A roadmap for an integrated assessment approach for climate change adaptation of concrete bridges

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Abstract

Bridges play a crucial role in modern societies, regardless of their culture, geographical location, or economic development. The safest, economical, and most resilient bridges are those that are well managed and maintained. Recently, climate change has been posed as one of the biggest concerns for the health of bridges. Although the uncertainty associated with the magnitude of the change is large, the fact that our climate is changing is unequivocal. As a result, making bridges resilient to climate change is a priority for the authorities. A well-planned early intervention may save lives and money. Until now, the focus of scientific research has mostly been on the climate science, but any practical plan for adaptation of bridges has to be rooted in other disciplines like physics, chemistry, engineering, economics, and finance. Therefore, the goal of this paper is to review the work already done from climate change to bridges and set a roadmap for an integrated assessment approach for climate adaptation of bridges. The approach is grounded in a probabilistic - and physics-based framework able to prioritize bridge adaptation measures as a function of bridge's location, climate scenarios, impacts, vulnerability, risk, and cost, in order to assist authorities in the decision-making process. As

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adaptation to climate change is highly context-specific, this approach is mainly focused on concrete bridges. The structural health monitoring technology is proposed as a mechanism to assess and continuously evaluate the structural condition of bridges and trigger adaptation measures as a function of its predicted severity.

Introduction

Bridges age naturally, but their structural deterioration can be accelerated by operational and environmental conditions (Figueiredo et al. 2019). Studies about the influence of operational and environmental conditions must go beyond daily traffic load, temperature, and humidity influences (Figueiredo and Brownjohn 2022). The environment is facing climate change, whose effect has not yet been taken into account in bridge codes and may have multidimensional adverse impacts on the operational performance, durability, and safety of existing bridges, as they are vulnerable to projected changes such as temperature, relative humidity, precipitation, and carbon dioxide (CO_2) concentration (Gkoumas et al. 2019).

In fact, climate change is currently one of the biggest concerns for the health of bridges (European Commission 2013). Although the magnitudes of those changes involve large uncertainties, the fact that our climate is changing is clear (Field et al. 2012). Due to their long-life span and great economic value, increasing the resilience of bridges to climate change is an important challenge for bridge authorities. As climate change may affect where bridges are built, how they are designed, and when they are subjected to maintenance procedures, it is relevant to ascertain their reliable performance against climate change risks (Ozbulut et al. 2016). An early and planned adaptation action will increase the durability and safety of bridges and therefore save money and, eventually, lives.

Even though research already exists about the effects of climate change on infrastructure, few studies have been downscaled to bridges and only a particular set of climate variables has been analyzed (Gkoumas et al. 2019). Moreover, the existing approaches consider the ambient climatic conditions as driving forces without taking into consideration the physics phenomena on bridge structural and material levels. We believe there is not yet comprehensive and holistic research on the real influence of climate change on the structural health of bridges.

Therefore, this paper intends to lay down a roadmap for an **integrated assessment approach** for climate adaptation of concrete bridges, built in three dimensions:

1) climate data,
2) physics-based modeling, and
3) cost-effectiveness of adaptation measures.

This approach puts together several fundamental areas: climatology, pattern recognition, hydrology/hydraulics, materials/chemistry, structural engineering, risk assessment, and life-cycle assessment (LCA).

Even though the approach can be generalized to every type of bridge, herein it is applied on concrete bridges, taking into account their specific conditions, both in terms of climate and construction practices (materials, structural systems, among others).

In this approach, the health and serviceability of concrete bridges is assumed to be compromised by the following projected changes: (i) increase of the frequency of heavy precipitation events, which can cause flooding and scouring; (ii) higher temperatures and frequency of heat waves, which are expected in the years ahead and can cause additional stresses and deficient behavior of bearings and expansion joints; (iii) increase levels of atmospheric CO_2 concentration and humidity, which may trigger concrete carbonation and increase corrosion (Khelifa et al. 2013); and (iv) sea level rise, which may cause relocation of bridges. There are other projected changes to be considered, but are not a priority at this stage, due to the uncertainty on either the projections or the impacts on bridges. For instance, the wind pattern evolution is under huge uncertainty, but it is negligible for most regular reinforced and prestressed concrete bridges. However, its impact on cable suspended bridges may be a concern (Nasr et al. 2019).

Risk scenarios of change in temperature, relative humidity, precipitation, and CO_2 emissions encompassed in the Intergovernmental Panel on Climate Change (IPCC) reports, which are determined based on the global climate models, are implemented in a probabilistic- and physics-based framework for structural deterioration prediction and incorporated into the structural health monitoring (SHM) process.

We believe that any proposal to assess the impact of climate change has to be incorporated into the SHM process, as discussed by Figueiredo and Brownjohn (2022), with the aim to assess and predict the health state of existent bridges under uncertain future environmental conditions (Vagnoli, Remenyte-Prescott, and Andrews 2018). Therefore, the SHM process is herein proposed as an assessment procedure to evaluate permanently the structural condition of bridges and a warning mechanism to trigger adaptation measures as a function of its predicted vulnerability. The Heat, Air, and Moisture (HAM) transport modeling, which has been used extensively for the assessment of the hygrothermal performance of buildings, is proposed herein to generate temperature and humidity gradients and furthermore reflect concrete degradation as a function of surface/air temperature and relative humidity projections. Three mainly complementary structural impact areas are addressed:

- Flooding and bridge scour,
- Accelerated degradation of materials, and
- Thermally induced stresses and movements.

As a function of bridge vulnerability, adaptation strategies will be recommended and backed by an LCA of deteriorated bridges, to account the uncertainties derived from the climate change and structural models.

But what differentiates the integrated assessment approach from the traditional bridge design? When thinking about adaptation, it is necessary to differentiate new and existing bridges. For new bridges, it is possible to update codes and the adaptation can be accomplished at the design phase. Revising existing guidelines requires changes to design criteria, including considerations for new and higher traffic loads, stronger foundations, and greater freeboard between the water level and the bridge deck. For existing bridges, which is the main focus of this paper, the updated codes may be used to design adaptation measures, but it is also necessary to develop an integrated approach to evaluate the vulnerabilities and set thresholds to trigger adaptation when required.

The traditional approach in adapting (existing) bridges to climate change is based on reaction to climatic events that already happened. In fact, bridges are typically only adapted as part of retrofit campaigns that are undertaken because the bridge was damaged. It is very rare that a bridge is adapted to climate change if the extreme event inflicted no structural damage. Conversely, the approach presented in this paper is pro-active. We define an approach which intends to guide the adaptation process before extreme climatic events occur, so that the bridge is prepared to face them when they do. It covers downscaling of climate change data to the bridge site, verifying the vulnerabilities using simplified degradation models, and quantifying the costs based on risk and life-cycle assessments.

This approach is in line with the priorities defined in the European Green Deal, as it ensures more sustainable and climate resilient infrastructure in Europe and beyond (European Commission 2013).

Besides this first section, this paper is organized as follows. The section "From climate change to bridges" links climate change and its potential impacts on bridges. Then, there is a section to exposes the roadmap and the three dimensions of the integrated assessment approach. The "Climate data" section explains how climatic records and climate change data can be obtain and downscaled to bridges. Next, it is shown how the SHM process and its technology can be used to prevent potential impacts of climate change on the structural health of our bridges, taking into account the climate variables. Then, a section summarizes general adaptation measures as a function of potential impacts and how we can assess the impact of climate change and come up with cost-effectiveness of adaptation measures. A "Climate-related maps" section shows the importance of maps for a friendly visualization of the impacts and vulnerability of bridges, to support political decisions for adaptation actions. The final section gives a summary of the integrated assessment approach and points out recommendations and future works to validate the approach.

From climate change to bridges

The effects of climate change on bridges have gradually caught the attention of both political bodies and the scientific community. Between 2004 and 2016, several key reports from the European Environmental Agency (EEA) and European Commission (EC) have provided the signposts to adapt Europe's bridges to climate change (EEA Report 2004, 2017; European Commission 2013). Even though the first reports tackled the issue as an infrastructure problem, bridges are now mentioned as particularly vulnerable to summer heat and heavy precipitation, causing expansion and high river flows, respectively. According to an EC Report (European Commission 2013), the impact of weather stresses represents 30% to 50% of current road maintenance costs in Europe.

Generally, while changes in average climate are not dramatic for bridges, the extremes of climate (floods, storms, and heat waves) provide the largest impacts on our bridges. Model projections indicate much increased frequency and intensity of such events as the 21st century progresses. For instance, in Figure 1, a schematic diagram shows the effects on extreme temperatures when both the mean and the variance increase, leading to much more record hot weather. An outstanding example is the heat wave in central Europe in 2003 (Houghton 2015).

According to the 2019 JRC Policy Report (Gkoumas et al. 2019), the European Union member states must invest and address maintenance issues to ensure serviceability and safety of our bridges. This includes investing in SHM systems (Figueiredo, Moldovan, and Barata Marques 2013) to respond to the extreme loading conditions caused by climate change and contributing to the faster deterioration of infrastructure. At the European level, groundwork on vibration-based SHM has been funded through FP6, FP7, and H2020 in projects addressing wider scopes (e.g., risk reduction, resilience, LCA, energy harvesting, and internet of things) and specific hazards (e.g., earthquakes, landslides, and flooding). The IRIS, BRIDGEMON and BridgeScan Projects are some examples. Still, few projects have tackled climate change and SHM together. One of the few exceptions is the RAIN Project, which was funded with almost 5M€ by FP7, between 2014 and 2017, for risk analysis of infrastructure networks in response to extreme weather. This project intended to identify critical infrastructure components subjected to extreme weather events and minimize the impact of these events on the infrastructure network of the European Union. Despite the wide range of projects, it is very difficult to find solutions for increasing the resilience of bridges to climate change.

Nasr et al. (2019) performed a review of the potential impacts of climate change on bridges, setting the increase of global temperature as one of the key impacts, which can create stresses in the same magnitude as the traffic loads, and result in expansion and contraction of the material. Changes in air temperature can hide changes in the bridges' responses caused by damage, as extensively studied in previous publications (Figueiredo et al. 2011, 2019). In 2019, Palu and Mahmoud (2019) found that most of the main load carrying girders could potentially reach their ultimate capacity when subjected to service load coupled with extra thermal stresses caused by climate change; additionally, although expansion joints are small components of bridges' superstructure, their malfunction can result in major structural problems like buckling.

The potential impact of rising temperature has already been tackled to promote standards' revision. The 2020 JRC Technical Report (Athanasopoulou et al. 2020) states that current European maps for thermal design are based on climatic data which, with some exceptions, are mostly 10 to 15 years old and ignore the potential effects of climate change. The report presents the general concept of the definition of thermal actions for structural design within the Eurocodes and discusses the potential implications of the thermal actions changes in structural design. It also presents a case study of Italy on future variations of climate factors that would directly affect the design values for thermal actions in the standards. (It was concluded that an increase in the maximum and minimum temperature used for structural design is expected all over Italy.) A methodology for developing thermal maps for structural design that takes into account the influence of climate change is also proposed. The report presents scientific and technical background intended to stimulate debate and serves as a basis for further work to study the implications of climate change on the thermal design of structures. In particular, bridges are regarded as structures that are expected to be influenced by stresses from extreme temperatures, and thus should be designed for temperature amplitudes justified from climate projections for the actual region.

Several studies, e.g. (Batchabani, Sormain, and Fuamba 2016; Kjellström et al. 2013), also reported that an increase in the risk of flooding is expected in the future, pushed by an increase in precipitation projected for some regions. Flooding events also foster the occurrence of anomalies related with either local or generalized scour of bridge piers and abutments (Kumar and Imam 2013). Scouring has been shown to be one of the most common cause of bridge failure (Cook, Barr, and Halling 2015); for instance, in 2001, the failure of the Hintze Ribeiro Bridge in Portugal that killed 59 people was caused by scouring and after several days of flooding events. Therefore, the impacts of extreme precipitation and flood frequency should be quantified. Some previous studies examined the probability of scour failure, without, however, considering the potential influence of climate change (Briaud, Gardoni, and Yao 2014). Risk-based frameworks considering the impact of climate change on the long-term performance of bridges are becoming increasingly relevant (Stewart and Deng 2015). For example, in 2013, Khelifa et al. (2013) assessed the probability of a bridge failure due to scour based on data from the 2009 US National Bridge Inventory. The analysis showed a range of potential bridge failures and corresponding economic loss across the states caused by climate change. In 2019, Imam (2019) presented risk-based frameworks for assessing the potential impacts of climate change on rail bridge structures subjected to scour that have been developed based on a number of case studies.

