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Thermal design of structures and the changing climate

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Foreword

The construction sector[1] is of strategic importance to the European Union (EU), as it delivers the buildings and infrastructures needed by the rest of the economy and society, having a direct impact on the safety of persons and the quality of citizens' life. The sector contributes to about 11.5% of the EU's Gross Domestic Product (GDP), providing directly about 12 million jobs in 3.3 million of companies[2].

Construction is a key element for the implementation of the European Single Market[3] and for other relevant EU strategies. Ensuring more sustainable and climate resilient infrastructure and buildings are key priorities of the European Green Deal (COM(2019) 640[4,5]). The adaptation of the construction sector to the inevitable impacts of climate change is foreseen in policy areas and initiatives under the Green Deal, noteworthy:

- the revision of the Construction Products Regulation (Regulation (EU) No 305/2011[6]) and the launch of the '*renovation wave*' initiative in the construction sector addressing challenges of more efficient and affordable energy and resources throughout the life cycle of buildings.
- the new Circular Economy Action Plan (COM (2020) 98 final[7]) and the new Industrial Strategy for Europe (COM(2020) 102 final[8]) intending to accelerate the transition of the EU industry to a sustainable model based on the principles of circular economy and announcing the launch of a new initiative for a Sustainable Built Environment.

In the framework of Administrative Arrangements between the European Commission's Joint Research Centre (JRC) and the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), the Safety and Security of Buildings Unit of the JRC is involved in the identification of further research needs for the adaptation of structural design to climate change. The activities acknowledge the importance of standardisation in strengthening Europe's resilience to the impact of a changing climate as an instrument to regulate the construction sector. Of major relevance to the construction sector is the role of the Eurocodes[9] that are a set of European standards (EN 1990 to EN 1999) for structural design. This work goes beyond the developments within the Mandate M/515 EN[10] for a detailed work programme for amending existing Eurocodes and extending the scope of structural Eurocodes.

The JRC Technical Report "*Thermal design of structures and the changing climate*" presents the work of JRC's scientific network on adaptation of structural design to climate change towards a methodology for new thermal design maps for structural design considering the changing climate. The report first outlines the EU Strategy on adaptation to climate change, highlighting the ongoing action plan for adapting the European standards to a changing climate. It 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 on future variations of climate

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[1] As defined by the Statistical classification of economic activities in the European Community (NACE) F section in Eurostat

[2] EUROSTAT 2018, Structural Business Statistics

[3] https://ec.europa.eu/growth/single-market_en

[4] https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF

[5] https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en

[6] Regulation (EU) No 305/2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC

[7] https://eur-lex.europa.eu/resource.html?uri=cellar:9903b325-6388-11ea-b735-01aa75ed71a1.0017.02/DOC_1&format=PDF

[8] https://ec.europa.eu/info/sites/info/files/communication-eu-industrial-strategy-march-2020_en.pdf

[9] The Eurocodes are a set of European standards (EN 1990 – EN 1999) for structural design. They provide common rules for the design of construction works and for checking their strength and stability against live extreme loads, such as fire and earthquakes. More details at the European Commission website "Eurocodes: Building the future" (https://eurocodes.jrc.ec.europa.eu/)

[10] M/515 Mandate for amending existing Eurocodes and extending the scope of structural Eurocodes (12 December 2012); http://eurocodes.jrc.ec.europa.eu/doc/mandate/m515_EN_Eurocodes.pdf

factors that would directly affect the design values for thermal actions in the standards. A methodology for developing thermal maps for structural design taking into account the influence of climate change is also presented.

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.

The editors and authors have sought to present useful and consistent information in this report. However, users of information contained in this report must satisfy themselves of its suitability for the purpose for which they intend to use it.

The report is available to download from the "Eurocodes: Building the future" website (http://eurocodes.jrc.ec.europa.eu).

Ispra, July 2020

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The authors acknowledge the World Climate Research Programme's Working Group on Regional Climate, and the Working Group on Coupled Modelling, former coordinating body of CORDEX and responsible panel for CMIP5. We also thank the climate modelling groups (listed in Table 1 of Chapter 4) for producing and making available their model output exploited for elaborations included in Chapter 5. We also acknowledge the Earth System Grid Federation infrastructure an international effort led by the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison, the European Network for Earth System Modelling and other partners in the Global Organisation for Earth System Science Portals (GO-ESSP).

The report builds on the activities of JRC’s scientific network addressing the implications of the climate change on structural design. The authors acknowledge the support and cooperation of the network members not participating as authors in the current report, namely:

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Abstract

The report presents the work of the Joint Research Centre's scientific network on adaptation of structural design to climate change focusing on the **thermal design of buildings and infrastructure considering the changing climate**. It presents scientific and technical background intended to stimulate debate and serve as a basis for further work to study the implications of climate change on the thermal design of structures.

The report first outlines recent EU policies in support of sustainability and climate resilience of infrastructure and buildings. It highlights how the construction sector is encouraged to adopt more sustainable and circular economy practices, extend the lifetime of buildings and strive for better performance of buildings and infrastructure throughout their life cycle. It further emphasises the ongoing action plan to adapt the European standards to a changing climate.

Following, the report explains the concept of the definition of thermal actions for the design of buildings and infrastructure using the European standards for structural design, i.e. the Eurocodes. It is showed that the adaptation of structural design to the implications of climate change is strongly linked with the assessment of changing characteristics of climatic actions (including thermal ones) in terms of the Eurocodes concept for the variable climatic actions.

Variations in temperature that would directly affect the design values for thermal actions in the European standards are studied in depth for the case study of Italy. It is concluded that an increase in the maximum and minimum temperature used for structural design is expected all over Italy. It is discussed that structures, as bridges for example, 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. However, the 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.

Thus, **new European maps for the thermal design of structures** should be developed using data that project more realistically the future climate. To this end, the authors present a methodology for developing thermal maps for structural design taking into account the influence of the changing climate and present an implementation of the methodology using the example of Italy.

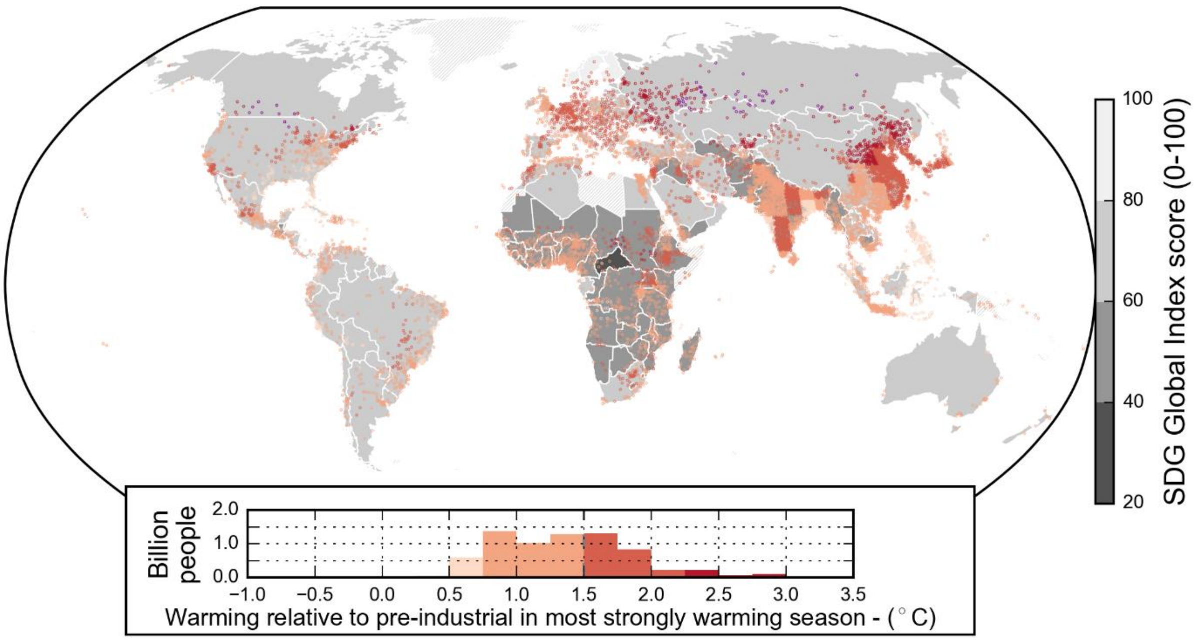
The figure below shows the landscape of dry earth and the bridge viaduct during extreme drought in Entrepenas reservoir in Guadalajara, Castilla, Spain (© Q - stock.adobe.com)

1 Introduction

Climate change is happening now and is expected to get worse in the future, even if global efforts to reduce emissions prove effective[11]. According to different observational records of global average annual near-surface (land and ocean) temperature, the last decade (2009–2018) was 0.91 °C to 0.96 °C warmer than the pre-industrial average[12]. Of the 18 warmest years on record, 17 have occurred since 2000. Moreover, the average annual temperature for the European land area for the last decade was between 1.6 °C and 1.7 °C above the pre-industrial level, which makes it the warmest decade on record (EEA, 2019[13]).

