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► **To cite this version:**

Lorenzo Casti, Franziska Schmidt, Fabio Biondini, Nisrine Makhoul, Romain Pittet. Climate Change Effects on Characteristic Values of Temperature Loadings. 4th fib International Conference on Concrete Sustainability (ICCS2024), Sep 2024, Guimarães, Portugal. pp.112-119, <10.1007/978-3-031-80672-8_14>. <hal-04904154>

HAL Id: hal-04904154

<https://hal.science/hal-04904154v1>

Submitted on 7 Oct 2025

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Climate Change Effects on Characteristic Values of Temperature Loadings

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Abstract. The assessment of existing reinforced concrete structures is currently a critical task to be dealt with by engineers and practitioners. Specifically, bridges and viaducts, that are composing important links in the infrastructure system, are subjected to changes in both the structural capacity and the demand over time, e.g., due to aging and structural deterioration processes as well as the evolution over time of intensity and frequency of climatic actions. In fact, climate change may have a significant impact on this evolution of both resistance and solicitations. In this context, assessing existing structures should be sustained by properly characterizing the actual loadings. In this paper, the impact of climate change on the evolution of climatic loadings is studied. The minimum and maximum temperatures are evaluated for the case of a cable-stayed viaduct located in France. The obtained results are eventually compared with the uniform temperature considered during the original design phase, and the ones proposed by the current Eurocodes regulations, with a discussion on the benefits and the limitations of the analysis, with emphasis on future developments.

Keywords: Structural Reliability, Existing Structures, Semi-Probabilistic Approach, Climatic Actions, Climate Change.

1 Introduction

The change in climate due to anthropogenic activities is an unequivocal reality accepted by (most of) the scientific community, leading, since the 1950s, to several unprecedented changes [1]. Climate change is expected to affect various environmental variables, in terms of mean and standard deviation, and to influence frequency and intensity of extreme events, having consequently an impact on both structural loading [2], e.g., snow load or wind speed, and structural capacity [3], e.g., enhancing deterioration mechanisms such as chloride and carbonate-induced corrosion. In this context, it is important to properly assess the performance of existing structures considering the long-term evolution of environmental parameters [4].

Structural loadings are often governing factors in the design and assessment of civil systems, and the proper definition of climatic actions may be crucial. Currently, the climatic loadings are defined by national and international standards, as the Eurocodes and the National annexes, e.g., for temperature loadings, [5, 6], which have been developed according to the assumption of a stationary climate and based on historical observations. Nevertheless, under climate change and due to the long service life of civil structures, e.g., 50 years (buildings) or 100 years (bridges, dams, stadiums, etc), these assumptions may lead to a misconception of the design loadings [7]. Integrating the impact of the changing climate into the definition of climatic actions is consequently a fundamental issue for performing appropriate design of new structures as well as evaluating the performance of existing ones and a main aspect in the definition of new standards, as aimed by the second generation of the Eurocodes [8].

This paper briefly discusses climate scenarios and models, focusing on the impact of climate change on structural demand, i.e., climatic actions. The minimum and maximum temperature which is the parameter used for structural assessment is defined for the case of an existing cable-stayed RC viaduct located in France considering non-stationarity in the evolution of the loading. Finally, the obtained values are compared with the original design [9] and the Eurocodes [5, 6] prescriptions for new structures in terms of uniform loading.

2 Climate change future scenarios

Future climate trends may be predicted through the definition of emission scenarios in relation to the evolution of specific drivers, e.g. population, economy, technology, energy, land use, and agriculture, and described by different reference scenarios, such as the four Representative Concentration Pathways (RCPs) [10]. RCPs have been recently integrated with the Shared Socioeconomic Pathways (SSPs) in order to consider a range of uncertainties in mitigation and adaptation challenges under climate change [11]. In this paper, SSP1-2.6, SSP2-4.5, and SSP58.5 are considered. SSP1-2.6 is related to sustainable development, assuming challenges to mitigation and adaptation are still low, whereas SSP5-8.5 is related to fossil-fuel development, supposing high and low challenges for respectively mitigation and adaptation. SSP2-4.5 is the middle-way scenario, consistent with medium challenges for mitigation and adaptation.

The future projection of meteorological variables, such as temperature and wind speed, are usually retrieved by exploiting climate models, which may be described as dynamical models simulating the physical and chemical interaction between the atmosphere, the land, and the oceans, with different levels of complexity [12] according to the selected scenarios [5].