Evaluating the effect of climate change on the initiation and propagation of corrosion is also currently an active research area. Several authors have studied the increase in the probability of corrosion initiation due to climate change, evaluating the reliability of deteriorating structures under the effect of climate change, and developing adaptation strategies to mitigate the risk of additional deterioration due to climate change (Imam 2019; L. O. Santos, Xu, and Virtuoso 2020; Wang, Stewart, and Nguyen 2012). Recent research has also shown that climate change can increase the risk of deterioration due to the temperature increase and the escalation in the likelihood of carbonation and chloride-induced corrosion (Wang, Stewart, and Nguyen 2012).

A 2020 JRC Report (Commission et al. 2020) concluded that estimates on the impact of corrosion at a global level (including buildings) indicate that the cost of corrosion to economies and society is significant; the eventual acceleration of the corrosion process due to climate change can further increase its direct and indirect costs, implying that this subject deserves further attention from the research community, with the purpose of assessing the best adaptation measures for the existing building stock. It suggests for further research:

- to increase the number of case studies in European built infrastructure addressing the effects of climate change on the corrosion of reinforced concrete and steel structures to allow the extraction of global conclusions;
- to support the development of adaptation strategies, at a pan-European scale, accounting for the effects of a changing climate on the corrosion;
- application of LCA to assess the cost-effectiveness of adaptation measures and evaluate the costs and benefits of those measures to optimize structures' performance when subjected to a changing climate.

A broad range of adaptation measures has been identified by Stewart and Bastidas-Arteaga (2019), namely: improved solutions for the design of new structures, retrofitting of existing structures, utilization of new materials, or changes to inspection and maintenance regimes. Implementation of regulations to improve air quality and reduce CO_2 concentration levels in urban regions is another possible solution through mitigation. Stewart and Bastidas-Arteaga also advise risk-based approaches to assess the optimal level of adaptation measures, in case they are indeed needed. However, the authors emphasize the great complexity and resources required to implement such approaches, which are subject to considerable uncertainty.

With the apparent evolution towards more extreme weather conditions, state transportation agencies are realizing the need for adaptive infrastructure systems (Ozbulut et al. 2016). For instance, the Swedish Transportation Administration has already developed a climate adaptation strategy, but they are still trying to develop methods for determining when and where such adaptation would be cost-effective (Nasr et al. 2020). Recently, Nasr et al. (2020) reviewed possible adaptations for bridges as a function of potential impacts, concluding that in addition to enhancing the longevity and performance of structural systems, these solutions need to be cost-effective.

Several authors have also tried to study the impact of climate change risks on life-cycle management. In 2017, Frangopol et al. (2017) presented a brief overview of the integration of risk, sustainability, and resilience measures into the life-cycle management of deteriorating infrastructure with an emphasis on bridges, while considering climate change effects. Rising global temperature, increased frequency of heavy precipitation events, and increased levels of atmospheric CO_2 were mentioned as three of the greatest concerns regarding climate change for highway bridges. The authors concluded that: (i) if bridges are subjected to more days with the sustained air temperature above 32°C, the integrity of the pavement may suffer and deterioration in roadway and bridge expansion joints may occur; (ii) an increased amount of precipitation may cause increases in soil erosion rates that in turn will cause damage to the foundations of bridges; and (iii) higher CO_2 levels will increase the likelihood and rate of carbonation-induced corrosion. In 2018, Khandel and Soliman (2018) presented a risk-based probabilistic framework for optimizing the management activities of bridges susceptible to damage flood-induced scour. The framework established the optimum maintenance solutions, which minimize the total life-cycle cost of the bridge under investigation and maximizes its service life.

With considerable uncertainty in the basic science of climate change and in the projections of future climate, especially on the regional scale, uncertainties are also present in our assessment of the impacts of climate change and the consequent prescription of adaptation measures. The IPCC claims many uncertainties in the projections particularly with regard to timing, magnitude, and regional patterns of climate change due to incomplete understanding of: sources and sinks of greenhouse gases; clouds, which strongly influence the magnitude of climate change; and oceans, which influence the timing and patterns of climate change (Houghton 2015). Nevertheless, in situations where we cannot evaluate the exact magnitude and timing of the values, we may be able to identify trends and their impacts on the bridges. Actually, in the bridge engineering field, Frangopol et al. (2017) also noted that the magnitude of climate projections is involved in large uncertainties and many studies within this field are not detailed enough to produce a scientific clarification. Therefore, improved judgmental assessments and more scientific evidence are necessary to reduce the epistemic uncertainties associated with the real impacts on our bridges.

In conclusion, even though research already exists on the effects of climate change on infrastructure, few studies has been focused on bridges, with only a particular set of climate variables being usually analyzed (Gkoumas et al. 2019), while the downscaling to specific bridges is missing. As adaptation to climate change is highly context-specific, so adaptation measures depend on the climatic, environmental, social, and political conditions in the target regions and sectors (Füssel 2007). The book “Climate Adaptation Engineering” by Bastidas-Arteaga and Stewart (2019) is one of the most comprehensive publications on climate change adaptation for infrastructure, defining measures to reduce vulnerability and increase the resiliency of built infrastructure. However, its wide scope lacks the details and specificities of bridges, which challenges the definition of practical aspects of risk assessment when deciding on the most cost-efficient measures to reduce bridge vulnerability to climate variables. As there is not yet comprehensive research on the real influence of climate change on the structural health of bridges, adaptation strategies have been proposed on a general basis and without a cost-effective analysis.

Integrated assessment approach for climate adaptation of bridges

The adaptation of bridges to climate change can be addressed following a comprehensive understanding presented in Figure 2. It consists of four key steps [adapted from (Lund University 2018)]: (i) understand the problem; (ii) identify critical impacts, vulnerabilities, and risks; (iii) weighing consequences; and (iv) identify suitable adaptation measures to reduce vulnerability and increase the resiliency of bridges (Strengthen? Do nothing? Or simply manage the increased risk?).

The health of bridges is assumed to be compromised mainly by four projected changes and associated impacts (Figure 3):

- increase of the frequency of heavy precipitation events, which can cause flooding and scouring;
- higher temperatures and frequency of heat waves expected in the years ahead, which can cause additional stresses in the bridge components, deficient behavior of expansion joints, and damage to non-structural elements like pavements and railways;
- increased levels of anthropogenic CO_2 concentration and relative humidity, which may trigger or increase the likelihood of concrete carbonation and accelerate corrosion; and
- sea level rise, which may cause relocation of bridges.

There are other projected changes not mentioned in Figure 3, which can still be taken into account, but they are not considered a priority at this stage, due to the uncertainty on either the projections or the impacts on bridges. A comprehensive list of all possible climate change variables and impacts can be found in (Nasr et al. 2019).

Acquiring a better understanding of the phenomena affecting our bridges is paramount and highly multidisciplinary, as these structures are susceptible to many different climate-dependent actions that have considerable uncertainty and different magnitudes in different regions of the world. As few studies have been performed on bridges, any effective adaptation strategy must be assessed at the physics level through more laboratory, numerical, and field bridge data. To accomplish that, the approach to climate adaptation presented here is built on three interconnected dimensions (Figure 4):

1. climate data;
2. physics-based modeling; and
3. cost-effectiveness of adaptation measures.

Basically, it starts with the construction of climatic records and climate change data for the location of each analyzed bridge. Then, the vulnerability of bridges to floods and scouring, degradation of the construction materials, and excessive thermally induced stresses and deformations are assessed, followed by the analysis of the cost-effectiveness of the adaptation measures. It involves several fundamental scientific areas: climatology, pattern recognition, hydrology and hydraulics, materials and chemistry, structural engineering, risk assessment, and LCA.

In order to analyze the impacts described in Figure 3, the following sections describe in detail specific areas of research needed to implement the integrated assessment approach (Figure 4). The impacts analyzed are limited to structural damage, meaning that pavement and railway damage are not addressed in this approach. The bridge relocation caused by sea level rise is only addressed in section 0, as the rise of sea water is not considered itself as a source of damage.

Climate data: Climatic records and climate change data

To establish the best strategy for climate adaptation, a thorough understanding of the regional climate is required. Therefore, historical climatic records and climate change data (precipitation, relative humidity, air temperature, and sea level rise) need to be compiled, estimated, and/or analyzed. The observed tendencies can be assessed considering historical data retrieved from bridge monitoring systems and other sources like weather stations, observational gridded data sets, or climate reanalysis (Herrera et al. 2019; Hersbach et al.

2020). Historical data can also be used to select the most suitable climate change models for each bridge, to create a multi model ensemble, and deal with single model uncertainties.

To assess the future vulnerability of bridges, impact assessment modeling should be performed. Impact assessment models are normally calibrated and validated with observed data, thus, to maintain a coherent approach, model climate data should fit observations. For this, after the selection of climate change models, an appropriate bias correction should be performed. The bias correction will scale climate model outputs to account for their systematic deviations when compared with historical data, and should ensure the preservation of the internal variability of the climate models when improving their fitting towards observations (Vaittinada Ayar, Vrac, and Mailhot 2021). One of the available approaches towards bias correction consists in applying the quantile mapping technique. This technique implies a statistical transformation that adjusts a cumulative distribution function of the modeled variables into the observed ones, through the quantile relation between variables (Figure 5).

Projections of CO_2 concentrations in the atmosphere should also be obtained and articulated with climate change projections, and future chloride concentrations in bridge materials should be estimated, considering climate change scenarios (Xie et al. 2018).

Analysis of climatic records. Structural data are retrieved from bridge monitoring systems and historical meteorological data are sourced from weather stations to find climate-related patterns. Typically, the observed climate data exhibits wide variability over a broad range of time and space scales. Variables such as air temperature, solar radiation, relative humidity, and precipitation are the driving agents of many processes which result in potential risks to bridges. Hence, it is essential to analyze local bridge data sets (temperature, relative humidity, strains, and displacements) with pattern recognition methods that have the potential to assess the whole range of climate fluctuations, as for instance, machine learning algorithms. Methods may comprise, for instance, nonparametric tests, such as Mann-Kendall and Sen's slope estimator tests, which are commonly used by researchers for analyzing climate trends in time series (Alemu and Dioha 2020). The authors' experience in machine learning also suggests the application of deep learning to find hidden patterns in the past data related to climate change upon thousands of observations from different sources (Silva et al. 2021). The analysis of the climate data sets will contribute to a better understanding of climate regimes in the region where the bridge is located.

Climate change projections until the end of the 21^st^ century. To enable the assessment of the possible future behavior of bridges, climate change projections for precipitation, relative humidity, temperature, sea level rise, and CO_2 concentrations must be put together. It is necessary to find a way to assess the chloride effect in future conditions, as no model-based climate change projections are available. One possibility is to use available climate projection data (e.g. temperature) for future corrosion analysis (see e.g. (Xie et al. 2018)). Several Regional Climate Models (RCMs) forced by alternative Representative Concentration Pathways (RCP) are currently available, providing a comprehensive range of plausible climate futures. Currently a new set of RCMs is under development with similar characteristics of RCP but containing descriptions of the socio-economic trends underlying each scenario: the Shared Socio-economic Pathways (SSP). The available climate change projections represent a broad range of possibilities to affect future exposure and vulnerability (Figure 6). According to the authors' experience, a selection of scenarios may include:

- SSP1-1.9 or SSP1-2.6 – it requires that CO_2 emissions start declining by 2020 and go to net negative levels around 2050 or 2070 (low-emission mitigation scenario and aligned with the Paris agreement objectives);
- SSP2-4.5 – it is an intermediate climate change scenario with emissions remaining around current levels until the middle of the century; and
- SSP5-8.5 – it is the worst-case climate change scenario, in close agreement with historical total cumulative CO_2 emissions (high-emission scenario) (IPCC 2021; Schwalm et al. 2017).