The Special 2018 Report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2018)[14] states, with high confidence, that global warming is likely to reach 1.5°C between 2030 and 2052, if it continues to increase at the current rate. **Figure *1*** presents the human experience of present-day warming, as discussed in the Special 2018 IPCC Report. It is evident that Europe is expected to experience, in several areas, warming of 1.5°C and higher.

Figure 1. Human experience of present-day warming. Different shades of pink to purple indicated by the inset histogram show estimated warming for the season that has warmed the most at a given location between the periods 1850–1900 and 2006–2015, during which global average temperatures rose by 0.91°C in this dataset (Cowtan and Way, 2014) and 0.87°C in the multi-dataset average (Table 1.1 and Figure 1.3). The density of dots indicates the population (in 2010) in any 1° × 1° grid box. The underlay shows national Sustainable Development Goal (SDG) Global Index Scores indicating performance across the 17 SDGs. Hatching indicates missing SDG index data (e.g., Greenland). The histogram shows the population living in regions experiencing different levels of warming (at 0.25°C increments) (Figure 1.1 in IPCC, 2018)[15]



The consequences of climate change are being felt increasingly in Europe and worldwide. Extreme weather and climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C (IPCC, 2018). Moreover, the frequency

[11]European Environment Agency (EEA): https://www.eea.europa.eu/themes/climate-change-adaptation

[12]The pre-industrial period refers to the multi-century period prior to the onset of large-scale industrial activity around 1750. The reference period 1850–1900 is used to approximate pre-industrial global mean surface temperature (IPCC, 2018)

[13]European Environment Agency (EEA): https://www.eea.europa.eu/data-and-maps/indicators/global-and-european-temperature-9/assessment

[14]Intergovernmental Panel on Climate Change (IPCC): http://www.ipcc.ch/report/sr15/

[15] The caption of the figure is as provided in IPCC, 2018

and intensity of extreme weather events have higher likelihood due to climate change. As noted in the European Environment Agency's (EEA) "The European environment — state and outlook 2020" report (EEA, 2020) " […] *Europe faces environmental challenges of unprecedented scale and urgency"*.

Efforts to control COVID-19 pandemic led to a drop on carbon emissions, and to localized improvements in air quality as revealed by Copernicus, the EU's climate monitoring service. However, the World Meteorological Organization (WMO)[16] states that is too early to assess the implications of emissions decline for long-term climate change. Moreover, a temporary slowdown of anthropogenic emissions has little impact on concentrations of greenhouse gases, which are responsible for long-term climate change. Thus, the United Nations claim: "[…] *climate change is not on pause*"[17], *i.e.*, climate patterns will continue to change, unless there are worldwide sustainable adjustments towards a more climate-friendly economy and individual practices.

Developing and implementing policies on mitigation and adaptation to climate change are worldwide challenges to communities and economies in the 21st century. Actions to adapt to the impacts of climate change should, however, be tailored to the specific circumstances in different parts of the world. The assessment of the impact of climate change on the built environment, and the identification of adaptation needs of infrastructure and buildings, are key aspects so as to set out adaptation strategies to climate change.

To this end, state-of-the-art building standards can play an important part in strengthening Europe's resilience and preparedness to the impact of the changing climate in the construction sector. In this context, the Eurocodes are a set of 10 European Standards, that provide common technical rules for the structural design of buildings and other civil engineering works and construction products. The Eurocodes cover in a comprehensive manner the basis of design, actions on structures, the principal construction materials, all major fields of structural engineering and a wide range of types of structures and products.

The Eurocodes are the product of a long procedure of bringing together and harmonising the different design traditions in the EU Member States, leading to more uniform levels of safety in construction in Europe. At the same time, the Member States keep the exclusive competence and responsibility for the levels of safety of the construction works, since the Eurocodes are flexible enough to account for differences in national applications. In fact, the Eurocodes include the Nationally Determined Parameters (NDPs), which are the parameters used for design that are left open in the Eurocodes for national choice, in order to take into account country differences in geographical, geological or climatic conditions, different design cultures and procedures for structural analysis, as well as different requirements for safety levels in the Member States.

The Safety and Security of Buildings Unit of the Joint Research Centre (JRC) conducts pre-normative research towards European standards for safety and security of the built environment, also addressing sustainability and resource and energy efficiency issues. The Unit is involved in activities for the adaptation of structural design to climate change in the framework of Administrative Arrangements between the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) and the JRC on support to policies and standards for sustainable construction. The activities focus, among other topics, on the update and harmonisation of the European design maps for climatic (wind, snow and thermal) actions taking into account the changing climate and used for designing with the Eurocodes.

In this context, the JRC established a scientific network to promote an interdisciplinary collaboration between experts in the fields of climate change, structural design, standard writers and policy makers. The members in the network are:

— The chairmen of two Sub-Committees (SC) of CEN/Technical Committee 250 "Structural Eurocodes" (CEN/TC 250)[18] relevant to the adaptation to climate change:

[16] https://public.wmo.int/en/media/news/economic-slowdown-result-of-covid-no-substitute-climate-action

[17] https://www.un.org/sustainabledevelopment/climate-change/

[18] The European Standardisation Committee (CEN) Technical Committee (TC) 250 has the overall responsibility for all CEN work on structural design codes. CEN/TC250 had developed and is maintaining the Eurocodes.

CEN/TC 250/SC 10 "Basis of Structural Design" and CEN/TC 250/SC 1 "Actions on Structures" and the convenor of the CEN/TC 250 Horizontal Group (HG) "Bridges". The chairman of SC10 and the convenor of HG "Bridges" also represent the University of Pisa in Italy. Both had previously participated in the European Snow Load Research Project (ESLRP, 1998) that produced the European snow load map incorporated in Annex C to EN 1991-1-3[19] (ESLRP, 1998).

— The Project Team (PT) Leader for task SC1.T5 "Climate change", under Mandate M/515 on the second generation of the Eurocodes, also representing the Czech Technical University in Prague in the Czech Republic.

— Experts on climatology, structural design, structural corrosion and economic assessment of climate adaptation from the Euro-Mediterranean Centre on Climate Change (CCMC) in Italy, the Czech Technical University in Prague, Delft University of Technology in the Netherlands, Coimbra University in Portugal, University of Nottingham in the United Kingdom and University of Nantes in France.

— Representatives of the Directorate-General for Climate Action (DG CLIMA), DG GROW and the JRC dealing with adaptation strategies to climate change, European standards, climate change projections and impact models.

The scientific network has already performed a pilot project on definition of snow load maps for structural design by use of recorded climatic data and climate change projections. A procedure for the derivation of snow load on the ground from data on daily temperatures and precipitation has been developed (Croce et al., 2018), which allows to derive characteristic snow loads from climate change projections and thus, to evaluate the future trends in the variation of snow loads. The work concludes that a European project on snow load maps shall be started as soon as possible, in order to update the existing snow load maps in Annex C of EN 1991-1-3 and to help National Authorities redraft their national snow load maps. The procedure established in the pilot project for defining the snow load from climate change projections allows to produce new national snow load maps in a harmonised way by using the best available knowledge. Thus, such a consistent development of maps will contribute to the reduction of inconsistencies at borders between neighbouring countries.

In June 2017, the network initiated work on thermal actions and the climate change. The initial discussion among the network emphasised that changes in the climate factors will directly affect the design values for climatic actions in the standards. The implications of periodic revisions of climate maps were underlined, namely the costs of establishing new climate maps, the enforcement of the new climate maps in the national regulatory frameworks for the Eurocodes and the resulting need for assessment and eventual retrofitting of existing structures. The work of the scientific network focused on a pilot project for deriving new thermal design maps for selected scenario(s) of climate change for the case of Italy.

The scientific network also conducted work focused on the expected implications of climate change on the corrosion of structures. The network reviewed available studies on the corrosion of reinforced concrete and steel structures due to climate change, and assessed the corrosion impact, costs and effectiveness of adaptation strategies. Further research needs regarding the impact of future climate change on the corrosion of buildings at the European level were identified. The results of this study are published in the JRC Report "*Expected implications of climate change on the corrosion of structures*" (2020)[20]. Starting in 2020, the scientific network will focus on the definition of wind loading, taking into account the changing climate.

[19]Eurocode 1: Actions on structures - Part 1-3: General actions - Snow loads, Annex C: European Ground Snow Load Maps

[20] M.L. Sousa, S. Dimova, A. Athanasopoulou, G. Rianna, P. Mercogliano, V.Villani, M. Nogal, H. Gervasio, L. Neves, E. Bastidas-Arteaga, G. Tsionis. Expected implications of climate change on the corrosion of structures. Publications Office of the European Union, 2020 (*in press*)

2 Adaptation of structural design to climate change

2.1 Policy context

Adaptation to climate change refers to an anticipatory approach to the adverse effects of climate change by taking appropriate action to prevent or minimise the damage they can cause, or by taking advantage of opportunities that may arise. **Adaptation measures** may extend from building flood defences and raising the levels of embankment to developing drought-tolerant crops or adapting building codes to future climate conditions and extreme weather events. Well planned, early adaptation action may save money and lives later[21].

The JRC PESETA IV[22] study showed that ecosystems, people and economies in the EU will face major impacts from climate change if we do not urgently mitigate greenhouse gas emissions or adapt to climate change. It is demonstrated that limiting global warming to well below 2°C would considerably reduce climate change impacts in Europe. Adaptation to climate change would further minimize unavoidable impacts in a cost-effective manner, with considerable co-benefits from nature-based solutions.