Global climate projections may be retrieved by exploiting the last Coupled Model Intercomparison Project (CMIP6) [13] according to the SSPs scenarios. The spatial resolution of climate models usually ranges from tens to hundreds of kilometers while civil engineering problems often require evaluation at the local scale. For this pur-

pose, downscaling techniques may be used in order to retrieve environmental projections for specific locations. The advantages and disadvantages of the most common techniques, i.e., statistical and dynamic downscaling, are discussed in [14]. Downscaled regional climate projections, consistent with the CMPI6, at the European level are available through the EURO-CORDEX initiative [15] and the Climate Change Knowledge Portal by the World Bank Group [16].

Generally, the output of climate models is significantly demanding in terms of time and computational effort. For this reason, climate models are usually performed one time, and the resulting climate projections are often combined in order to obtain more reliable results, exploiting multi-model ensemble approaches such as the Ensemble Mean [17].

3 Climate change impact on structural demand

The design and the assessment of structural systems require the analysis of several loadings over the time life of the structure which is usually significantly extended, i.e., 50-100 years. Considering bridges, the evolution of actions in time, e.g., traffic and climatic loading, is a fundamental aspect to be accounted for properly characterizing the structural performance. In this context, climate change is reported to have a significant impact in enhancing different risks related to structural actions [3, 2].

Particularly, climatic actions may be severely impacted by climate change. In the Eurocodes context, the climate loadings are described in general documents, as the EN1991-1-5 [5] for temperature loadings. These actions are usually location-specific, depending on the considered country and region, and therefore are included in National Annexes (NA) of the Eurocodes, e.g., the French NA for temperature [6], which integrate the information provided in the previously mentioned documents. The characteristic values associated with climatic actions $q_{k,clim}$ are defined considering the 2% annual exceedance probability, leading to a return period of approximately 50 years, according to the EN1990 [18].

The definition of the current values of the climatic actions is based on classic extreme value analysis of past historical observations of the environmental parameters [19], usually assuming extreme value type I distribution or Gumbel distribution appropriately fitting the measurements for the definition of the characteristic value. Consequently, $q_{k,clim}$ may be defined as follows::

$$q_{k,clim} = \mu + \sigma [-\ln(-\ln(1 - p))] \quad (1)$$

where μ is the location parameter, σ is the scale parameter of the fitted distribution and $p = 0,02$ is the 1-year probability of exceedance [18].

Moreover, the $q_{k,clim}$ is based on the hypothesis of stationary phenomena; this assumption is considered questionable in context of changing climate. Indeed, climate change is leading to the evolution of the frequency and intensity of extreme events as well as the modification in time of the parameters characterizing the extreme value distributions. Consequently, in this context, non-stationarity should be accounted for

when calibrating characteristic value of the loadings over the lifetime of a structural system.

Different approaches are proposed in this sense, although linear models are usually adopted [20]. In this paper, the non-stationarity is accounted for by exploiting the definition of appropriate time windows, in which the problem is reconducted to a stationary one [21]. This approach is proposed in different research, e.g., by Croce et al. [22] and Arnold et al. [7], allowing the characterization of the trend and variability of the extreme value parameters in each window. Nevertheless, the selection of the length of the time window can significantly influence the results [7]. In the European standardization context, data related to 30 years of observations are recommended for reliable evaluation of climatic loadings, with a minimum observation duration of 20 years [5]. Generally, a time window length between 30 and 40 years is suggested [22].

4 Case Study

4.1 Cable-Stayed Bridge over the Isère River, France

An existing prestressed cable-stayed bridge built in 1991 in the Isère district in France is considered. The structure consists of a 5-span bridge, supported by 2 abutments, 3 piles, and 1 pylon. The structural typology was selected in order to overpass a gap of approximately 300 m in correspondence with the Isère River. The bridge is under investigation for safety based on partial factor methods for existing structures [23].

The bridge is located in the region of Rhône-Alpes, as depicted in Fig. 1, and is exposed to different climatic loadings, e.g., temperature, wind, and snow. In this paper, only temperature loading is considered.