The SSP/RCP represent different concentrations of the full suite of greenhouse gases, aerosols, and chemically active gases (S. Carvalho et al. 2020; S. C. P. Carvalho, Santos, and Pulquério 2017; Dias et al. 2020). Climate change indicators should consider a comprehensive range of RCM developed under phases 5 or 6 of the Climate Model Intercomparison Project (CMIP). These include simulated historical data (used, for instance, for comparisons with observed data) as well as concentration trajectories for RCP2.6, RCP4.5, RCP6.0, and RCP8.5 (CMIP5) or SSP1-1.9, SSP1-2.6, SSP2-4.5, SSP3-7.0, and SSP5-8.5, among others (CMIP6). For the global concentrations of CO_2, the projections may be obtained from data provided in peer-reviewed publications (Riahi et al. 2017), and compiled, for instance, in the SSP Database (IIASA 2022).

Statistical downscaling of the selected climate models for each case study. The observed records (in-situ monitoring data) can be used to validate the simulated climate retrieved from RCM and to preform bias correction of projected data until the end of the century. After the RCM selection is completed, a bias correction should be performed for each case study, in order to estimate climatic series and indices (e.g., heat waves, consecutive days without precipitation, and recurrence intervals estimation). This approach will minimize the systematic errors detected in the available RCM and prepare the data needed for bridge impact modeling computation. To deal with this challenge, it is recommended using a statistical downscaling, which can be performed, for instance, for daily precipitation and temperature, using pre-established methods (Vaittinada Ayar, Vrac, and Mailhot 2021; Willems and Vrac 2011). After bias correction, climate change series can be used, and indices estimated to inform the risk sensitivity assessment tasks.

Geo-referenced database. As a by-product of this analysis, geo-referenced databases of the bridge stock across larger geographical regions, containing relevant characteristics, such as structural type, material, and age, can be built.

Physics-based modeling: health assessment and monitoring

Introduction

In the last three decades, SHM has been a promising tool in bridge management, as it potentially permits one to perform permanent condition assessment to reduce uncertainty in the planning and designing of maintenance activities, as well as to increase the service performance and safety of operation (Figueiredo and Brownjohn 2022). The general idea has been the transformation of massive data obtained from monitoring systems and numerical models into meaningful structural information, also known as knowledge (Farrar and Worden 2013).

SHM has tried to perform damage identification through a five-level hierarchy (detection, localization, type, severity, and prognosis) and based on information from two independent approaches: physics- and data-based.

Physics-based approaches attempt to identify damage by relating the measured data from structures to data retrieved from their numerical models (e.g., calibrated finite element (FE) models) (Figueiredo et al. 2019). They are mainly rooted in FE model updating techniques and perform structural damage identification by comparing the measured structural responses with the ones derived from baseline FE models, tailored for that specific structure and validated against its undamaged behavior. The structural responses recorded by monitoring systems are used to iteratively update some calibration parameters (e.g., stiffness properties and boundary conditions), defined at the finite element level, such as to minimize a set of objective functions that reflect the difference between the computed and the measured structural responses (Mirzaee, Abbasnia, and Shayanfar 2015; Papadimitriou, Chatzi, and Grompanopoulos 2019). The values of the calibration parameters that minimize the objective functions indicate the presence and, possibly, the localization and extent of damage.

To deal with large amounts of data and perform the damage identification automatically, data-based approaches have been used in the context of the statistical pattern recognition paradigm, where machine learning plays an important role (Figueiredo and Brownjohn 2022). Typically, machine learning algorithms are used to detect damage through variations in some damage-sensitive features extracted from the structural response data that are outliers in respect to the undamaged data. Several machine learning algorithms, with different working principles, have been proposed in the last decades to separate changes in the features caused by structural damage from those caused by varying operational and environmental conditions (Figueiredo and Cross 2013; Figueiredo et al. 2011; Reynders, Wursten, and de Roeck 2014; Santos et al. 2016; Santos, Figueiredo, and Costa 2015).

As discussed by Figueiredo and Brownjohn (2022), SHM plays a role in terms of assessment of the impact of climate change on the health of bridges and we believe it can be used within both approaches. While a physics-based approach can be used to diagnose damage (especially the severity of damage) caused by climate change scenarios, a data-based approach can function as a warning mechanism to prevent climate change effects on the structural health of our bridges.

Figure 7 shows a schematic procedure to integrate SHM into a probabilistic assessment of the impact of climate change on the structural health of existing bridges based on a physics-based approach. It uses projections of climate change data and observed long-term monitoring data to make physics-based informed projections of several parameters related to the health of bridges. To couple climate risk evaluation and health monitoring techniques, it integrates existing procedures for the assessment of climate threats into the SHM of bridges, leading to a probabilistic SHM framework.

Basically, projections of air/ambient temperature, relative humidity, solar radiation (global and diffuse), precipitation, and CO_2 concentrations from climate models are downscaled to each bridge location (microclimate) and on the construction/material level (surface phenomena). Next, long-term monitoring data like structural responses (displacements, strains, concrete temperature, etc.), surface temperature, relative humidity, and river-bed depth are used to adjust those projections and calibrate physics-based models. Both adjusted climate projections and monitoring data feed physics-based models in order to assess and to output structural parameters, namely, thermal-induced stresses, displacements at expansion joints, concrete carbonation, corrosion of reinforcing bars, and scouring. Those outputs are further compared to reference values to evaluate the structural condition and to trigger alarms. The physics-based modeling is carried out through river-bed modeling, HAM modeling, and FE modeling.

Finally, a data-based approach can be used to identify patterns or trends in the long-term monitoring data related to climate change. In this case, pattern recognition techniques, like neural networks, are fundamental to identify trends.

Flooding and bridge scour

This analysis intends to predict future scour problems due to the potential influence of climate change on river flows. For some seasonal variables, such as mean precipitation, natural variability is large and there is no certainty that long-term changes will become detectable (Kjellström et al. 2013). However, regarding extreme precipitation, values may increase considerably (Geurts, Steenbergen, and Bentum 2010) and projections point, in general, towards significant increases according to IPCC (2014). Also, a warmer atmosphere involves larger amounts of water vapor, leading to more intense single precipitation events, or to snowmelt, resulting in higher flood levels.

Several factors have influence on individual catchments response to projected regional changes in temperature and precipitation, and therefore in the flood generating mechanism. Also, the catchment responses are strongly different, whether intense precipitation of short duration is considered, or longer periods of heavy rainfall. Catchment size and topographic relief are also critical in determining the dominant processes producing peak flows. These factors contribute to large differences for flood magnitudes under a future climate, which turns the analyses into casuistic studies.

Once climatic records and climate change data are analyzed (section 0) enabling an adequate and objective assessment of future trends of precipitation patterns and characterizing the associated levels of uncertainty, widely accepted runoff models [e.g., HSPF (EPA 2011)] can be used to assess the effects in flooding patterns (Sitterson et al. 2017). As several factors have relevant influence on the local response to predict regional climatic changes, namely the precipitation intensity and duration, the catchment area, shape and topographic relief, the analyses end up having a strongly casuistic character.

It adds to the above considerations that, although normal practice involves bridge design based on 100-year lifespan, under climate change challenges, a full variability of floods should be considered up to the design 100-year flood as less extreme floods but with increasing in frequency may lead to more severe scouring conditions. Such approach can be seen as more robust and accurate, as greater sensitivity of bridges is expected when more frequently submitted to flooding (Stanford University 2017). This result appears to support the idea that analyses include a wide range of flood scenarios, as opposed to a single 100-year threshold.

Regarding flood vulnerability assessment under climate change, the recommended procedure involves the characterization of bridge vulnerability to new flooding conditions and how can these increase the risk of foundation scouring or lead to deck insufficient freeboard. Analysis for scouring prediction can be developed following the framework presented by Imam (2019) as well as by Bento (Bento et al. 2018; Bento, Viseu, Pêgo, and Couto 2021; Bento, Viseu, Pêgo, Bento, et al. 2021), based on the representative climate scenarios.

Regarding the scouring prediction (sensitive hydraulic aspect regarding bridge safety), a reference scenario should be established for the bridge assuming static climate conditions. The potential maximum scour depths can be estimated using a combination of methods and approaches based on experimental/laboratory, numerical, and prototype/field data: available empirical models (Melville and Coleman 2000); numerical modeling tools for the analysis of generalized scour (e.g., HEC-GeoRAS® and Mike Hydro River®); numerical simulation of local scour by means of available three-dimensional computational fluid dynamics (CFD) codes, e.g., OpenFoam®, Flow-3D®, etc.; experimental simulation of local scour, using a tilting flume (Figure 8); and prototype data from bathymetry to calibrate the calculated stream power and potential for scour development.

A statistical approach should be considered to deal with the uncertainty of scouring influencing factors, namely the bridge features (pier submerged geometry and foundation depth), river morphodynamics (morphology, bed material, flow regimes), and accuracy of the scour prediction models themselves. For instance, Monte Carlo-based procedures can be considered to deal with uncertainties.

As after the definition of the reference scenario, the prediction of future scour due to the potential influence of climate change data must be performed, considering not only severe extreme floods, but also the accumulated effects of less severe but more frequent flooding events, as expected to occur as a result of climate change. This quantification is a recognized challenge (DEFRA 2016; Meyer and Weigel 2011), so only the most relevant parameters shall to be identified, namely the flood discharges and durations translated into flood hydrographs. Recent studies point out that the flow magnitude is the main parameter that influences scour.

Therefore, the analysis should primarily address the consequences of river flow increase due to climate change. The flow increase for each selected bridge can be estimated based on climate change projections (section 0) and expressed in statistical terms, because alterations of the climatic conditions increase the uncertainty regarding the prediction of extreme river flows (Field et al. 2012). Flood duration is another relevant factor whose influence in scour development should be assessed.

Finally, comparison of Monte Carlo simulations of scour for the reference and climate change scenarios should allow an estimation of failure probability variation between both and support the decisions on type of adaptation measures to implement.

To summarize, by means of adequate analysis tools to assess bridge piers and abutments scour criticality (river-bed scour reaching the footing upper elevation), the probability of bridge foundation failure can be estimated for different flood scenarios. By analyzing and comparing several scouring countermeasures, bridge vulnerability can be reassessed and the estimated adaptation costs calculated. The approach will also enable the estimation of the variables required for the cost-effectiveness analysis of adaptation measures.

Accelerated degradation of materials

This analysis aims to assess the effects of climate change on the durability of bridges, in particular on carbonation and, thus, on corrosion. In fact, carbonation is one of the most important parameters that can influence the corrosion of reinforcing steel bars, leading to decreases of concrete pH and, then, to the reinforcement bars despassivation.

The goal is to estimate the increase of conditions for carbonation, the resulting corrosion damage and the magnitude of associated economic costs, taking into account regional climate change scenarios.

The progress of aggressive agents in concrete cover, like chloride ions or carbonation, must be monitored in several concrete bridges through different sensor types embedded in concrete. Usually, a set of sensors is used for this propose, composed by galvanic current sensors, corrosion potential sensors, concrete resistivity sensors, and thermometers.

Next, an overall assessment of the impact of potential climate scenarios on selected corrosion metrics (Saha and Eckelman 2014) needs to be developed and compared to a reference situation. For this purpose, it is necessary to consider the variations in environmental factors such as air temperature, relative humidity, and CO_2 concentrations that are provided by climate projections and socioeconomic scenarios.

The projections of changes in air temperature and relative humidity as well as CO_2 and chloride concentrations are used to analyze their impact on the classification of exposure environments according to the standard EN 206. Several methods can be employed, such as: stochastic approaches to study the chloride ingress and its effect on corrosion initiation; the dose-response functions to describe the magnitude of the corrosion of a steel element as a function of exposure to a stimulus or stressor after a certain exposure time; and probabilistic approaches to assess corrosion damage taking into account the influence of climate change on regions characterized by different geographical conditions (Peng and Stewart 2016).

HAM modeling. The HAM transport analysis is proposed to generate temperature and humidity gradients and furthermore reflect concrete degradation as a function of surface/air temperature and relative humidity projections, according to the climate change scenarios. The HAM transport analysis is based on FE models of bridges' sections, and provides important information about the:

- surface temperature,
- temperature in materials,
- moisture content in materials, and
- relative humidity on surface as well as in materials.