The European Commission already in 2013 adopted "**The EU Strategy on Adaptation to Climate Change**" (COM (2013) 216[23]), presenting a set of measures to be taken from local to regional and national levels for improving the EU's preparedness for current and future climate impacts, anticipating the adverse effects of climate change[24]. The accompanying Staff Working Document "**Adapting infrastructure to climate change**" (SWD (2013) 137 final[25]) recognised a group of key vulnerable sectors in the EU, like energy and transport infrastructure, as well as buildings. The document stressed the central role played by technical standards in this area. In particular, the **Eurocodes** were considered a suitable instrument for addressing climate resilience in different infrastructure sectors.

The strategy has been welcomed by the Member States and positively evaluated in 2018 (SWD(2018) 461 final[26]). Even though all Member States adopted an adaptation strategy[27], it was shown that Europe is still susceptible to climate impacts within and outside its borders and there are areas where more work needs to be done to prepare vulnerable regions and sectors.

In December 2019, the European Commission presented the **European Green Deal**[28] (COM (2019) 640[29]), an ambitious roadmap aiming to make Europe the world's first climate-neutral continent by 2050. The Green Deal supports a sustainable growth strategy, transforming the EU into a modern, resource-efficient and competitive economy. ***Figure 2*** illustrates the various policies areas of the Green Deal strategy. The financing pillars of the transition are highlighted in blue, i.e., the *European Green Deal's Investment Plan* (EGDIP, COM(2020) 21 final[30]) and a Proposal for Regulation establishing the *Just Transition Fund* (COM(2020) 22 final[31]).

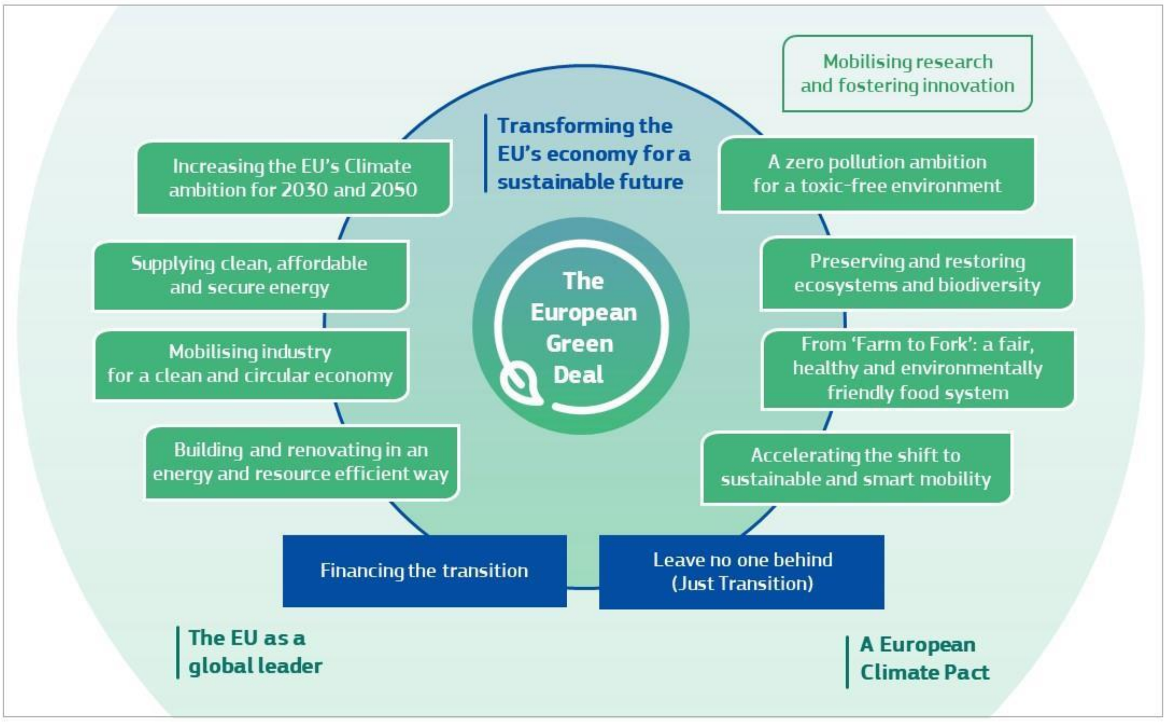
The Green Deal is the one of the six priorities of the European Commission's 2020 Work Programme (COM(2020) 37 final[32]). The Programme was adjusted in May 2020

[21]Adaptation to climate change as explained by the Directorate-General for Climate Action (DG CLIMA) web resources: https://ec.europa.eu/clima/policies/adaptation_en
[22]More details at: https://ec.europa.eu/jrc/en/peseta-iv
[23] https://ec.europa.eu/transparency/regdoc/rep/1/2013/EN/1-2013-216-EN-F1-1.Pdf
[24]https://ec.europa.eu/clima/sites/clima/files/docs/eu_strategy_en.pdf
[25] https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/swd_2013_137_en.pdf
[26] https://ec.europa.eu/info/sites/info/files/swd_evaluation-of-eu-adaptation-strategy_en.pdf
[27]https://climate-adapt.eea.europa.eu/countries-regions/countries
[28]https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en
[29] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN
[30] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0021
[31] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020PC0022
[32] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:0037:FIN

(COM(2020) 440 final[33]), as part of *Europe's Recovery Plan* (COM(2020) 456 final[34]) to the COVID-19 pandemic. The EU's recovery aims to guide and build a more sustainable, resilient and fairer Europe for the next generation. The green and digital transitions are considered even more important challenges in the aftermath of the COVID-19 crisis.

In the heart of the Green Deal is the Commission's proposal for the first **European Climate Law** (COM (2020) 80 final[35]). The proposal aims to write into law, the goals set out in the European Green Deal for Europe's economy and society, ensuring that all EU policies contribute to this goal and all sectors of the economy and society play their part. In parallel, the **European Climate Pact**[36] is one of the first climate action initiatives to be launched under the Green Deal and an effort for sharing information, showcasing solutions and eventually engaging citizens and all parts of society in climate action. It is expected to be launched in the last quarter of 2020.

Figure 2. The European Green Deal (COM(2019) 640)



Another one of the main blocks of the European Green Deal is the **New Circular Economy Action Plan** for a cleaner and more competitive Europe, adopted in March 2020 (COM (2020) 98 final[37]). Focus is given on the sectors that use most resources and where the potential for circularity is high, including construction and buildings.

The climate change challenge also puts additional pressure on achieving greater efficiency in buildings. Management of cities facing accelerated population growth will be a major challenge: modern technology will play a key role in enabling resilient infrastructures for more efficient services and contribute to combating climate change. In this respect, the **EU Industrial Strategy** (COM(2020) 102 final[38]) adopted in March 2020, supports the twin challenge for a green and digital industrial transformation. A key aim will be to stimulate the development of new markets for climate neutral and circular products.

[33] https://ec.europa.eu/info/sites/info/files/cwp-2020-adjusted_en.pdf
[34] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:456:FIN
[35] https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1588581905912&uri=CELEX:52020PC0080
[36] https://ec.europa.eu/clima/policies/eu-climate-action/pact_en; the European Climate Pact was open for public consultation from 4th March to 27th May 2020.
[37] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN
[38] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0102

Many future key EU legislation and policies at the heart of the European Green Deal include the adaptation to the impacts of climate change[39]. In particular, the Commission aims to put forward a new, more ambitious, Adaptation Strategy in early 2021, building on the current one, which was adopted in 2013 and positively evaluated in 2018. The background framework of the new strategy is presented in a blueprint document that accompanies the public consultation of the new EU strategy[40]. The new adaptation strategy will be in full synergy with the other strategic initiatives under the European Green Deal relevant to the construction sector such as, the *Renovation Wave*[41] and the *Sustainable Industry*.

In parallel, the Commission will review the **Construction Products Regulation** (Regulation (EU) No 305/2011[42]) to ensure the lowest cost for decarbonisation of the built environment, through (i) the design of new and renovated buildings in line with the principles of a circular economy, (ii) the increase of digitalisation, climate-proofing, and clean energy use, and (iii) the optimisation of lifecycle performance and life expectancy of built assets.

