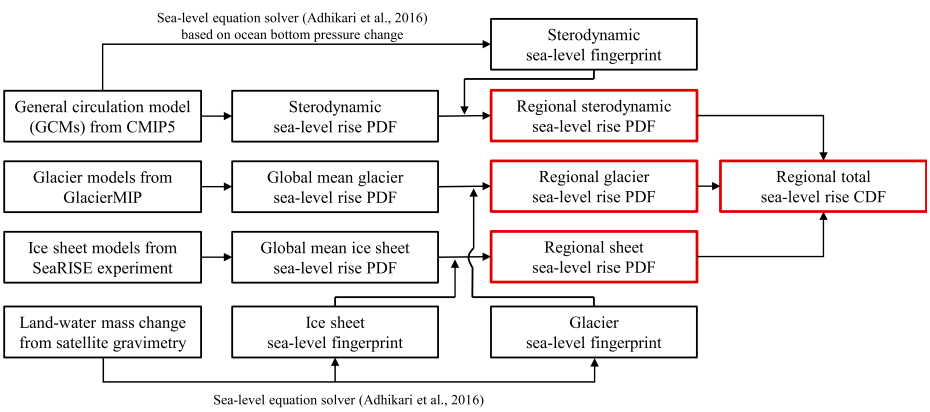

Fig. 3: Proposed framework for estimating regional total sea-level rise hazard[107]

present. The sea-level rise hazard shown in *Fig. 4* is calculated based on the procedure shown in *Fig. 3*. For illustrative purposes, the Macau Special Administrative Region is selected as the analysed area following Ref. [101] to investigate the potential application of the proposed framework, as discussed later. As shown in *Fig. 4*, it can be inferred that sea-level rise hazard varies considerably depending on the ocean location. Therefore, an appropriate sea-level rise hazard should be evaluated accordingly based on the corresponding analysed coastal area. The evaluated sea-level rise hazard can be utilized to investigate the potential intensification of coastal hazards due to sea-level rise.

Integration with Other Coastal Hazards

In order to integrate the effects of sea-level rise uncertainties into other coastal hazards, such as tsunami and storm surges, a rigorous numerical-based simulation considering different cases of sea-level rise should be carried out. Reference [101] provided a demonstration in investigating the tsunami hazard increase due to sea-level rise in the Macau Special Administrative Region. Prior to performing the tsunami simulations, they deterministically decreased the bathymetry and topography to simulate sea-level rise effects. Complementary to their study, the conditional tsunami hazard can be integrated with the sea-level rise hazard provided in *Fig. 4* according to the total probability theorem proposed by Ref. [107].

Figure 5a shows the conditional tsunami hazard curve given a specific sea-level rise value estimated by Ref. [101] based on numerous tsunami propagation analyses. The tsunami hazard curves for the northeast Macau Peninsula are evaluated under 0.0, 0.5, and 1.0 m of sea-level rise. For demonstration purposes, the return period expression is converted into exceedance probability and interpolated to facilitate the evaluation of the total probability theorem numerically (e.g. MCS, numerical integration), as shown in *Fig. 5b*. By convolving the conditional tsunami hazard curve with the sea-level rise hazard provided in *Fig. 4c*, a tsunami hazard curve considering the effects of sea-level rise can be obtained, as shown in *Fig. 5c*. The tsunami hazard curve increases when considering the effects of sea-level rise. Depending on the exposure of the analysed infrastructures, the potential impact of small tsunamis should not be underestimated since it could generate a considerable amount of economic loss, casualties, and disaster waste that could impede the recovery process.[115,116] Moreover, although the results presented in this study are demonstrated with an emphasis on the year 2100, the time frame for decision-making has to be justified depending on stakeholder interests. Further study is needed to investigate time-dependent sea-level rise effects in other regions under tsunami hazard.

The inclusive coastal hazards integrated with sea-level rise effects could provide more appropriate climate change adaptation strategies. In terms of tsunami risks, a mitigation plan should be implemented through an adequate design of coastal defense structures to minimize the associated consequences. The current philosophy of coastal structure safety level should be reconsidered based on the corresponding hydraulic standards of the coastal protection, the inherent capacity to withstand a certain level of tsunami impact (including several plausible failure modes such as overtopping of seawall and dikes instability due to progressive erosion), and the increasing return period of the tsunami due to sea-level rise. Since the previous study has pointed out that sea-level rise could also extend the tsunami impact spatially,[101] a higher safety level of coastal defense should be addressed for more populated and capital intensive regions.

In addition to the coastal defense as a systematic mitigation effort, the tsunami damage on bridge structures should be controlled through more adequate design criteria to allow a rapid restoration process. Under the intensified tsunami impacts due to sea-level rise effects, the bridge's substructure should be designed in a satisfactory performance such that it remains functional and intact for emergency transport (e.g. controlling the excessive deformation and well design against washout). Hence, the above concerns imply that the risk of tsunami under sea-level rise effects necessitates a more comprehensive reassessment of standards for the design or assessment of structures to promote resilient coastal communities.