The analysis is either 1D or 2D and accounts for the coupled thermal and hygric processes that take place on the surface of the construction as well as in the materials (Karagiozis, Künzel, and Holm. n.d.). HAM modeling has been used extensively for the documentation of the hygrothermal performance of building components and buildings (Koh and Kraniotis 2021), while it has also functioned as a link between climate-induced loads and structural analysis (Choidis et al. 2021).

For the realization of the coupled hygrothermal analysis climate data are essential input. As such, historical climatic records, or typical years (representative of a local climate), and climate change data, can be employed, depending on the nature of the specific project. In addition, thermophysical and hygric material properties are required, which can be either originated from integrated databases in relevant HAM tools, e.g., WUFI Pro (Frauhofer IBP 2021). Not least, boundary conditions, which describe the heat as well as the moisture balance on the surface of the studied bridge section, should be defined.

The results of the HAM analysis can be integrated into the structural analysis and relevant FE models to obtain temperature-induced stresses, moisture-induced degradation, etc. Moreover, the results from the 1D or 2D can be linked to specific add-on applications for further evaluation of corrosion risk.

Thermally induced stresses and movements

In the European Union, the EN 1991-1-5 was defined in 2003 as a European standard to give design guidance for thermal actions arising from climatic and operational conditions on buildings, bridges, and civil engineering works (EN 1991-1-5 2003); the national annex gives temperature values and recommendations for each state member. What happens if the temperature basis has changed since then in each country? For the new bridges, we can change the standard. And what about the existing bridges? To those ones, an answer can be given by running thermo-mechanical analysis for specific regional conditions, given certain bridge constraints.

The goal of a thermo-mechanical analysis is to develop probabilistic FE models of bridges that are potentially vulnerable to temperature variations and use them to assess the consequences of the climate change in terms of stress incrementation and displacements at the expansion joints. Long-term monitoring data can be used to inform the models. Large increments of the extreme temperatures may induce considerable thermal stresses in the structural elements in tandem with traffic loads, especially in smaller bridges. On the other hand, higher displacements at the expansion joints are expected in longer bridges. Therefore, one must evaluate if higher gradient temperatures in the superstructure is prone to generate stress increments that can cause structural damage (e.g., concrete cracking), or displacements at the joints that are large enough to cause malfunction.

Reference values for the parameters of the FE models. Provided that long-term monitoring data is available for the target bridge, the data can be analyzed to find reference values for the monitored structural parameters (e.g., joint movements, rotations, or strains) and correlations between these parameters and the temperature. For instance, the reference value of the opening of an expansion joint can be adopted as stipulated in the structural blueprints if monitoring data is unavailable. However, if monitoring data is available, one should observe that creep and shrinkage effects are causing the opening of the expansion joint to be different from that in the blueprints, and the reference value should be taken accordingly. Moreover, the monitoring data can be used to extrapolate current reference values into the future. For this purpose, statistical process control tools are applied to the time histories of the different measured parameters, such as the multiple linear regression technique.

Multi-scale FE models. The reference values of the structural parameters are used to develop two types of FE models: a macro-scale FE model and micro-scale FE models. The macro-scale model comprises the whole structure (Figure 9) and is aimed at studying the global effect of temperature increments, including the dilatations at the expansion joints and temperature-induced internal forces in the structural elements of hyperstatic bridges. The input data of macro-scale FE models include, besides operational loads, global temperature increments taken from the downscaled regional climate models. The non-uniform heating of the structural elements is not modeled, as they are generally simplified to their axes or mid-planes. Conversely, micro-scale FE models (Figure 10) are designed to capture the stress increments *inside* the structural elements, caused by their non-uniform heating. Any number of critical structural elements can be modeled, either at their cross-section level or in three dimensions. The input data of micro-scale FE models are the temperature distributions coming from the HAM models, as they capture the gradients that are causing internal stress increments. The results of the macro- and micro-scale FE models can be combined to model the overlapping of all effects.

Generation of probabilistic FE models. To take into account the random and epistemic uncertainties that affect our knowledge on the future conditions of bridges, both macro- and micro-scale FE models should be defined probabilistically, rather than deterministically. To do that, for each bridge, a baseline model of the bridge must be calibrated to recover its monitored behavior, before being probabilistically extended to cover the uncertainties. The steps of the process are:

i. a FE model of the bridge is built using the reference values of the structural parameters. The model must be simple enough to run tens of thousands of analyses in a reasonable timeframe;

ii. the model is calibrated to best recover the natural frequencies and mode shapes of the real bridge. The targets are obtained by averaging the vibration characteristics obtained from monitoring at night-time, to minimize the spurious effects of operational variability and solar exposure. The calibration parameters are the uncertain properties of the structure, typically material properties, boundary conditions, and operational parameters (e.g., traffic loads);

iii. the probabilistic variability of the uncertain parameters of the bridge is calculated such that the variance of the cluster of natural frequencies, calculated using the FE models, recovers as closely as possible the variance of the natural frequencies recorded on the real structure;

iv. the baseline model obtained in step (ii) is extended by prescribing the probabilistic variability calculated in step (iii) to the uncertain parameters of the bridge. A probabilistic approach is also adopted for the quantification of the traffic loads. For bridges with predominantly light traffic, a (cumulative) Poisson distribution, fitted to the observed traffic, is used to assess the probability of a given number of vehicles to be on the bridge at a given moment. Conversely, for bridges with congested traffic, a binomial distribution can be used;

v. as many micro-scale FE models as needed are created using the same reference values and probabilistic variability for the structural parameters.

Probabilistic forecasting of temperature effects. The cluster of probabilistic FE models obtained as described above is used to generate probabilistic distributions of the thermal-induced stresses in the structural elements and displacements at the expansion joints. As a large number of FE models need to be ran, an API to a finite element software may be used to automatically perform the analyses (Bud et al. 2022). The results are generated considering the evolution of the extreme temperatures according to the climate scenarios and structured on a timeline covering the rest of the 21st century.

Cost-effectiveness of adaptation measures

Towards adaptation measures

Climate change impacts can be controlled in two general ways: mitigation and adaptation. Mitigation is related to the reduction of greenhouse gases emissions (e.g., CO_2); however, due to the inertia of the climate system, the coming decades are projected to exhibit a substantial increase in the rate of climate change regardless of the emission scenarios (Füssel 2007). On the other hand, incorporating future projections into bridge planning can help authorities prepare for a different future by applying adaptation measures and strategies, which can significantly decrease the potential impacts of climate change on bridges. Adaptation means anticipating the adverse effects of climate change and taking appropriate action to prevent or minimize the damage they can cause (European Commission 2013). Here is the problem we need to overcome: authorities pay the costs of adaptation up front, but its economic benefits may not come for years down the road.

The key to success is to integrate climate preparedness into existing planning mechanisms, not treating it like something new. The adaptation measures can be implemented in different stages related to design, construction, operation, maintenance, repair, and replacement of bridges.

Adaptation is also managing bridge vulnerabilities. Suppose a bridge being affected by a climate variable like the increasing of temperature. Figure 11 shows the relationship between the management of the critical temperature threshold, and the time taken to plan and implement adaptation measures during operation of a bridge. In this case, the adaptation strategies aim to reduce vulnerability by increasing the critical threshold (Willows and Connell 2003).

There are already few examples of bridges as well as roads and railways, where the expected climate change has been taken into account in the design and construction stages. For example, the Confederation Bridge in Canada was built to allow for a rise of one meter in sea levels.

There are also examples of adaptation measures taken in existing bridges. For instance, in the United Kingdom (UK), parts of the 135-year-old Hammersmith Bridge in London have been wrapped with foil to reflect sunlight and keep the bridge at a moderate temperature so its materials do not expand and crack. In order to reduce the risk of hot weather causing expansion-related damage, also in the UK some rails have been painted in white (Network Rail n.d.). In Sweden, a new road and a railway in the Gota River Valley were raised to reduce the flooding risk caused by future sea levels. The level of the railway was chosen slightly higher considering the greater consequences of flooding, e.g., the impact on electrical systems. The ultimate increase in elevation was up to 1.5 m over current levels where the flood risk was the greatest. The project was the first large infrastructure project in Sweden that was adapted to a rising sea level (Swedish Portal for Climate Change Adaptation n.d.). The Swedish Transport Administration has already developed a climate adaptation strategy, which provides a list of general activities for adaptation to a changing climate.

Generally, how can we adapt existing bridges and increase their resilience against such impacts? Nasr et al. (2020) summarized and laid down some general adaptation measures as a function of potential impacts, like: design for higher maximum temperatures in replacement or new construction; greater use of expansion joints (Meyer and Weigel 2011); paint the bridge white to introduce an albedo effect and reduce overheating; cathodic protection; increase in concrete cover thickness, improve quality of concrete (strength grade), protective surface coatings, and barriers; use of stainless steel, galvanized reinforcement, corrosion inhibitors, and electrochemical chloride extraction; increase ongoing maintenance and preservative treatment; use of new materials; develop nature-based solutions for climate change; and reinforce or protect existing foundations (jacketing and scouring protections like riprap).

With so many general measures and strategies, how can we make decisions for thousands of concrete bridges across Europe? This is what this paper is about: future decisions for adaptation of bridges must be supported by bridge engineering science, using the integrated assessment approach shown in Figure 4 to determine which adaptation measures to implement and at what point in time climate adaptation becomes economically viable as a function of structural deterioration and the expected climate influence.

Therefore, the goal is to develop a probabilistic decision-based framework for bridges. The innovation - and significant challenge - is the inclusion of climate change effects. Therefore, ad hoc models that consider uncertainty and can predict the bridge deterioration profile need to be developed. Furthermore, with the knowledge of maintenance, repair, and adaptative measures, a better planning of these actions can be developed, and their cost estimated with more accuracy.

An important outcome for authorities (or stakeholders) is the support for the bridge assessment decision. For instance, if climate adaptation measures are needed, if they are economically viable or if need to be deferred. The work done by Frangopol et al. (2017), Khelifa et al. (2013), and Khandel et al. (2018) in bridge life-cycle is herein reviewed to form a draft of the idea. Thus, two tasks, which are of utmost importance are detailed as follows.

Risk assessment

Is it worth adapting (i.e., strengthening) a structure, like a bridge, with a low probability of hazard/exposure but large consequences? Although unlikely, an extreme event is prone to occur and may bring devastating consequences. As questioned in (Lund University 2018), can we let some bridges be destroyed during such an extreme event? How can we ensure safety for the users in such cases? What are the indirect costs of closing a road or rail as a precaution?

The goal is to select and optimize a set of adaptation measures taken from those proposed in section 0, and compute the corresponding associated risks. Therefore, we need to combine this framework with decision methods, in order to define which are the “best” decisions based on engineering evidence.

The risk is a measure of expected loss, which quantifies the effect of uncertainty on factors that influence the loss. The classical definition of risk is given by (Nasr et al. 2020):

$$Risk\ (R) = Hazard \times\ Vulnerability \times\ Consequences \tag{1}$$

which weighs several probability terms, such as *Hazard* – related to the probability of the climate hazard (e.g., heat and precipitation) in the context of different climate scenarios; *Vulnerability* – related to the probability of damage, i.e., how critical is the bridge to damage given the potential hazard; *Consequences* – what can happen or what is the loss if the hazard is successful in causing the damage (e.g., direct cost, social costs, lives lost due to the bridge collapse). The goal is to find adaptation measures to reduce the exposure and vulnerability of bridges and, ultimately, to reduce the current risk (ΔR) of certain consequences.

For instance, for the sake of simplicity, let us consider the risk associated with an economic loss related to a bridge collapse due to corrosion. A framework needs to be planned to compute the current risk through the following expression (Bastidas-Arteaga and Stewart 2019):

$$E(L) = \Pr(C) \cdot \Pr(H|C) \cdot \Pr(D|H) \cdot \Pr(L|D) \cdot L \tag{2}$$

where Pr(C) is the annual probability that a specific climate scenario will occur, Pr(H|C) is the annual probability of a climate hazard (temperature, humidity) conditional on the climate scenario, Pr(D|H) is the probability of corrosion for the baseline (without adaptation) for a known level of temperature and humidity, Pr(L|D) is the conditional probability of economic loss given occurrence of the damage, and L is the loss or consequence if full damage occurs. The expected loss after adaptation is given by:

$$E_{adapt} = \sum (1 - \Delta R)E(L) - \Delta B \tag{3}$$

where ΔR is the reduction in risk caused by climate adaptation measure, *E(L)* is the normal risk and ΔB is the cobenefit of adaptation. Therefore, the decision problem is given by the maximization of the benefit-to-cost ratio (*BCR*):

$$BCR = \frac{\sum E(L)\Delta R + \Delta B}{C_{adapt}} \tag{4}$$

where C_{adapt} is the cost of the adaptation measures including opportunity costs that reduce the risk by ΔR. The decision variable BCR is one, among others such as net present value, that can be studied. This is a multi-objective problem, in which the biggest challenge is the estimation of the probabilities. The probabilities of the hazards may be obtained with support of climate change data in section 0. The vulnerability of the bridge is obtained from the models and experimental data.