Moreover, the Commission will launch a new comprehensive **Strategy for a Sustainable Built Environment** to exploit the potential for increasing material efficiency and reducing climate impacts. This Strategy will ensure coherence across the relevant policy areas such as climate, energy and resource efficiency, management of construction and demolition waste, accessibility, digitalisation and skills. Circularity principles will be promoted throughout the lifecycle of buildings by, among others:

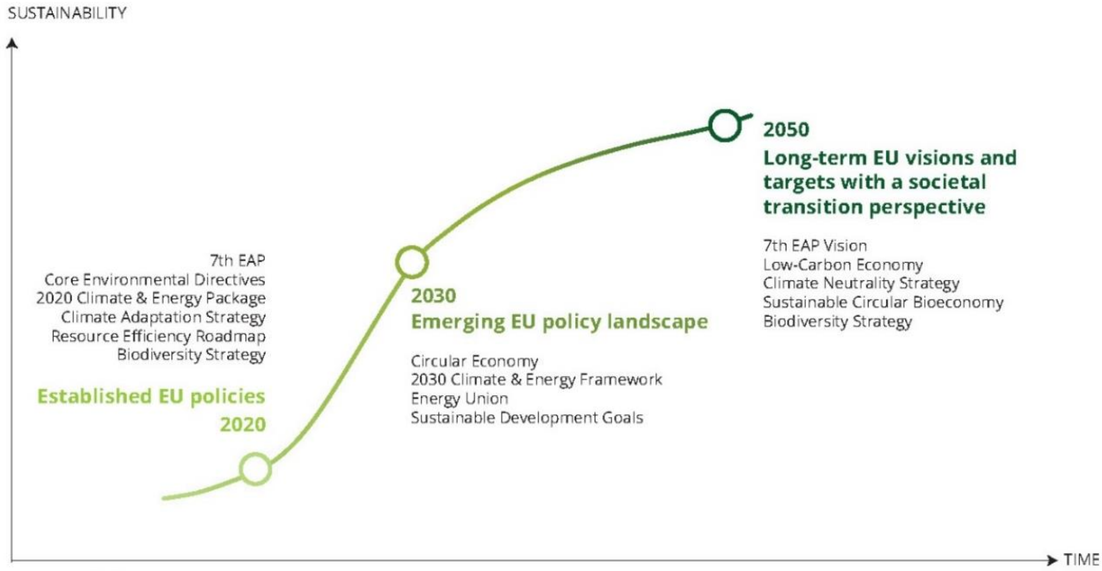
— Addressing the sustainability performance of construction products in the context of the revision of the *Construction Product Regulation*[43].
— Promoting measures to improve the durability and adaptability of built assets in line with the *Circular economy - Principles for buildings design*[44], published in February 2020.

Using Level(s)[45] which is a voluntary reporting framework to improve the sustainability of buildings, in order to integrate life cycle assessment in public procurement and to explore the appropriateness of setting of carbon reduction targets and the potential of carbon storage.

As illustrated in ***Figure 3***, the EU climate and environmental policy landscape increasingly connects the environmental, social and economic dimensions of sustainability through a range of policies, strategies and instruments aiming to address the short-, medium- and long-term time horizons. The policies, strategies and instruments mostly related to climate change have been discussed above where as several others complete the sustainability policy landscape, as the 7th Environment Action Program[46], the Core Environmental Directives, the 2030 Climate & Energy Framework[47], the Energy Union and the climate neutrality strategy[48]. The EU also plans to continue leading the way to a circular economy at the global level and use its influence, expertise and financial resources to implement the **2030 Sustainable Development Goals**[49].

[39]https://ec.europa.eu/clima/policies/adaptation_en
[40]https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12381-EU-Strategy-on-Adaptation-to-Climate-Change/public-consultation
[41] https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-renovation-wave
[42] Regulation (EU) No 305/2011 laying down harmonised conditions for the marketing of construction products and repealing Council Directive 89/106/EEC
[43] https://ec.europa.eu/growth/sectors/construction/product-regulation/review_en
[44] https://ec.europa.eu/docsroom/documents/39984
[45] https://ec.europa.eu/environment/eussd/buildings.htm
[46] https://www.eea.europa.eu/policy-documents/7th-environmental-action-programme
[47] https://ec.europa.eu/clima/policies/strategies/2030_en
[48] https://ec.europa.eu/clima/policies/strategies/2050_en
[49] https://sustainabledevelopment.un.org/post2015/transformingourworld

Figure 3. The emerging EU environmental and climate policy landscape (EEA: SOAR, 2020)



2.2 Standardisation work

The impacts of climate change are particularly pertinent to infrastructure and buildings given their essential role in the functioning of our societies and economies. They are characterised by a long lifespan and high economic value and thus need to adapt to, and be resilient to future impacts of a changing climate. Buildings and infrastructure can be vulnerable to climate change because of their design (e.g. because of their low resistance to storms) or location (e.g. in flood-prone areas, landslides, avalanches). They can be damaged or rendered unfit for use by any changing climatic condition or extreme weather event: rising of sea level, extreme precipitation and floods, occurrences of extreme low or high temperatures, heavy snowfalls, strong winds, etc. (SWD(2013) 137 final[50]).

In view of the central role European technical standards can play in addressing climate resilience of infrastructures and buildings, assessment of the impact of climate change on new and existing structures is a key aspect in the future evolution of standards (SWD(2013) 137 final). The Commission is working with European standardisation organisations to look at how far standards, codes and other rules need to be strengthened so that transport, energy, buildings and other infrastructure can cope with climate impacts and extreme events. This is indeed intended for the second generation of the Eurocodes (Mandate M/515 of the European Commission, 2012[51]), and all other standards relevant to transport infrastructure, energy infrastructure, and buildings/construction (Mandate M/526 of the European Commission, 2014[52]).

In particular, the **Mandate M/515** of the European Commission to the European Committee for Standardisation (CEN), requested the assessment of the climate change implications for the Eurocodes, the European standards for structural design. The work of CEN/Technical Committee 250 "Structural Eurocodes" (CEN/TC250) under the Mandate M/515 started in 2016 and the second generation of the Eurocodes is expected to be published by 2023. According to CEN/TC250 Response to Mandate M/515 (CEN/TC250, 2013), the standardisation works relevant to the adaptation to climate change encompass:

— Publication in 2017 of the final report of the Project Team SC1.T5 (PT5) "*Climate change*" (Fikke et al., 2017). It provides advice to the Eurocode writers on how to refer to and implement possible effects from the future changes in the climate in Europe. The report presents comprehensive analysis of the climate parameters of the Eurocodes and the related uncertainties.

[50] https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/swd_2013_137_en.pdf
[51] https://ec.europa.eu/growth/tools-databases/mandates/index.cfm?fuseaction=search.detail&id=523
[52] https://ec.europa.eu/growth/tools-databases/mandates/index.cfm?fuseaction=search.detail&id=546

- Work of the Project Teams on the revision of the Eurocodes Parts on snow loading, wind actions and thermal actions.
- On-going works by a Project Team on interdependence of climatic actions (wind, snow, thermal and atmospheric icing) and determination of relevant partial factors and load combination factors.

The final report of the Project Team on SC1.T5 "*Climate change*" under Mandate M/515 was published in 2017 and provided advice to the Eurocode writers on how to refer to and implement possible effects from the future changes in the climate in Europe. The report provided a comprehensive analysis of the climate parameters of the Eurocodes and of the related uncertainties. It referred to the most recent reports and scientific findings available, as well as to various socio-economic and other summary reports.

The report concluded that the science of global climate change is still not sufficiently developed to identify any substantial methods for quantification of extreme values (with given return periods) for neither temperature, wind, rain, snow nor any combination of these, to be valid for the forecast of changing climate in Europe. It recommended re-examining at regular intervals (no more than 10 years) the weather parameters significant for specification of characteristic values, by using conventional methods (extreme value analyses). However, it was highlighted that bridges and other structures influenced by stresses from extreme temperatures should be designed for temperature amplitudes which may be justified using climate projections for the actual region. The report also recommended emphasizing and adjusting the inspections and maintenance schemes for structures approaching their expected life time.

The **Mandate M/526** of the European Commission requested the European Standards Organisations (ESOs) to contribute to building and maintaining a more climate resilient infrastructure throughout the EU in the three priority sectors: transport infrastructure, energy infrastructure, and buildings/construction. The work performed under this mandate does not addresses the Eurocodes, which are subject to Mandate M/515 and includes:

- Establishing the Adaptation to Climate Change Coordination Group (ACC-CG)[53] by CEN-CENELEC, to support the implementation of the EU Strategy on Adaptation to Climate Change.
- Drafting, testing and issuing of the CEN CENELEC document a 'Guide for addressing climate change adaptation in standards'. Guide 32[54] is intended to help standard writers address the consequences and implications of climate change. It includes a simple checklist to help establish whether climate change adaptation is relevant to a particular standardisation activity and a decision tree to help identify which actions should be taken.
- Drafting, testing and issuing of the NEN/CEN CENELEC document "Tailored guidance for standardisation technical committees: how to include climate change adaptation in European infrastructure standards" (draft 9, 30 April 2019)[55]. The Guide is designed specifically for writers of CEN-CENELEC infrastructure standards (and similar documents).
- Identification of twelve standards as priority for revision during the first phase of the works on the Mandate M/526.

The work of the ACC-CG is expected to finish at the beginning of 2022. Its scope was extended in 2019 to cover further infrastructure standards and standards on adaptation options, as well as to facilitate the dialogue between meteorological institutions and the standard-writing communities (including under Eurocodes) in an effort to improve the use of climate models in standardisation.

It shall be mentioned, that development of maps of climatic actions for design with the Eurocodes taking into account the implications of climate change, is not planned neither under Mandate M/515, nor under Mandate M/526. In view of this fact, the activities of the

[53] https://www.cencenelec.eu/standards/topics/environment/pages/climatechangeadaptation.aspx
[54] https://www.cencenelec.eu/standards/Guides/Pages/default.aspx
[55]https://www.nen.nl/Standardisation/Adaptation-to-Climate-Change/Mandated-project-Adaptation-to-Climate-Change.htm

scientific network on implications of the climate change on structural design, presented in the Introduction of this report, support important synergies with the Mandates M/515 and M/526.