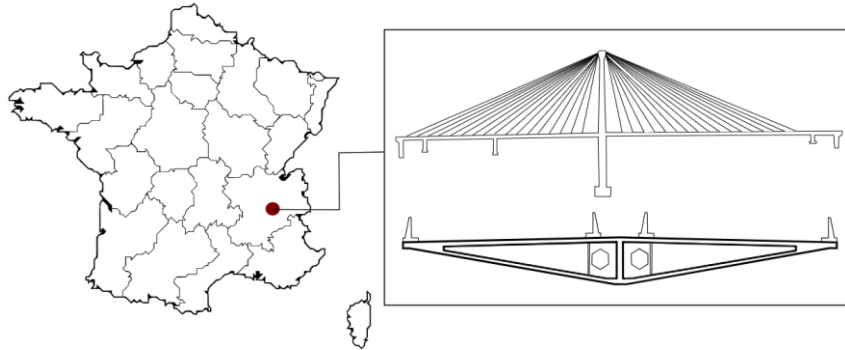


Fig. 1. Location of the bridge.

4.2 Temperature Future Projections

In the analysis presented in this paper, only maximum and minimum temperatures are considered, although the methodology may be applied to different climatic actions such as snow loading. The temperature projections, representative of the period 1950

- 2100, in the region of Rhône-Alpes are downloaded from the Climate Change Knowledge Portal [16]. The control or historical experiment is defined between 1950 and 2014 while the future projections are depicted in the period 2015 – 2100 for three different scenarios, i.e., SSP1-2.6, SSP2-4.5, and SSP5-8.5. The ensemble mean approach is considered for the combination of different climate projections. The retrieved annual maximum and minimum temperature projections are depicted in Fig. 2, considering median, 10th and 90th percentiles. In the following, just the median projections are considered.

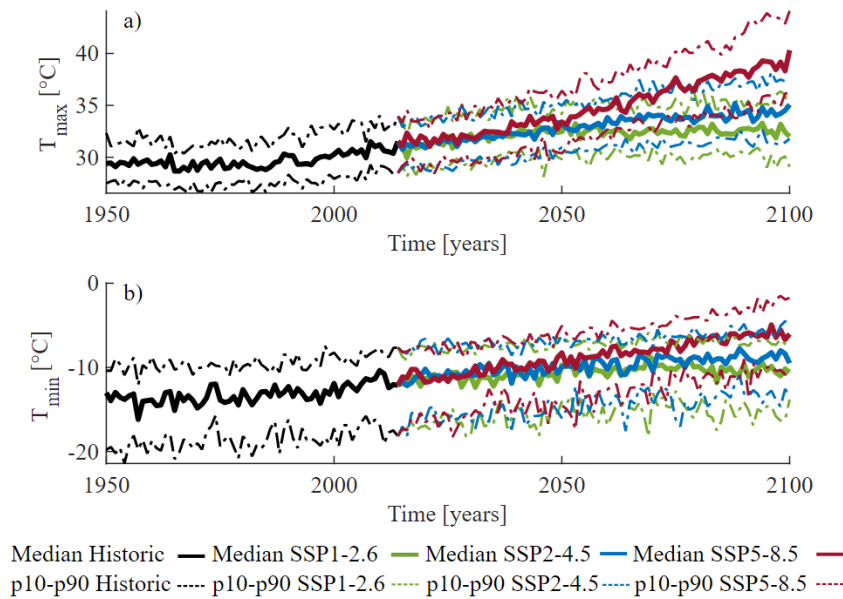


Fig. 2. a) Annual maximum and b) minimum temperature projections for different climate change scenarios from 1950 to 2100.

4.3 Definition of characteristic value of temperature under climate change

The characteristic values of minimum and maximum temperature, T_{min} and T_{max} , are fundamental parameters for the definition of thermal loadings in the structure [5]. For the definition of appropriate T_{min} and T_{max} along the whole lifetime of the studied viaduct, the time windows approach is exploited, aiming to incorporate the non-stationarity of the temperature evolution under climate change in the evaluation.

The time window length k is assumed equal to 40 years and a 10-years shift between subsequent windows is considered. Eventually, for each time window, the data series are fitted to a Gumbel distribution, as reported in Fig. 3. The non-stationary evolution of temperature due to climate change may be clearly observed in Fig. 3.

The characteristic value of temperatures $T_{min,i}$ and $T_{max,i}$ are computed for each time window (Eq. (1)) and then the minimum T_{min} and maximum T_{max} values between all the time windows are retrieved.