Development of life-cycle models under deterioration

Herein, the first step is to develop and calibrate models to estimate structural deterioration of a wide range of structures and environmental conditions. A stochastic approach must be used, and it should consider the uncertainty of the parameters that influence the deterioration of bridges, i.e., both aleatoric (existing variability of properties) and epistemic (lack of knowledge) uncertainties. Due to their flexibility and ability to incorporate a range of maintenance and repair actions, stochastic Petri Nets (PN) (Yianni et al. 2017) are promising to model the life-cycle performance of bridges and their components. Stochastic PN allow a graphical representation of a probabilistic model and are based on a limited set of elements and events. They allow us an intuitive modelling of a complex system. Stochastic PN have been shown to be able to model accurately the lifetime of structures, including inspection, deterioration, maintenance, and repair, allowing for the inclusion of environmental conditions (Rungskunroch, Jack, and Kaewunruen 2021; Yianni et al. 2016).

Although PN have been used to evaluate the performance of deteriorating bridges, a gap still exists on the use of these convenient (practical) data-based models for the analysis of structures under the effects of climate change. As such, the major challenge will be the calibration of the proposed PN models. An initial baseline model should be calibrated based on existing bridge condition records, using the maximum likelihood approach, as the one discussed in (Calvert et al. 2020). These models will then be corrected to account for climate change hazards, in particular erosion in submerged foundations (scouring), the increased risk of carbonation and chloride contamination in concrete structures, and stresses in the structural system due to temperature changes and the interactions between these (Calvert et al. 2020).

Results from the physics-based modeling together with experts' judgement, can be used to produce a set of life-cycle models under different climate change scenarios and local environmental conditions; e.g., estuaries of large rivers where chloride contamination is critical, urban locations where pollution is the fundamental driver of corrosion, and rural interior areas where carbonation is the fundamental corrosion mechanism. These deterioration models can be combined with models defining the impact, both in the short- and long-term, of adaptation measures including design changes (e.g., increased cover depth), preventive measures (e.g., crack sealing, protection of piers) and reactive maintenance (e.g., replacement of corroded reinforcement). These measures might increase the performance of a structure (e.g., reactive maintenance), decrease the deterioration rate (e.g., preventive maintenance and changes in design) or reduce the uncertainty in deterioration and performance (e.g., SHM). Combined, they will form a manifold of adaptation strategies, in which a decision variable such as the BCR value will be compared and presented by the proposed life-cycle analysis tool.

Climate-related maps

After the climate change risk was analyzed on a significant number of bridges, climate-related maps for a friendly visualization of the impacts and vulnerability on bridges in a certain geographical region can be produced to support political decisions for adaptation action. Vulnerability is the degree to which a system is susceptible to adverse effects of climate change. Note that vulnerability to extreme events (e.g., flood) can be reduced by adequate adaptation measures.

Such maps can be presented to authorities responsible for managing both catastrophic climate impacts (civil protection agencies) and the more pervasive long-term effects on bridges (bridge authorities). They should be extended well beyond the idea already developed for European cultural heritage in the Noah's Ark Project (Sabbioni, Brimblecombe, and Cassar 2012). These maps fill the gap existing in studies on the effects of future climate variations on infrastructure, and link climate science to the effective potential impact to our bridges. The maps should show overall patterns of threats by representing, for example, modeled 30-year averages of climate variables or climate-related impacts.

Three types of maps are suggested, based on global and regional models; the most suitable models will be selected based on the recent past data measured from meteorological data (bridge monitoring systems or local weather stations):

- climate maps – climate change is mapped in terms of projected changes relevant to bridges (e.g., air temperature, precipitation, CO_2 concentration, and relative humidity). They represent the basis of other type of maps. For instance, Figure 12 shows the modelled 30-year averages of annual precipitation for recent past, near future, and far future using a global model;
- damage maps – define vulnerability areas where bridges may develop certain type of damage (scouring, concrete carbonation, corrosion, etc.) induced by climate change. For instance, dose-response functions may be used to describe the magnitude of the corrosion of a steel reinforcement as a function of exposure to a stimulus or stressor (e.g., chloride deposition) after a certain exposure time;

- natural-event maps – show areas where bridges may be vulnerable to collapses caused by landslides or relocation caused by sea level rise. For instance, studies of landslide trends show that the trigger factors are the rainfall amount on the day of landslide and the total rainfall in the previous two weeks (Sabbioni, Brimblecombe, and Cassar 2012).

Conclusions and recommendations

The bridge authorities need to plan and execute timely intervention in order to cope with increased exposure of bridges to natural hazards due to climate change. The right adaptation strategy taken timely saves bridge maintenance costs later, and is a good efficiency. Many studies have conceived general adaptation strategies for civil engineering structures, without a focus on the specificity of individual bridges. This paper proposes an integrated assessment approach grounded in a probabilistic- and physics-based framework to provide adaptation measures for bridges, where the safety of people and the decision to take action are defined through the SHM process and an LCA.

From a bridge engineering point of view, the outcome of this integrated assessment approach can be summarized as follows:

- define climate-related pattern effects on long-term (more than the reference period of three decades) past monitoring data from a set of bridges;
- undertake vulnerability analysis to ensure that existing bridges are adapted, and new bridges are built with enhanced resilience: flooding, which can accelerate scouring at bridge piers; CO_2 concentration, which can accelerate degradation of materials; the influence of thermal changes in tandem with traffic loads; and the rise of sea levels;
- build climate-related maps to link climate science to the effective potential impact to our bridges, taking into account vulnerability analysis on bridges per region;
- set the cost of action and inaction regarding the impacts of climate change in terms of: monetary cost alone; human losses caused by disasters; and bridge relocation;
- provide bridge-specific adaptation measures backed by risk assessment and LCA of existing bridges, in order to take into account the uncertainties derived from both climate and structural modeling;

- provide information to bridge authorities about what point in time climate adaptation becomes economically viable;
- provide findings to update the design codes to account for the effects of climate change on new bridges; this can be done via a dynamic scaling factor included in the national annexes of the Eurocodes;
- provide findings for improving maintenance and inspection manuals to accommodate the effects of climate change; and
- provide a warning system capable of triggering a signal when the safety of a bridge is reaching a critical capacity accelerated by climate change.

The key to success of bridges in a changing climate is to integrate climate preparedness into existing planning mechanisms, not treating it like something new. The adaptation measures can be implemented in different stages related to design, construction, operation, maintenance, repair, and replacement of bridges. As highlight by Lindgren et al. (2009), adaptation measures can be part of regular bridge maintenance routines. It might include periodic visual inspection focusing the expected damage scenarios and improved maintenance operations. This is an issue that also needs further investigation.

It is important to mention that future studies should be grounded on inventory bridge database and monitoring data sets (displacements, strains, temperatures, and relative humidity) from several concrete bridges monitored for roughly three decades. This period is considered as the monitoring time needed to acknowledge that the mean value obtained from a data set represents the predominant value of the location, and a reference against which observations or climate projections are compared (WMO 2007).

The authors also recommend that all data sets should be made available and released for public domain through publications, in order to speed up this research field and to transform climate science uncertainty into cost-effective adaptation measures.

Finally, this approach has been posed for concrete bridges, but the general concept can be easily extended to other type of bridges, by employing their specific constraints and features. Furthermore, the impacts analyzed here are limited to structural damage, but an extension of this approach can also be made to pavement and railway damage.

Data Availability Statement

No data, models, or code were generated or used during the study.

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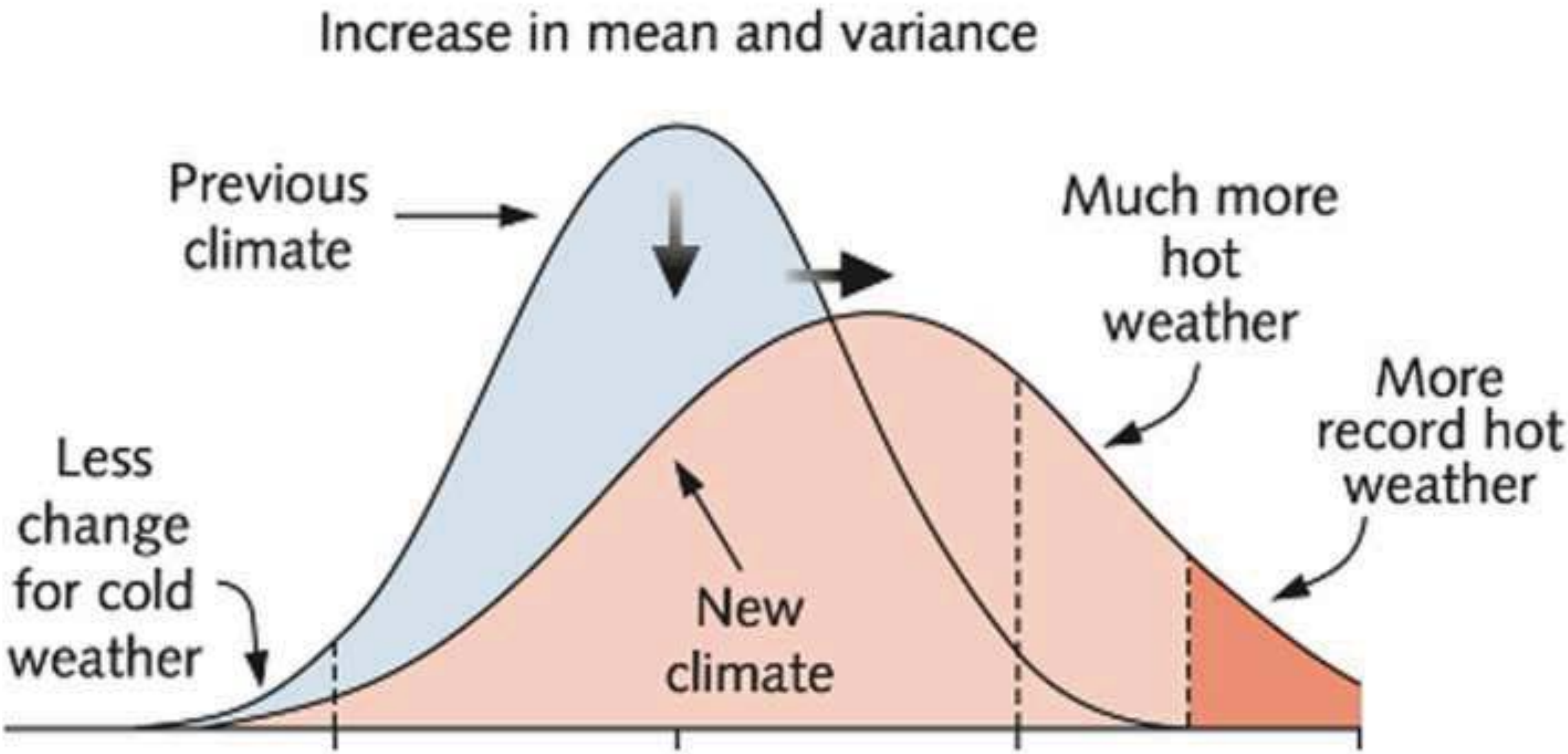
List of Figures


Increase in mean and variance
Previous climate
Much more hot weather
More record hot weather
Less change for cold weather
New climate

Identify suitable adaptation measures
Weighing consequences
Identify critical impacts, vulnerabilities, and risks
Understand the problem