2.3 Conclusions

The EU has been putting in place a comprehensive package of strategies, plans and measures, and a legislative and regulatory framework as well, for addressing sustainability and climate resilience of infrastructures and buildings. Notably, European technical standards play a central role in strengthening Europe's resilience to the impact of climate change since they are important instruments to regulate the construction sector and to guarantee the safety of investments in it. Thus, adaptation to the unavoidable impacts of climate change is a key aspect to take into account in the future evolution of standards and in particular the Eurocodes, being the state-of-the-art European standards for the structural design of buildings and other construction works.

3 Thermal actions in the Eurocodes and the climate change

3.1 General

Standardisation plays an important part in strengthening Europe's resilience to the impact of a changing climate, since it is an important instrument to regulate the construction sector. In this context, the publication of the Eurocodes by the European Committee for Standardisation (CEN) in May 2007, marked a major milestone in the European standardisation for construction.

The Eurocodes are a set of European standards (EN 1990 – EN 1999) for structural design. They provide common rules for the design of construction works and for checking their strength and stability against live extreme loads, such as fire and earthquakes. The Eurocodes are state of the art reference design codes for buildings, infrastructure and other civil engineering structures, aiming for more uniform levels of safety in construction in Europe. All Eurocodes' Parts were published in 2007, while their implementation in the European countries started in 2010. Currently, there is considerable interest in the use of the Eurocodes outside the EU and several third countries are already in the process of or have already adopted them as national standards.

The Eurocodes are used in different regulatory systems due to their flexibility to adapt to each country's specific conditions and construction practice. In fact, the Eurocodes take into account country differences in geographical, geological or climatic conditions, different design cultures and procedures for structural analysis. They are already implemented within most of the CEN member countries (Dimova et al., 2015) and currently several third countries have adopted or are considering adopting them at national level[56].

The Commission Recommendation of 11th December 2003 (2003/887/EC)[57] on the implementation and use of the Eurocodes for construction works and structural construction products recommends undertaking research to facilitate the integration of the latest developments in scientific and technological knowledge into the Eurocodes. In December 2012, the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW) issued the Mandate M/515 EN for detailed work programme for amending existing Eurocodes and extending the scope of structural Eurocodes. The Mandate includes, among other topics, standardisation works relevant to climate change. This second generation of the Eurocodes is expected to be published after 2023. The Directorate-General for Climate Action (DG CLIMA) issued in 2014 the Mandate M/526 EN, requesting the European Standardisation Organisations (ESO) to initiate standardisation activities in the fields not covered by the Mandate M/515 EN, in support to the implementation of the EU Strategy on Adaptation to Climate Change.

One of the main concepts of the Eurocodes is the Design Working Life (DWL), which is defined as the period for which the structure shall be used with anticipated maintenance but without major repair (EN 1990 "Eurocode: Basis of structural design", Section 1.5.2.8). EN 1990 gives indicative design working lives for design purposes for various types of structures. The DWL of buildings and other common structures designed with the Eurocodes is 50 years, and the DWL of monumental buildings and bridges is envisaged as 100 years. Consequently, buildings and common structures designed in 2020 will have to withstand climatic actions (snow, wind, thermal) and extreme events expected in 2070, while bridges and monumental buildings designed in 2020 will have to withstand climatic actions and extreme events expected in 2120[58]. Moreover, Section 2.4(1) of EN 1990 'Basis of design' states that "*the structure shall be designed such that deterioration over its design working life does not impair the performance of the structures below that intended, having due regard to its environment and the anticipated level of maintenance*".

[56] https://eurocodes.jrc.ec.europa.eu/showpage.php?id=8.map&alone
[57] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32003H0887
[58] Concept of DWL as explained in the document "*Guidance on the climate Proofing of Infrastructure Investment Projects in the period 2021-2027*" by DG CLIMA (draft version 16).

3.2 Definition of the thermal actions in the Eurocodes

Generally, the effect of thermal action on a structure is a complex issue that depends on the geographical location and meteorological conditions at the specific location of the structure. Hence, this type of load is difficult to define precisely (Radovanovic and Grebovic, 2015). The magnitude of the thermal effects depends on local climatic conditions, together with the orientation of the structure, the overall mass of the structure, external finishes (e.g. cladding in buildings), and in the case of buildings, heating and ventilation regimes and thermal insulation. Daily and seasonal changes in shade air temperature, solar radiation, reradiation, etc., will result in variations of the temperature distribution within individual elements of a structure.

EN 1991 "Eurocode 1: Actions on structures" provides comprehensive information on actions to consider in the design of buildings and other civil engineering works. It comprises three parts that deal with climatic actions:

- Part 1-3: General actions - Snow loads;
- Part 1-4: General actions - Wind actions;
- Part 1-5: General actions - Thermal actions.

EN 1991-1-5 "*Eurocodes 1 – Actions on structures – Part 1-5: General actions – Thermal actions*" gives the principles and rules for calculating thermal actions on buildings, bridges and other structures, including their structural elements. Principles needed for cladding and other appendages of buildings are also provided. Thermal actions on a structure (or a structural element) are those actions that arise from the changes of temperature fields within a specified time interval.

The main representative value of a given climatic action is its characteristic value, based on the probability of 0.02 of its time-varying part being exceeded for a reference period of one year. This is equivalent to a mean return period of 50 years for the time-varying part. This definition of the characteristic value, given in EN 1990 "Basis of structural design", is accepted in the relevant Parts of EN 1991 dealing with climatic actions. It is noted that the draft of EN 1990 for the second generation of the Eurocodes does not change the definition of the characteristic value of climatic actions.

The characteristic values of thermal actions defined in EN 1991-1-5 used in the design of structures which are exposed to daily and seasonal climate change are:

- T_{max}: maximum shade air temperature with an annual probability of being exceeded of 0.02;
- T_{min}: minimum shade air temperature with an annual probability of being exceeded of 0.02.

The uncertainties inherent in the climatic actions defined in the Eurocodes are considered in Section 4.2. The clauses of the Eurocodes which specify the Nationally Determined Parameters (NDPs) that introduce the maps for thermal actions, are found in normative Annex A: "Isotherms of national minimum and maximum shade air temperatures" (A.1(1) NOTE 1 of EN 1991-1-5). The NDP regulates the information (e.g. maps of isotherms) on both annual minimum and annual maximum shade air temperature. Annex A.1 (1) NOTE 1 is a parameter left open in the Eurocodes for country-driven choices with regard to the maximum and minimum values of shade air temperatures. These temperatures are defined for the annual probability of being exceeded of 0.02 and are based on the minimum and maximum hourly temperature recorded at the mean sea level in open country.

Annex A in EN 1991-1-5 includes also adjustments for other values of probabilities, heights above sea level and local conditions. Part 1-5 of EN 1991 also provides the NDPs 6.1.3.2(1)[59] and 7.2.1(1)[60] that have a similar description to the NDP Annex A.1(1) NOTE 1, *i.e.*, give *Information (e.g. maps of isotherms) on minimum and maximum shade air temperatures* to be used in a country; the former is related to temperature changes in

[59] EN 1991-1-5, Section 6: Temperature changes in bridges
[60] EN 1991-1-5, Section 7: Temperature changes in industrial chimneys, pipelines, silos, tanks and cooling towers

bridges and the latter to temperature changes in industrial chimneys, pipelines, silos, tanks and cooling towers. Most countries have adopted the same map in the Annex A.1(1) NOTE 1 as in the NDPs 6.1.3.2(1) and 7.2.1(1).

3.3 Maps for thermal actions for design with the Eurocodes

The Eurocodes, and in particular EN 1991, do not include maps for climatic actions as such task is left up to the competent authorities at national level (usually the National Meteorological Institute). Hence, the users of the Eurocodes are obliged to use the maps for climatic actions specified in the National Annexes to the Eurocodes of the country where the structure to be designed will be situated. Naturally, climatic data for use with the Eurocodes are not to be found independently by the users.

The elaboration of maps for climatic actions is a complex procedure. The JRC Report "*Elaboration of maps for climatic and seismic actions for structural design with the Eurocodes*" (Formichi et al., 2016) presents the general principles for the derivation of the snow load maps based on the European research project on snow loads, carried out in the period 1996-1999. Further to considerations pertaining to the peculiarities of snow loads, the concept on the elaboration of snow load maps as presented in the report is generally valid also for thermal actions. Moreover, the report presents examples of the elaboration of maps for climatic actions in Greece, Bulgaria and Italy.

The national implementation of the Eurocodes as regards the choice of NDPs relevant to definition of climatic actions, is analysed in the JRC report on the state of harmonised use of the Eurocodes (Sousa et al., 2019). The report concludes that as regards the definition of wind and thermal actions, a good harmonisation has been achieved with acceptance rate of the recommended values of 72% and 70%, respectively. As regards the definition of snow actions, the acceptance rate of the recommended values is 51%. The report further presents the state of national maps for snow, wind and temperature loads.