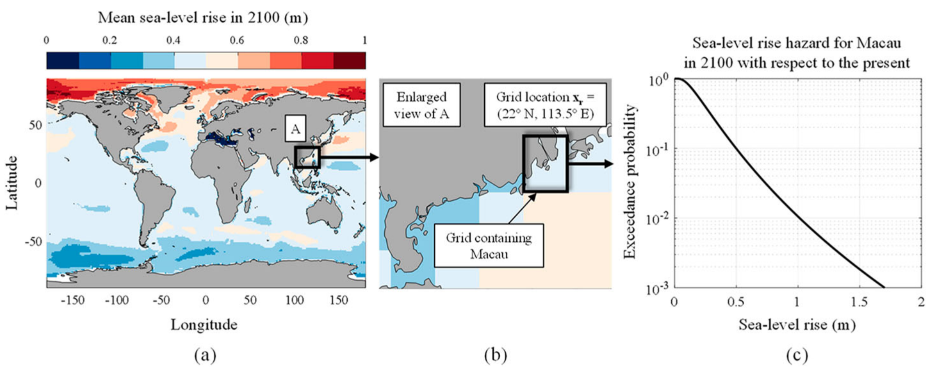

Fig. 4: (a) Regional total sea-level rise hazard map, (b) location and analysed grid containing Macau, and (c) sea-level rise hazard for Macau

Conclusions

By considering specific examples where climate change may produce changes of load patterns, this paper provides some key topics when dealing with the effects of climate change in three different continental regions: Europe, North America, and Asia. Common engineering experience suggests that it is more effective to immediately adapt design strategies for foreseen climate change effects rather than excessively investing into upgrading of insufficiently durable and unreliable structures in the future. Provisions for uncertainties in present design procedures provide a buffer against early manifestations of climate change effects. Using advanced climate modelling to resolve these uncertainties is therefore the first logical step towards adjustment of design procedures to account for the imminent and expected impacts of climate change. The presented overview of various effects of climate change on built infrastructures leads to the following conclusions:

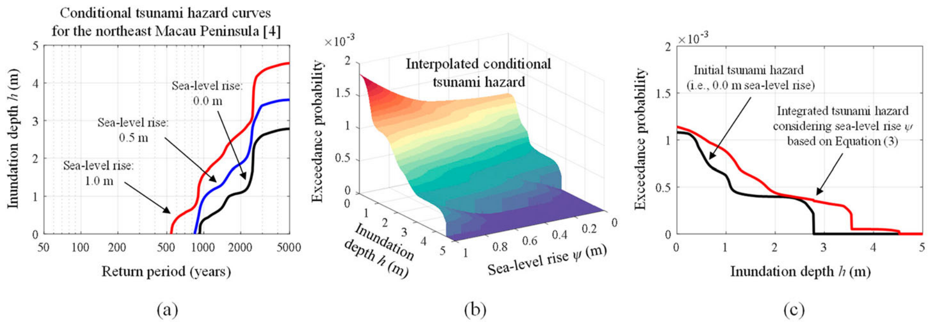

Fig. 5: (a) Conditional tsunami hazard curves for the northeast Macau Peninsula provided by Li et al.[97]*, (b) interpolated conditional tsunami hazard curve, and (c) integrated tsunami hazard curve considering sea-level rise effects*

(i) climate change has an impact on future extreme environmental actions on structures and should be considered. However, more data, models and other information are necessary in order to better extrapolate future predictions of environmental actions, for example, wind, hurricane, heat, snow and flood actions;

(ii) essential contribution of meteorologists and statisticians to civil engineering includes improved projections for trends and extremes in local weather events, and specification of uncertainties in events associated with 100- to 1000-year return periods;

(iii) periodic review of statistical data and probability models related to environmental actions is required;

(iv) revisions of design and assessment standards are recommended to reduce the impacts of climate change on the performance of structures. The scope of such revisions should include limited state failure verifications, global failure aspects and foreseen consequences of extreme weather events on built infrastructure. Steps are to be made as soon as possible due to the inertial effect of decisions accepted at present on the future built environment. Yet these revisions should be made with caution as short-term recent data might indicate short-term (say decadal) climate variations which might be falsely interpreted as a part of long-term changes. Commonly, long time series (decades) are needed depending on the variability of an observed variable and rate of changes; for instance, ASCE[117] mentions 40–50 years in relation to analysis of rainfall records and the World Meteorological Organization calculates climate normals on the basis of averages over 30 years;

(v) structural behaviour models affected by climate change will become more important as some structures can be expected in the future to be "overloaded" to some extent due to climate change; sufficiently robust structures should be provided to sustain such overloading without excessive damage.

Critical infrastructure represents a key element of all sectors of the economy (e.g. transportation, energy) and their continuous operation is of critical importance. Climate change can significantly affect infrastructure, especially in, but not limited to coastal environmental (e.g. bridges, coastal energy power plants etc.), not only in terms of the increase in the occurrence/severity of extreme events threatening their expected structural performance (e.g. storm surge acting along with sea-level rise) and increasing potential losses but also regarding their structural condition (e.g. degradation of built materials). Therefore, one major goal is to determine specific relationships relating hazard levels and structural vulnerability to climate change effects. This understanding will help towards the development of integrated risk assessment approaches and better design and assessment codes, considering both changes in resistance and load processes, and cost–benefit optimization under uncertainty, for informed decision-making on necessary actions to protect critical infrastructure and to enhance resilience of infrastructures to extreme weather events in the short, medium and long-term.

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