Figure 3

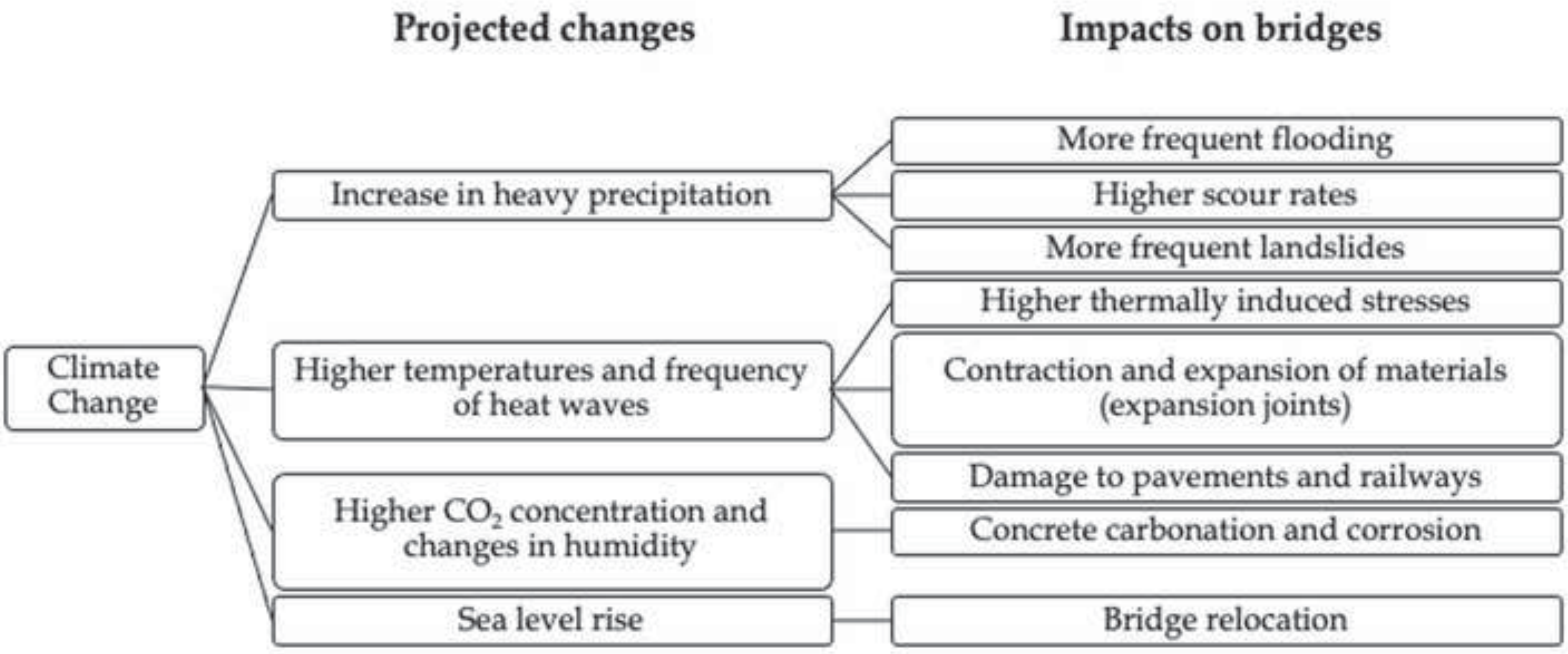

Projected changes
Impacts on bridges
Climate Change
Increase in heavy precipitation
Higher temperatures and frequency of heat waves
Higher CO_2 concentration and changes in humidity
Sea level rise
More frequent flooding
Higher scour rates
More frequent landslides
Higher thermally induced stresses
Contraction and expansion of materials (expansion joints)
Damage to pavements and railways
Concrete carbonation and corrosion
Bridge relocation

Figure 4

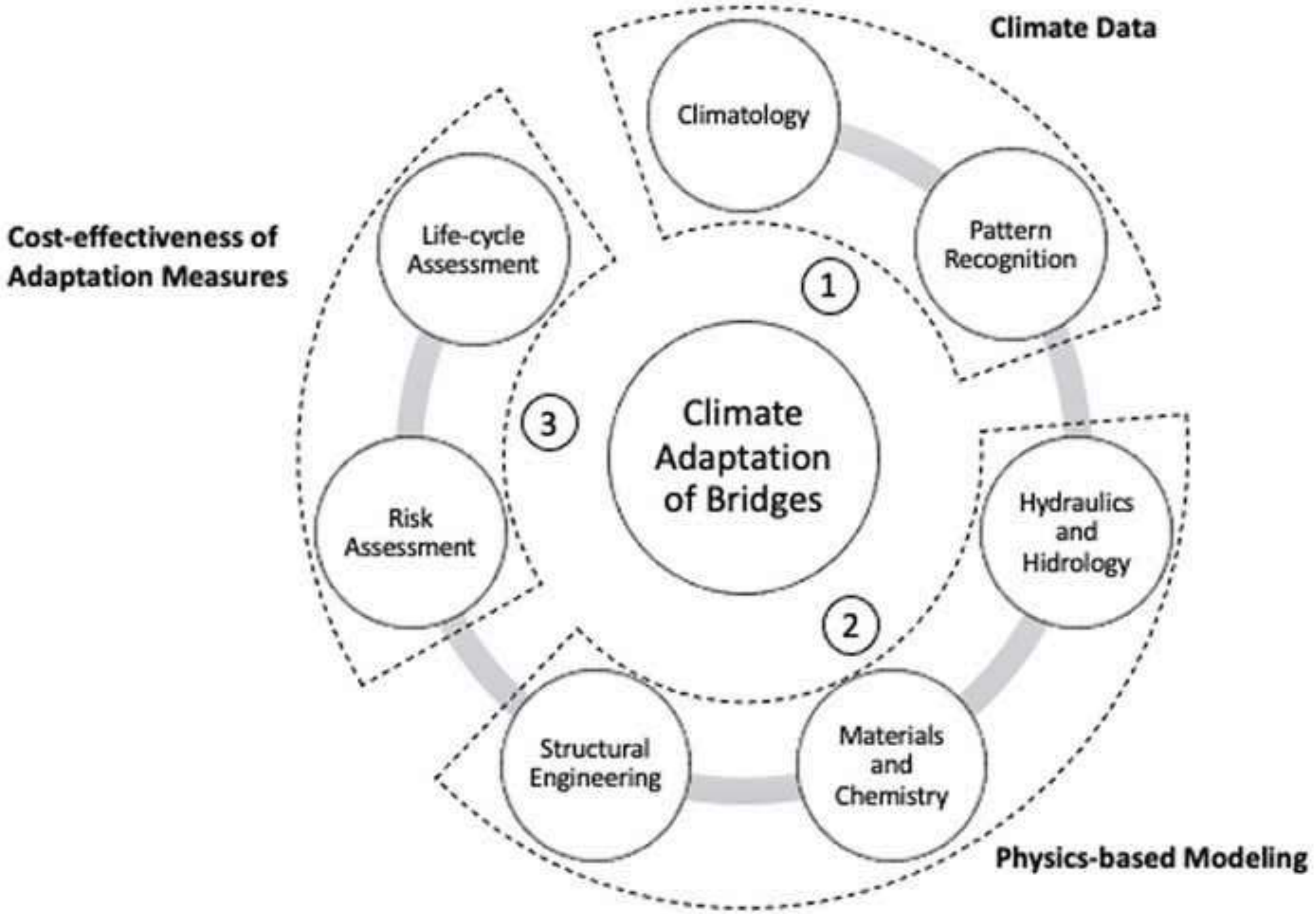

Climate Data
Climatology
Pattern Recognition
Cost-effectiveness of Adaptation Measures
Life-cycle Assessment
1
3
Climate Adaptation of Bridges
Risk Assessment
Hydraulics and Hidrology
2
Structural Engineering
Materials and Chemistry
Physics-based Modeling

Figure 5

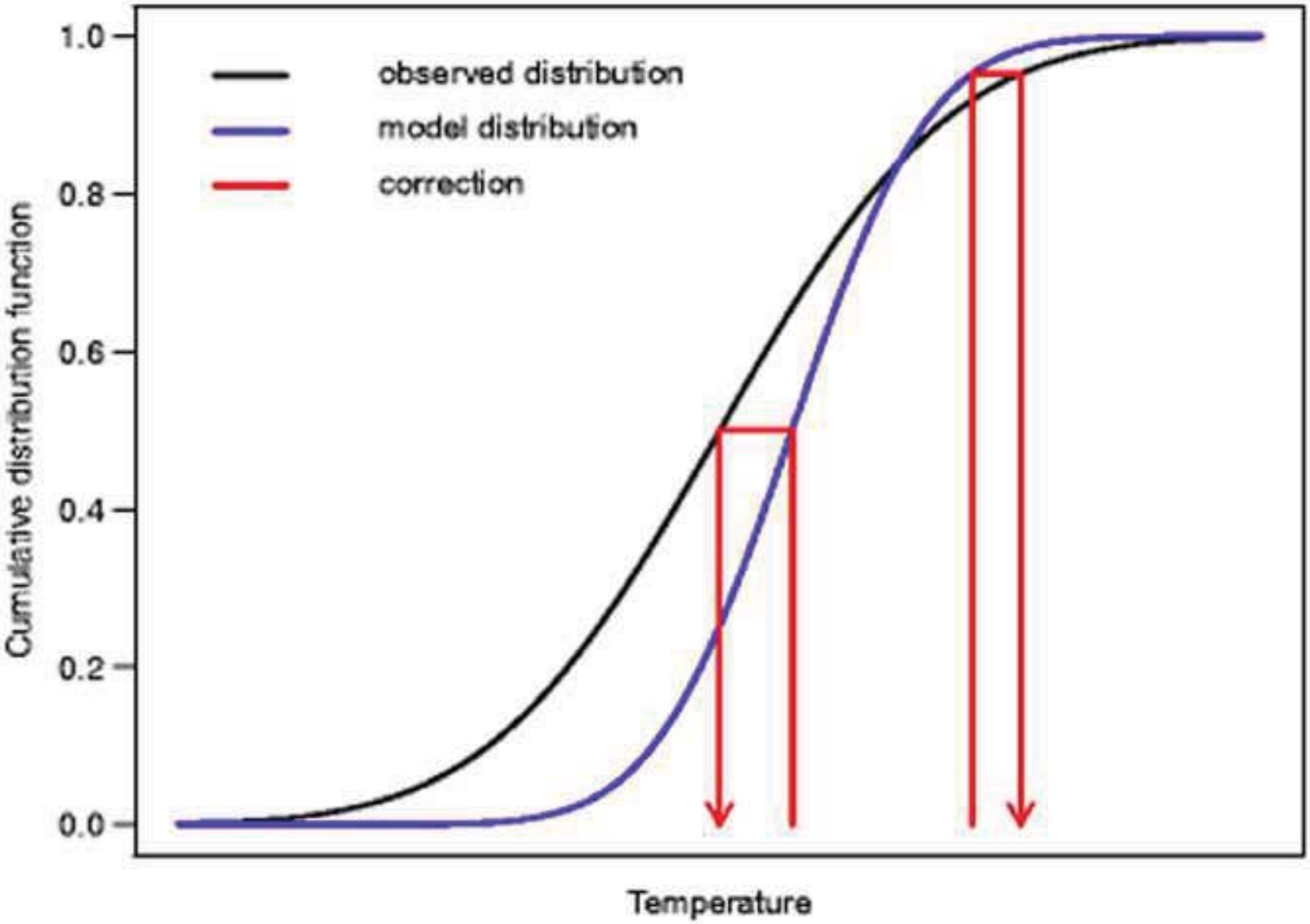

observed distribution
model distribution
correction
Cumulative distribution function
1.0
0.8
0.6
0.4
0.2
0.0
Temperature