Figure 4 presents an overview of the maps of minimum shade air temperatures, T_{min}, adopted by the EU Member States where as ***Figure 5*** presents the available maps of maximum shade air temperatures, T_{max}, as analysed in the report.

The national choices made by the EU Member States for the minimum shade air temperature range from a minimum value less than – 50°C, in Finland, to a maximum value equal to 0°C, in Portugal and in Croatia. The maximum shade air temperatures range from 24°C in the Orkney Islands in Scotland to 46°C in Bulgaria.

Overall, there are good examples of harmonisation in border values of the thermal action maps for neighbouring countries. However, the collected maps present dissimilar layouts and reveal discontinuities at countries borderlines, mainly in the levels of the minimum shade air temperatures, making it difficult to harmonise the use of EN 1991-1-5 "Thermal actions" in neighbouring areas of different Member States.

Figure 4. Minimum shade air temperature maps adopted by the Member States (Map made with Natural Earth. Free vector and raster map data @ naturalearthdata.com. Data sourced from the JRC Nationally Determined Parameters database. Originally published at Sousa et al., 2019)

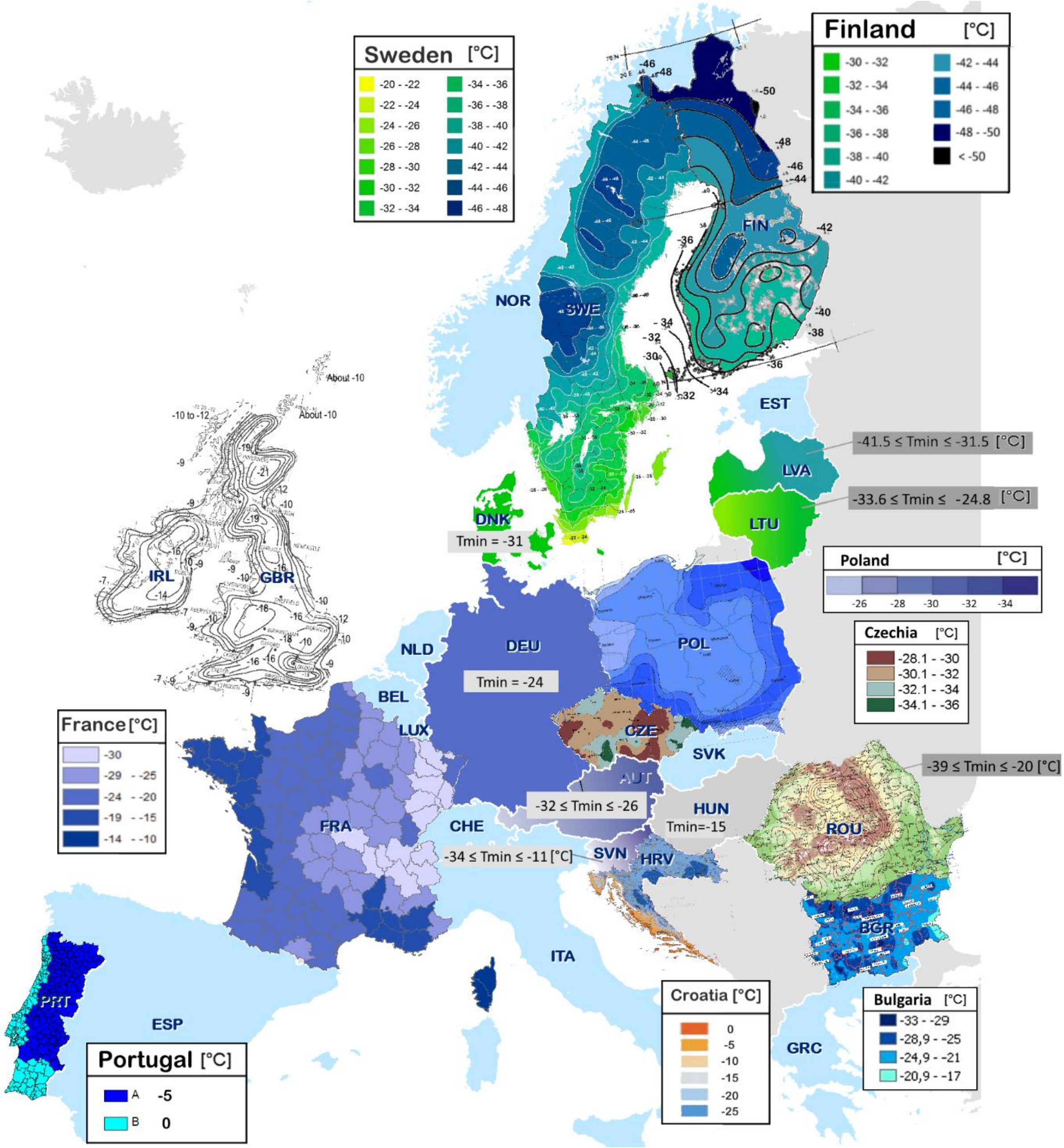
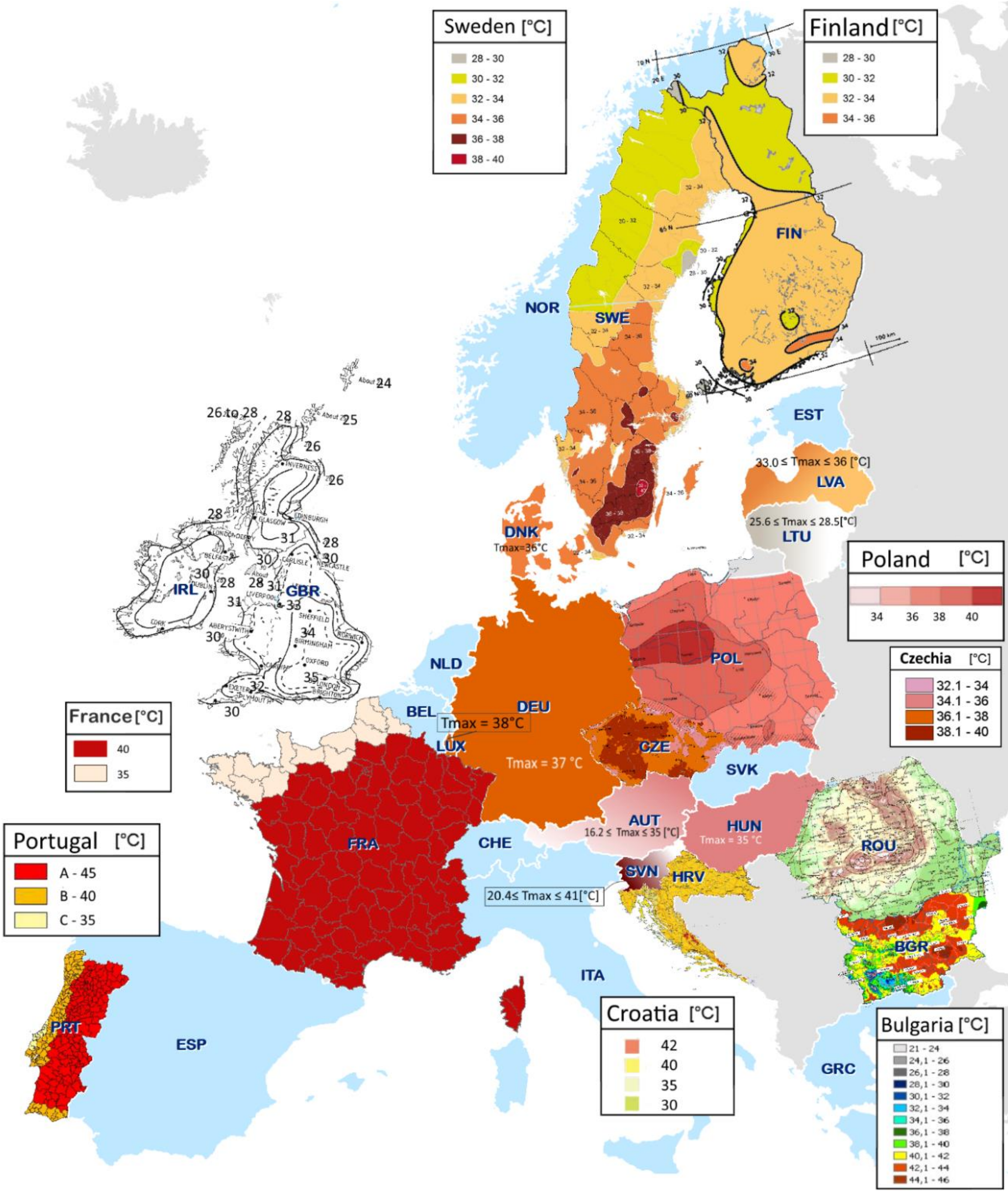


Figure 5. Minimum shade air temperature maps adopted by the Member States (Map made with Natural Earth. Free vector and raster map data @ naturalearthdata.com. Data sourced from the JRC Nationally Determined Parameters database. Originally published at Sousa et al., 2019)



3.4 Conclusions

As stated in Section 2.2 of this report, updated thermal action maps to be used with the Eurocodes and taking into account the changing climate are not expected to be produced by the on-going standardisation works under Mandate M/515 on the Eurocodes. Nevertheless, to proceed with adaptation of structural design to the implications of climate change, the expected changes in the climatic actions (including thermal ones) shall be assessed in terms of the Eurocodes concept for the characteristic values of the variable climatic actions.