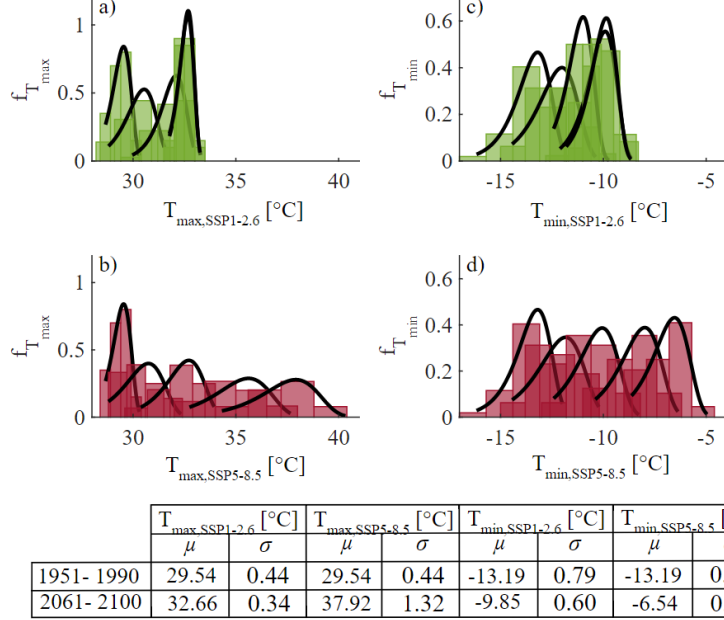


Fig. 3. Gumbel distribution fitting for the time window 1951-1990, 1981-2020, 2011-2050, 2041-2080, and 2061-2100. a) T_{max} for SSP1-2.6; b) T_{max} for SSP5-8.5; c) T_{min} for SSP1-2.6; d) T_{min} for SSP5-8.5.

4.4 Uniform temperature variation of the bridge

In order to define the uniform temperature $T_{e,max}$ and $T_{e,min}$ for the bridge, the characteristic value of temperatures T_{max} and T_{min} should be summed with the non-linear temperature variation components $\Delta T_{e,max}$ and $\Delta T_{e,min}$ according to the Eurocode 1991-1-5 [5], which are defined in the French National Annex equal respectively to +2 °C and +8 °C [6]. The results in terms of uniform maximum and minimum temperature according to the original design, Eurocode prescription for new structures, and climate change scenarios are reported in Table 1.

Table 1. Uniform maximum and minimum temperature according to different scenarios.

	Original Design [9]	Eurocodes [6]	SSP1-2.6	SSP2-4.5	SSP5-8.5
$T_{e,max}$ [°C]	+30	+42	+36.5	+38	+45
$T_{e,min}$ [°C]	-40	-22	-10	-10	-10

In the original design, the uniform maximum and minimum temperatures are respectively underestimated and overestimated with respect to the Eurocodes and the climate change scenarios. Concerning Eurocodes prescriptions, the minimum temperature is the most conservative respecting all the considered SSPs while the maximum component is over-conservative concerning SSP1-2.6 and SSP2-4.5. Observing the

obtained results, it is possible to highlight the impact of climate change in moderating minimum and enhancing maximum temperature.

5 Conclusions

A general methodology for the evaluation of characteristic value of temperature loadings considering climate change future projections, in the European standardization context, is proposed and applied to the case study of an existing bridge located in France. The results, obtained in terms of uniform temperature actions on the bridge deck, have been compared to the original design values and the Eurocodes prescriptions.

The results show the impact of climate change on temperature actions, leading to question the current validity of the stationarity assumption at the base of Eurocodes design, as reported in Fig. 3.

Further investigation is necessary to properly characterize the local climate in the surroundings of the bridge, increasing the resolution of the climate change projections. Moreover, the design values for temperature loading should be estimated with proper calibration of partial safety factors exploiting tailored methodologies for existing structures. An assessment in this sense for the same case study is provided in [23]. Eventually, the climate change effects are expected to significantly influence structural capacity, enhancing aging and deterioration processes, e.g. corrosion, and this aspect should be implemented, integrating this impact on the calibration framework.

Acknowledgments

This research project work was performed within the European project Clear-DOC, which has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie COFUND grant agreement No 101034248. The authors thank APRR (Saint-Apollinaire, France) for the support and experience provided to improve the quality of this paper.

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