Figure 6

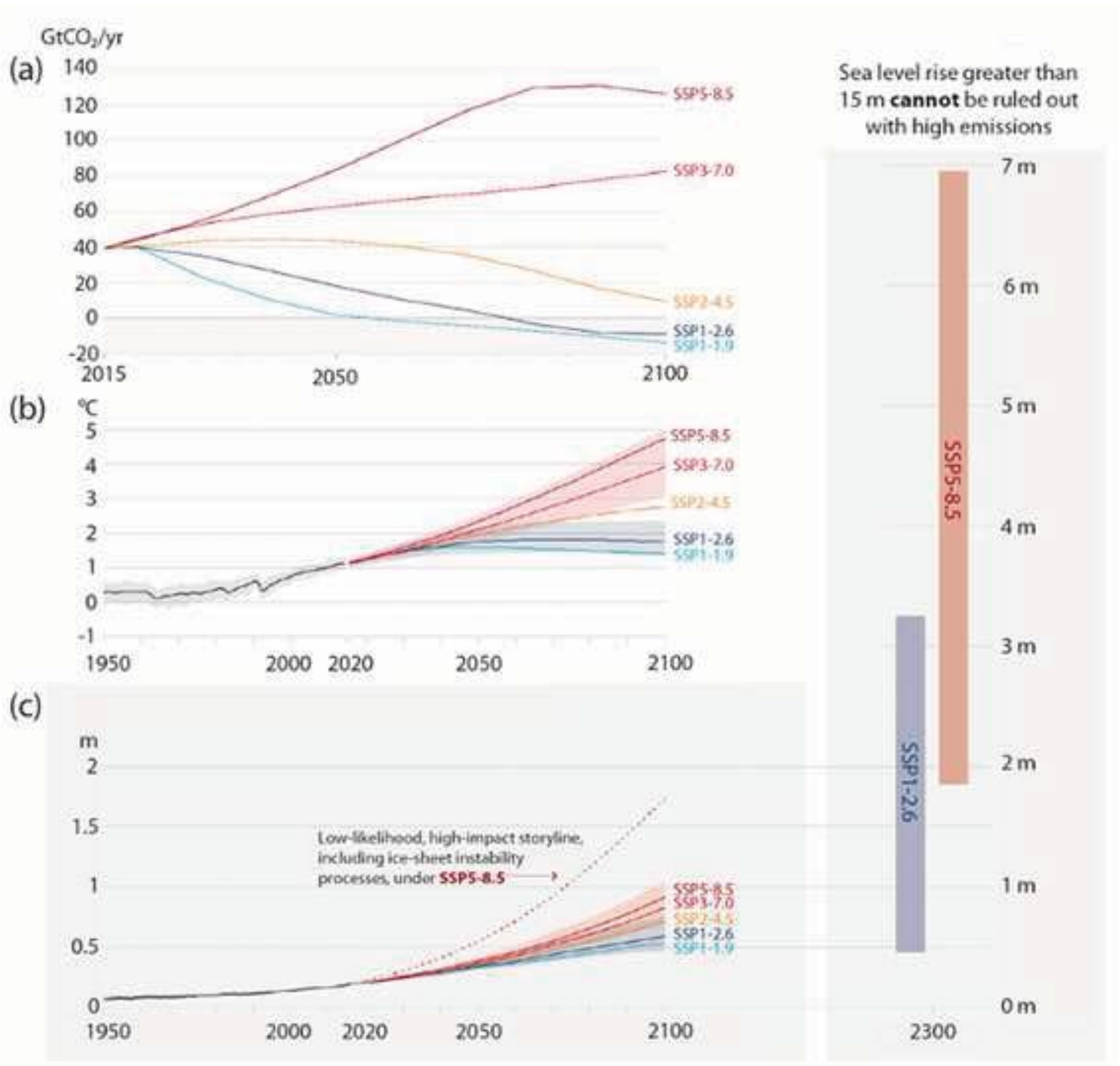

(a)
GtCO$_2$/yr
140
120
100
80
60
40
20
0
-20
2015
2050
2100
SSP5-8.5
SSP3-7.0
SSP2-4.5
SSP1-2.6
SSP1-1.9
(b)
°C
5
4
3
2
1
0
-1
1950
2000
2020
2050
2100
SSP5-8.5
SSP3-7.0
SSP2-4.5
SSP1-2.6
SSP1-1.9
(c)
m
2
1.5
1
0.5
0
1950
2000
2020
2050
2100
Low-likelihood, high-impact storyline, including ice-sheet instability processes, under **SSP5-8.5**
SSP5-8.5
SSP3-7.0
SSP2-4.5
SSP1-2.6
SSP1-1.9
Sea level rise greater than 15 m **cannot** be ruled out with high emissions
7 m
6 m
5 m
4 m
3 m
2 m
1 m
0 m
SSP5-8.5
SSP1-2.6
2300

Figure 7

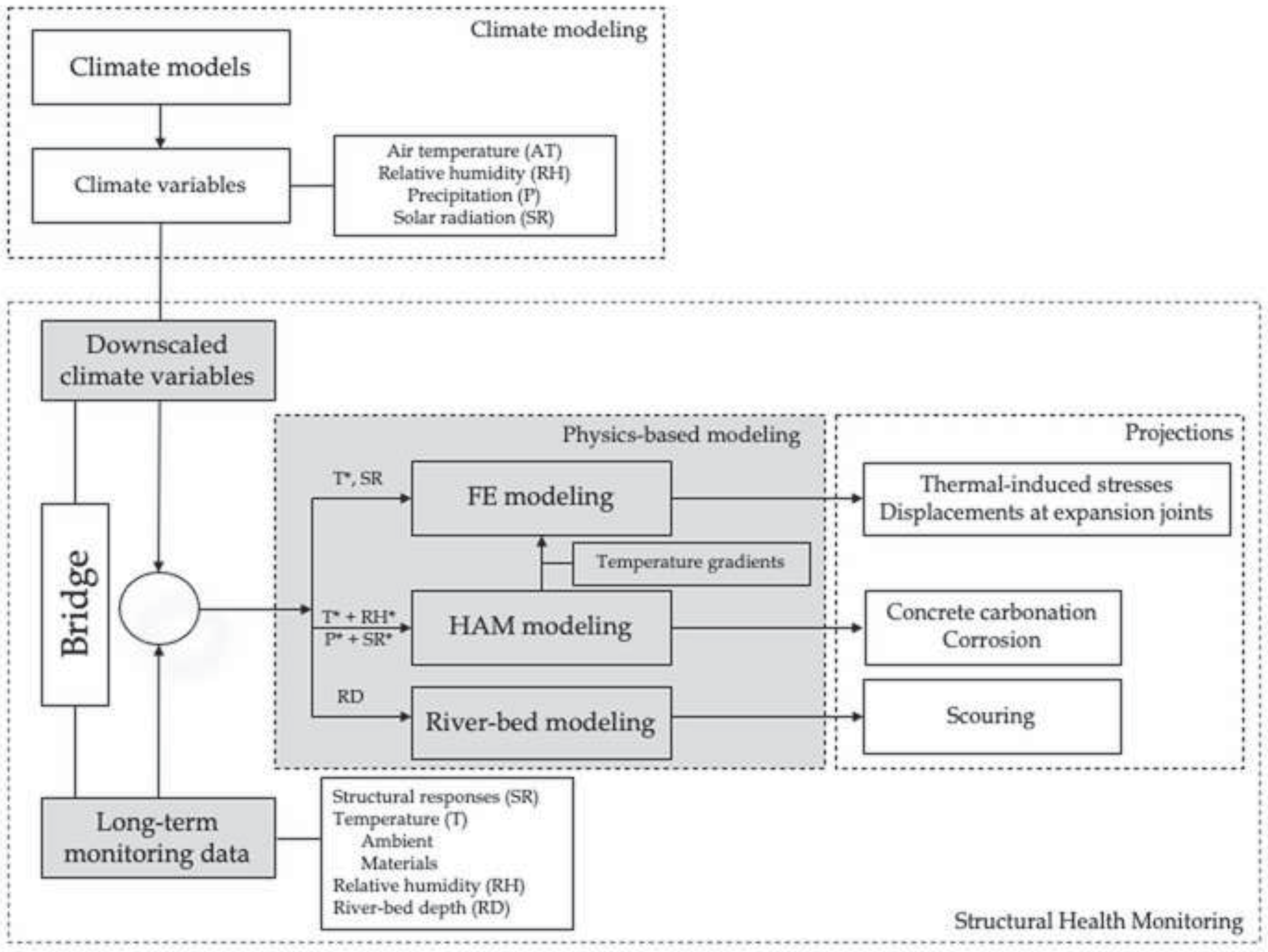
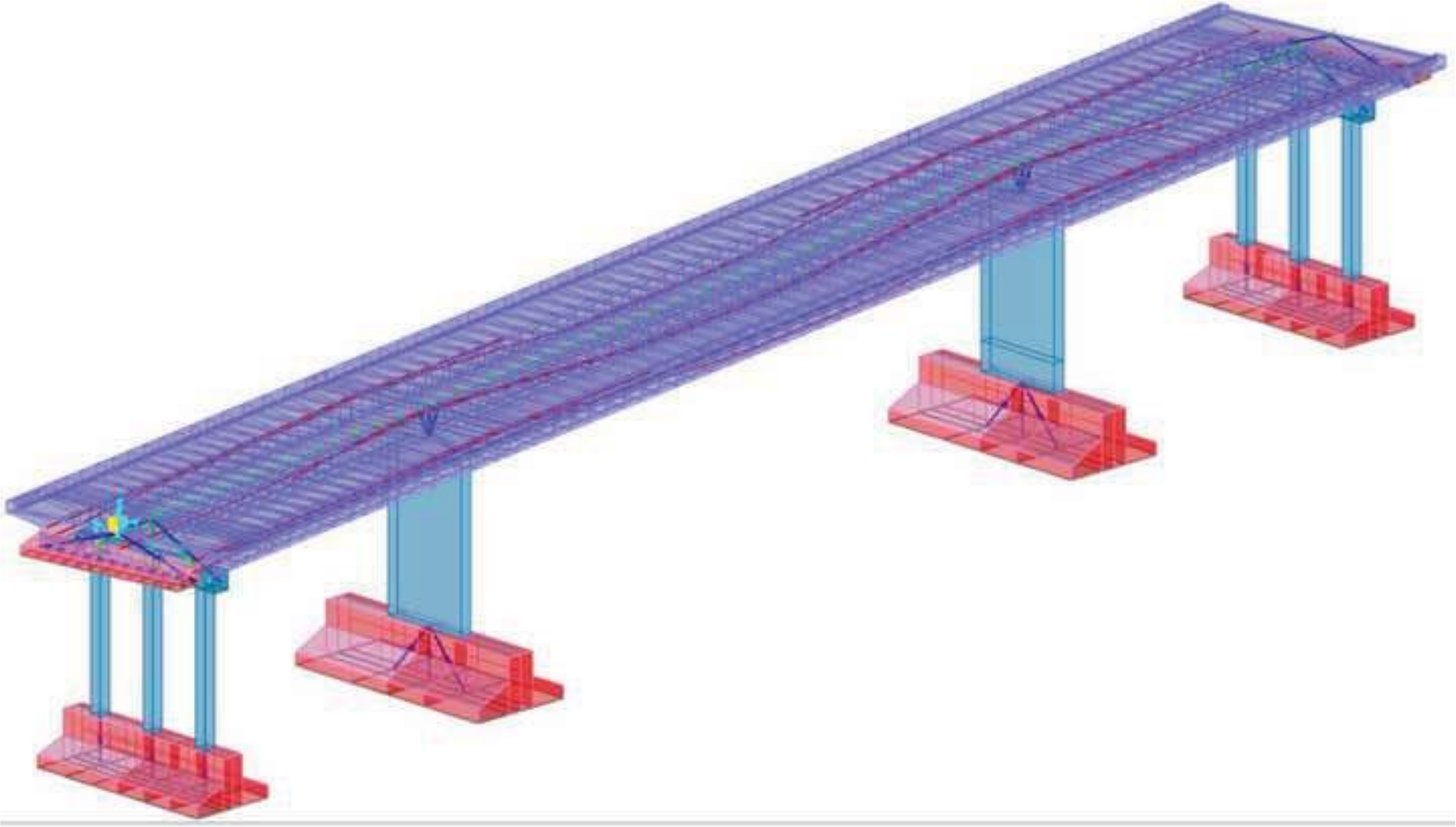

Climate modeling
Climate models
Climate variables
Air temperature (AT)
Relative humidity (RH)
Precipitation (P)
Solar radiation (SR)
Downscaled climate variables
Bridge
Long-term monitoring data
Structural responses (SR)
Temperature (T)
Ambient
Materials
Relative humidity (RH)
River-bed depth (RD)
Physics-based modeling
T*, SR
T* + RH*
P* + SR*
RD
FE modeling
Temperature gradients
HAM modeling
River-bed modeling
Projections
Thermal-induced stresses
Displacements at expansion joints
Concrete carbonation
Corrosion
Scouring
Structural Health Monitoring