The production of European maps for definition of snow, wind and thermal loading taking into account the climate change will help National Competent Authorities to redraft their national annexes in a harmonised way by using the best available knowledge, and will contribute to the reduction of the inconsistencies at border(s) between neighbouring countries. These maps can be published in informative annexes in the respective Eurocodes Parts of the second generation of the Eurocodes, as is currently the case of the European scale snow load map, which is incorporated in Annex C "*European Ground Snow Load Maps*" to EN 1991-1-3.

Moreover, with respect to the final report of the Project Team on SC1.T5 "Climate change" under Mandate M/515, the most relevant conclusions related to thermal actions in line with the work presented in this report, are as follows:

— Models for extreme value calculations of basic variables will need to be updated based on new knowledge on variation of climate parameters, both with respect to traditional input data as well as model data and analysing tools.
— The trends on temperature show increasing values over all Europe, although still not satisfactory quantifiable with respect to standard purposes.
— Bridges and other structures influenced by stresses from extreme temperatures should be designed for temperature amplitudes justified from climate projections for the actual region.
— Estimates of characteristic values of climatic actions should be updated with intervals no longer than ten years.

4 Case study: expected variations in temperatures for Italy due to climate change

4.1 General

This chapter presents the expected variations in temperatures for Italy due to climate change. Italy has been selected as a case study to allow the comparison with the estimations displayed in Chapter 6 that were already underway at the time the work started.

4.2 Methodology

As mentioned in section 3.2, EN 1991 Part 1-5 "General actions - Thermal actions" defines the characteristic values of thermal actions (F_k) on buildings, bridges and other structures as the minimum and maximum shade air temperatures for the site with an annual probability of being exceeded of 0.02, which is equivalent to a mean return period of 50 years. The Eurocodes specify the thermal actions at national level, e.g., from national maps of isotherms, to take into consideration different climatic conditions, as explained in detail in Chapter 3.

For Italy, Froli et al. (1994) carried out a study serving as basis to derive the characteristic values of thermal actions. The authors, using observed data obtained from different sources for a time span between 1951 and 1990, performed a statistical interpretation of the yearly maximum and minimum temperature values. It should be noted that a more recent study (AghaKouchak et al., 2013) found that the expected variations in weather induced by global warming (IPCC, 2013), may entail substantial changes in terms of the mean temperature value, especially on the extreme tails of the temperature probability distribution function.

This chapter presents the expected variations in temperature characteristic values for Italy due to climate change. For this case study, the variations in the characteristic value of T_{max}, T_{min} and diurnal temperature range (i.e. the difference between maximum and minimum daily temperature) are given by the climate simulations of the EURO-CORDEX ensemble (Giorgi & Kutowski, 2016; Kotlarski et al., 2014; Casanueva et al., 2016). EURO-CORDEX[61] is the European branch of the international CORDEX[62] initiative, a program sponsored by the World Climate Research Program (WRCP)[63] aimed to develop an internationally coordinated framework for regional climate change projections for all land regions worldwide.

In the case study discussed in this chapter, that is, the assessment of the regional climate change projections with a higher resolution, downscaling was performed dynamically through Regional Climate Models (RCMs)[64] nested on the Earth System Models (ESMs)[65]

[61]http://www.euro-cordex.net/

[62]CORDEX: Coordinated Regional Climate Downscaling Experiment (https://www.cordex.org/)

[63]https://www.wcrp-climate.org/

[64]A regional climate model (RCM) is a numerical climate simulation model forced by specified lateral and ocean conditions from a general circulation model (GCM) or observation-based dataset (reanalysis) that simulates atmospheric and land surface processes, while accounting for high-resolution topographical data, land-sea contrasts, surface characteristics, and other components of the Earth-system. Since RCMs only cover a limited domain, the values at their boundaries must be specified explicitly, referred to as boundary conditions, by the results from a coarser ESM (or Global Climate Model, GCM) or reanalysis; RCMs are initialized with the initial conditions and driven along its lateral-atmospheric-boundaries and lower-surface boundaries with time-variable conditions. RCMs thus downscale global reanalysis or GCM runs to simulate climate variability with regional refinements (source: American Meteorological Society, Glossary of meteorology).

[65]Earth system model (ESM): A coupled atmosphere–ocean general circulation model (AOGCM) in which a representation of the carbon cycle is included, allowing for interactive calculation of atmospheric carbon dioxide (CO2) or compatible emissions. Additional components (e.g., atmospheric chemistry, ice sheets, dynamic vegetation, nitrogen cycle, but also urban or crop models) may be included. (source: IPCC Glossary)

for the area of interest (Wilby, 2017). To favour the comparison among the findings, the same domain and horizontal resolution were used by all components of the ensemble[66].

In the analysis performed for the case study of Italy, the variations between the reference current period 1971-2000 and the future time span 2056-2085 were considered. The latter selected span is illustrative of the midterm scenario of year 2070, the central point of the interval 2056-2085. The analysis took only into account a future Representative Concentration Pathway (RCP), that is, the RCP8.5. This scenario estimates an increase in the radiative forcing value of about 8.5 W/m^2 at a global scale in the year 2100 with respect to preindustrial era, based on findings of socio-economic approaches. It represents, at the moment, the more pessimistic (i.e. high greenhouse gas emission scenario) but "business as usual" available scenario, proposed by the IPCC.

Moreover, seventeen simulations with a horizontal resolution of 0.11° (about 12 km) were taken into account, see ***Table 1*** below.

Table 1. Summary of climate simulation chains, provided by EURO-CORDEX ensemble at 0.11°, considered in the case study.

Code	Institution	Driving model (ESM)	RCM
1	CLMcom	CNRM-CM5_r1i1p1	CCLM4-8-17_v1
2	CNRM	CNRM-CM5_r1i1p1	Aladin53
3	SMHI	CNRM-CM5_r1i1p1	RCA4_v1
4	KNMI	EC-EARTH	RACMO22E_v1
5	DMI	EC-EARTH	HIRHAM5_v1
6	CLMcom	EC-EARTH	CCLM4-8-17_v1
7	SMHI	EC-EARTH	RCA4_v1
8	IPSL-INERIS	IPSL-CM5A-MR_r1i1p1	WRF331F_v1
9	SMHI	IPSL-CM5A-MR_r1i1p1	RCA4_v1
10	CLMcom	HadGEM2-ES	CCLM4-8-17_v1
11	KNMI	HadGEM2-ES	RACMO22E_v1
12	SMHI	HadGEM2-ES	RCA4_v1
13	CLMcom	MPI-ESM-LR_r1i1p1	CCLM4-8-17_v1
14	MPI-CSC	MPI-ESM-LR_r1i1p1	REMO2009
15	SMHI	MPI-ESM-LR_r1i1p1	RCA4_v1
16	MPI-CSC	MPI-ESM-LR_r1i1p1	REMO2009
17	DMI	NorESM1-M	HIRHAM5

[66] In this case, as ESMs and RCMs vary among the different simulations, it is considered a multi-model ensemble; on the other side, experiments in which the same simulation chain is adopted but varying tuning and physical parameterizations are commonly known as single-model ensemble.

Table 1 presents the institutions that performed the climate simulations and the adopted global Earth System Models (ESM) that provided the boundary and the initial conditions to the Regional Climate Models (RCM) nested on the EURO-CORDEX domain. Details about the specific models are retrievable from EURO-CORDEX.

For each simulation, each year and each grid point, maximum values of the maximum air temperature and minimum values of the minimum air temperature were extracted for the current and future time span. A generalized extreme value (GEV) distribution (Coles, 2001) was fitted to the obtained temperature series. Finally, the differences between the current and future temperature values with a mean return period of 50 years were computed.

4.3 Estimated variations in T_{max} characteristic values

The variations in the characteristic values of T_{max}, between the future and current time span are reported in **Figure *6*** in terms of the ensemble mean of the simulations. ***Figure 7*** and ***Figure 8*** show the lower and higher boundaries of the confidence intervals computed respectively by subtracting or adding the square deviation to the mean value, obtained by considering all available simulations.

In average terms, the analysis shows that an increase in T_{max} can be expected on the entire domain. The mean value of the expected T_{max} variation is 4°C (with a 25th percentile equal to 3.7°C, and a 75th percentile equal to 4.4 °C). The most remarkable variations are estimated in North-West and the Alpine Region (up to 6°C). Such trends confirm that mountain regions could represent areas that are particularly sensitive to climate change.

The findings presented in ***Figure 7*** confirm the generalised expected increase in the T_{max} characteristic values. As expected, the lower boundary of the confidence interval presented lower values than the ensemble mean showed in **Figure *6***; the temperature mean value in ***Figure 7*** is 1.9°C (with a 25th percentile equal to 1.4°C, and a 75th percentile equal to 2.3 C). The temperature increase is quite homogeneous on the entire area; in this case, minor increases were assessed in the Adriatic Coasts and Central Sardinia, while higher growths are shown in the Alpine region and the Central-Meridional Apennine backbone in central Italy.