Figure 8

Figure 9



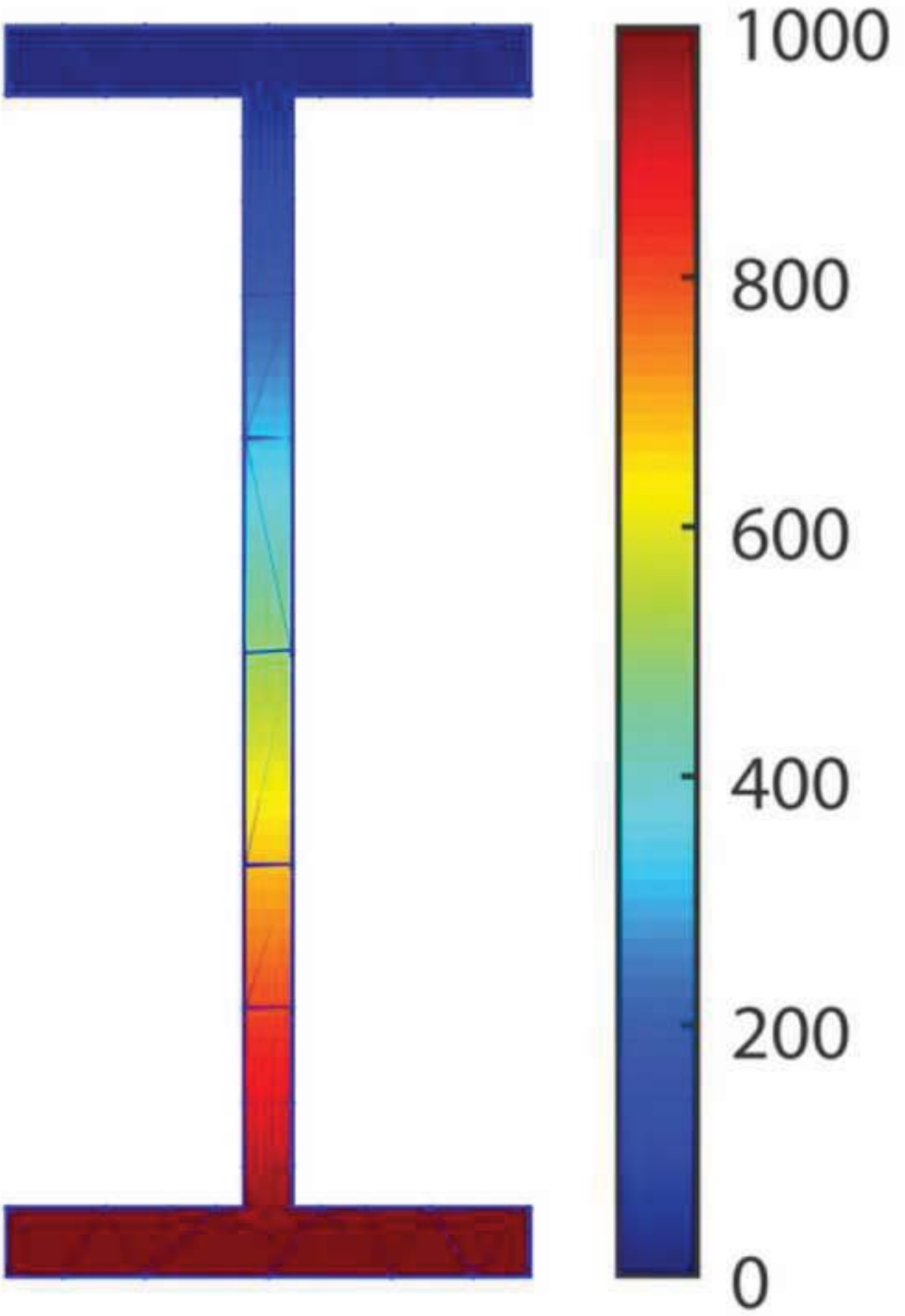

1000
800
600
400
200
0

Figure 11

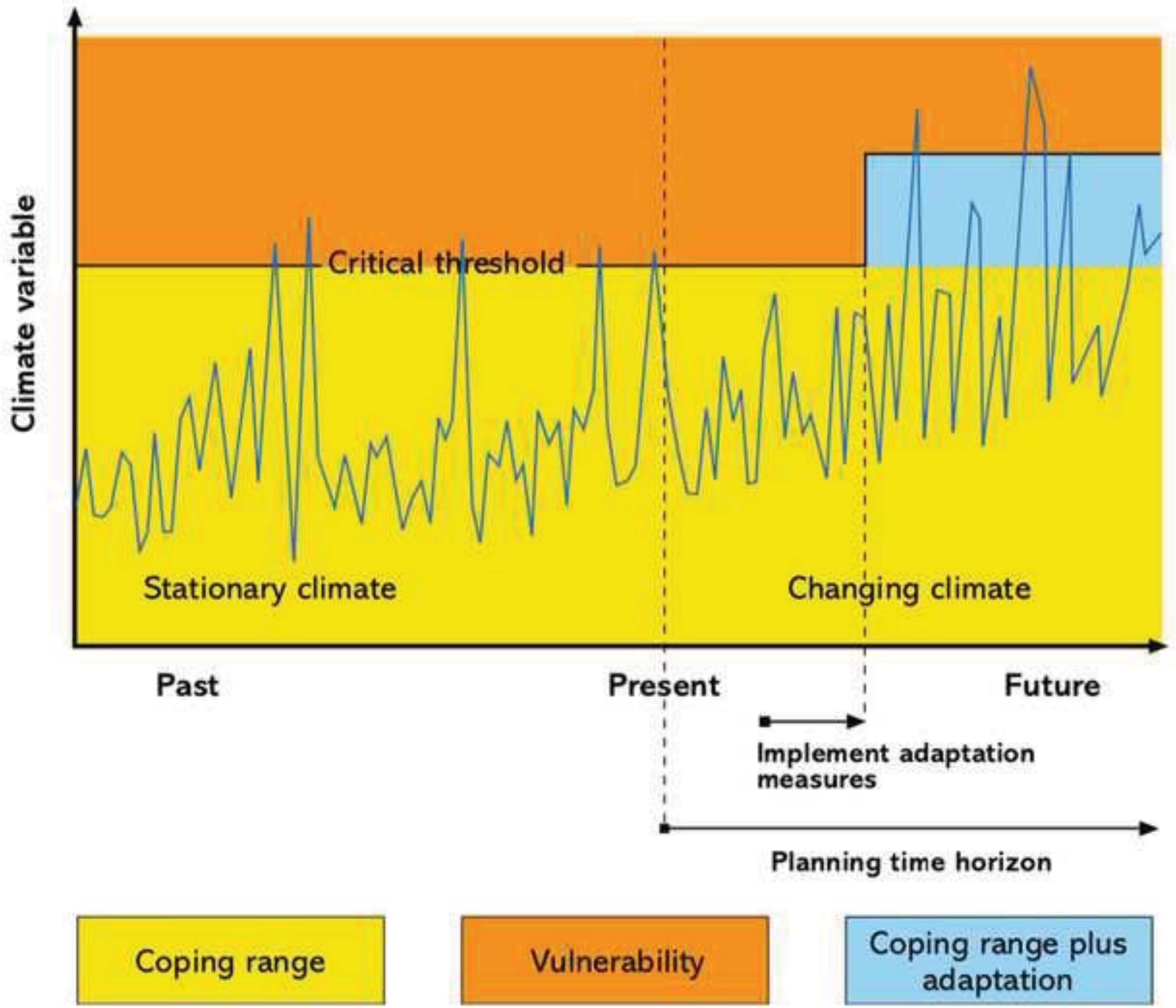
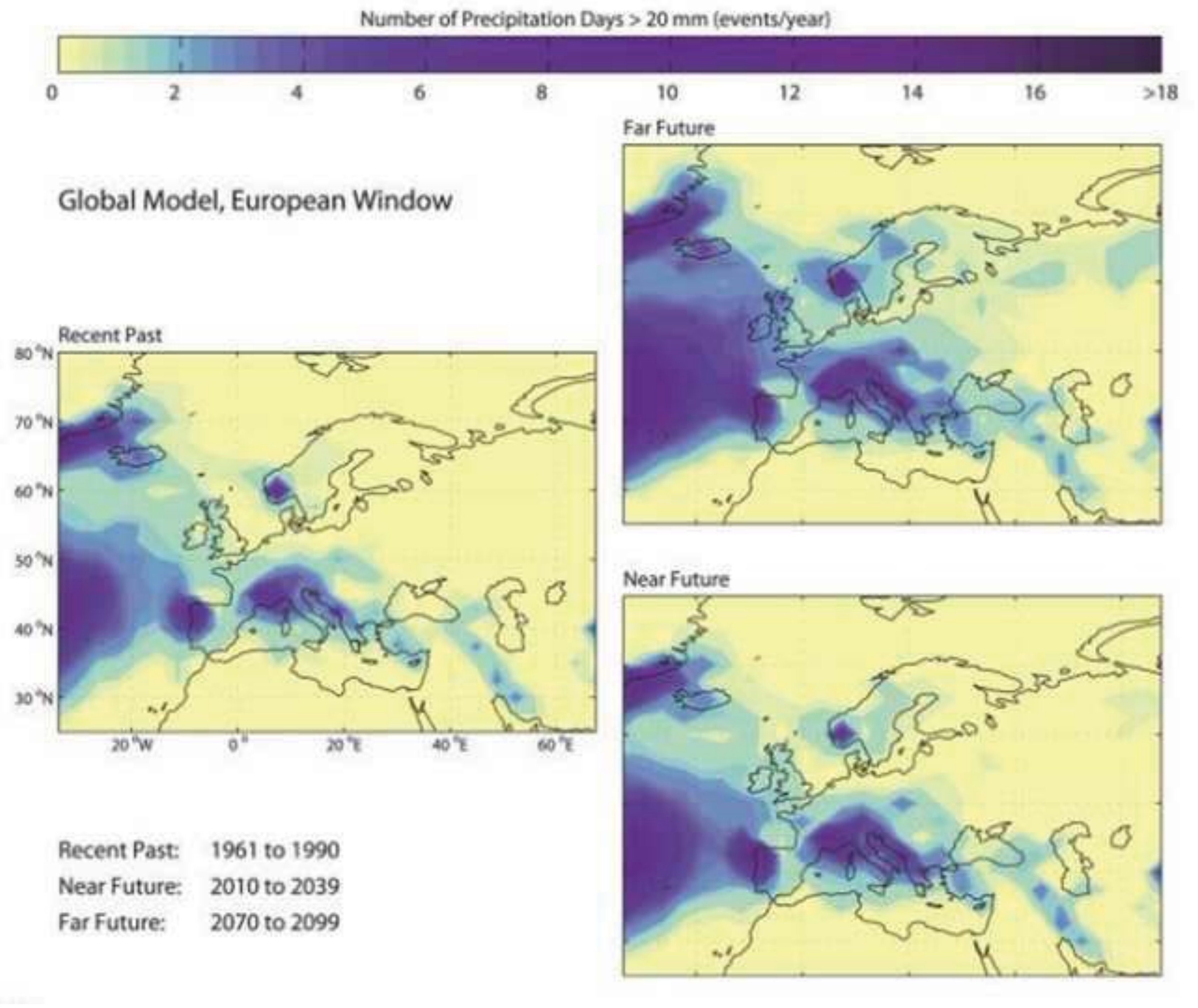

Climate variable
Critical threshold
Stationary climate
Changing climate
Past
Present
Future
Implement adaptation measures
Planning time horizon
Coping range
Vulnerability
Coping range plus adaptation

Figure 12


Number of Precipitation Days > 20 mm (events/year)
0
2
4
6
8
10
12
14
16
>18
Global Model, European Window
Far Future
Recent Past
80 °N
70 °N
60 °N
50 °N
40 °N
30 °N
20 °W
0 °
20 °E
40 °E
60 °E
Near Future
Recent Past: 1961 to 1990
Near Future: 2010 to 2039
Far Future: 2070 to 2099