In contrast, considerably higher values were estimated for the upper boundary of the confidence interval shown in ***Figure 8***; the temperature mean value is equal to 6.3°C (with a 25th percentile equal to 5.8°C, and a 75th percentile equal to 6.7°C); in this case, spatial patterns confirm the tendencies reported in the previous cases.

Moreover, it is interesting to note that in three cases, the interquartile range (IQR)[67], i.e. the difference between the 75th and 25th percentiles, did not exceed the value of 1°C, thus returning a substantial homogeneity on the investigated domain.

The spatial variation of the square deviation, Δ, for T_{max} values in Italy is reported in ***Figure 9.*** It is noted that there is no evident clustering; the values do not exceed 4°C and over areas where larger increases were assessed (***Figure 6***), Δ values are generally lower than 2°C.

[67] The interquartile range, also called the midspread or middle 50%, or technically H-spread, is a measure of statistical dispersion, being equal to the difference between 75th and 25th percentiles

Figure 6. Expected variation in T_{max} characteristic values as provided by the ensemble mean of simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).

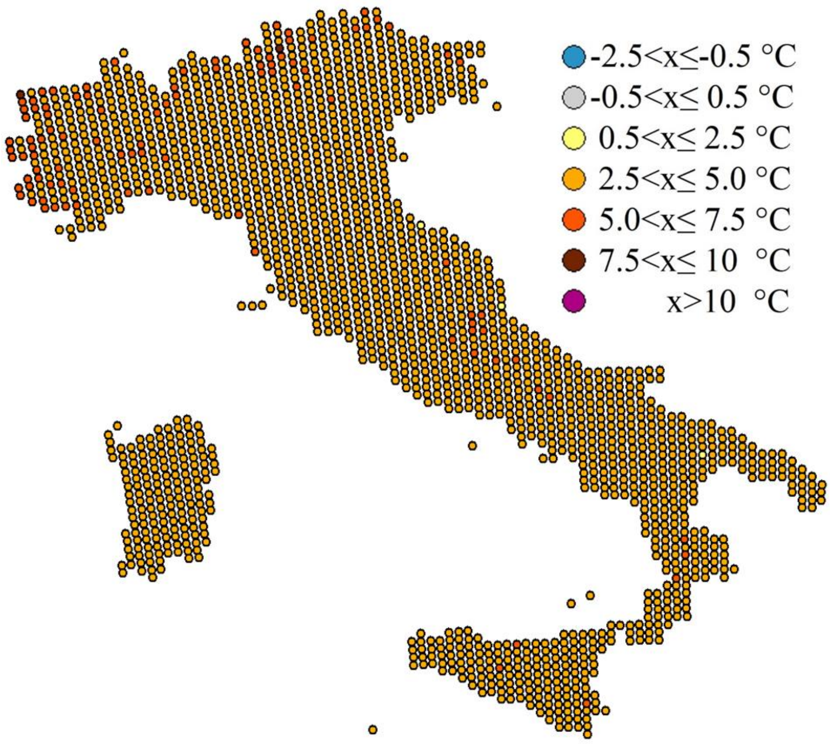


Figure 7. Expected variation in T_{max} characteristic values computed by subtracting the square deviation to the ensemble mean, considering all available simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).

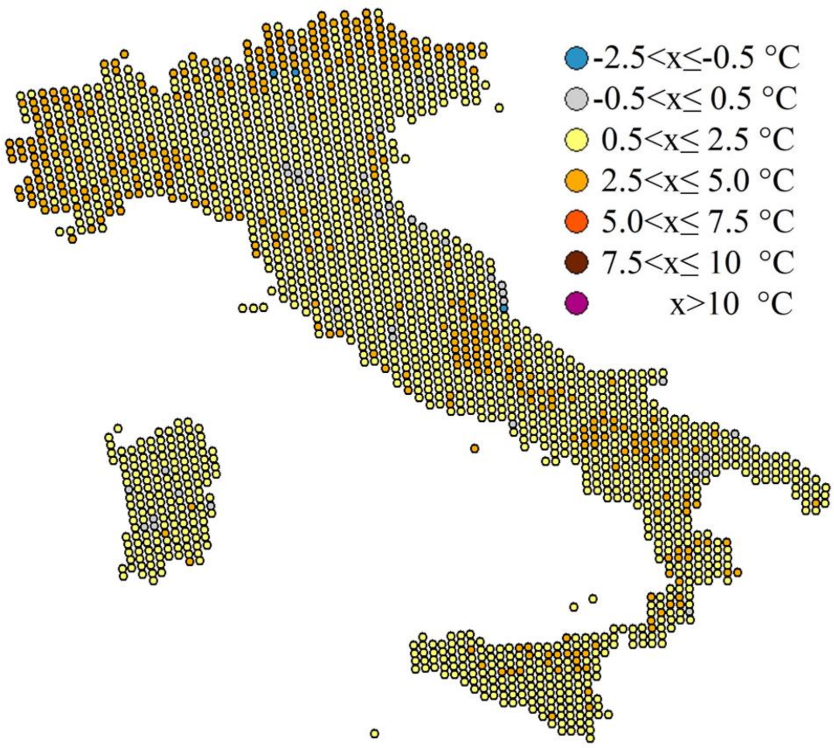


Figure 8. Expected variation in T_{max} characteristic values computed by adding the square deviation to the ensemble mean, considering all available simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).

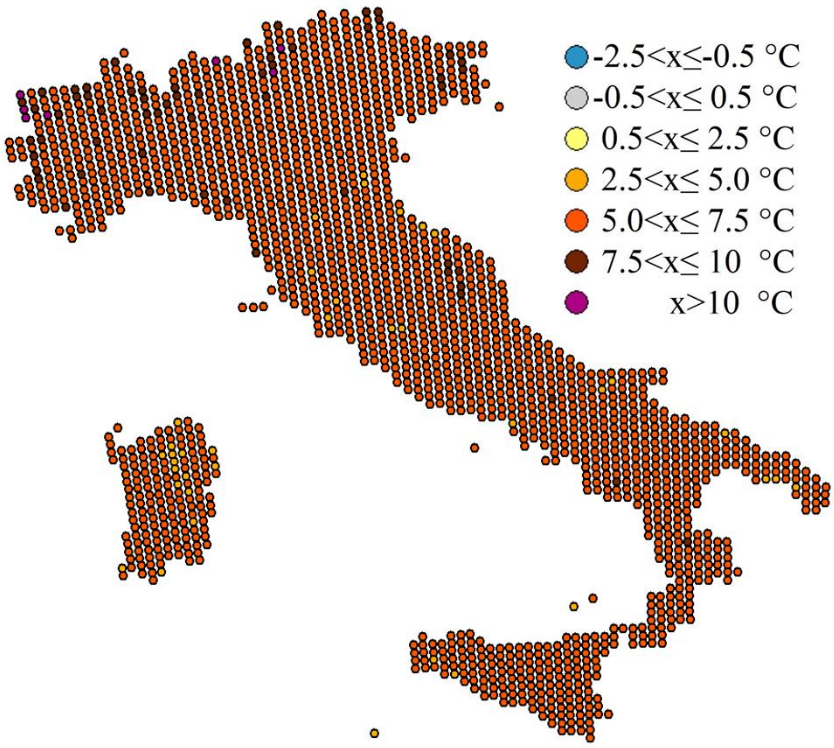
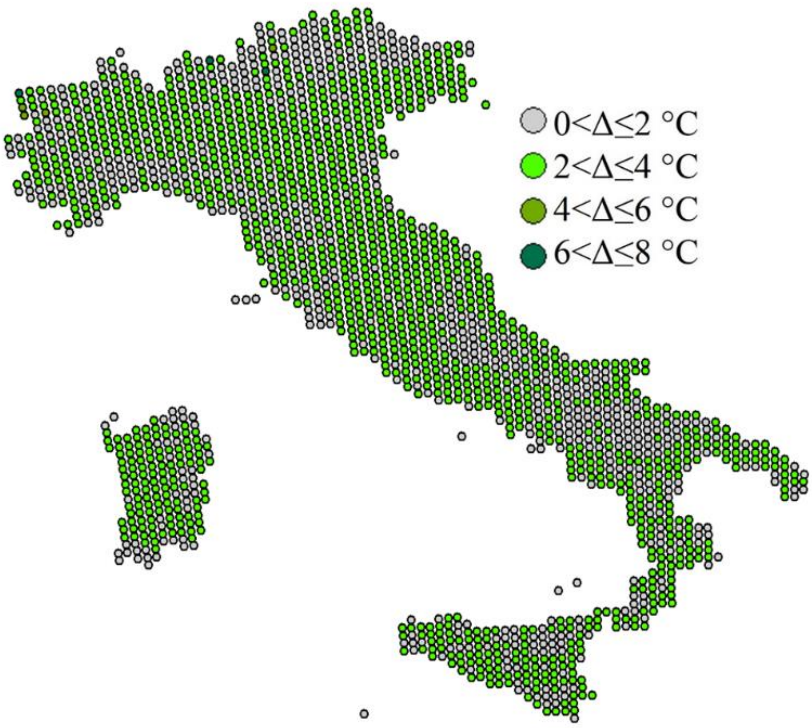


Figure 9. Expected variation in the square deviation Δ for T_{max} values by considering all available simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).

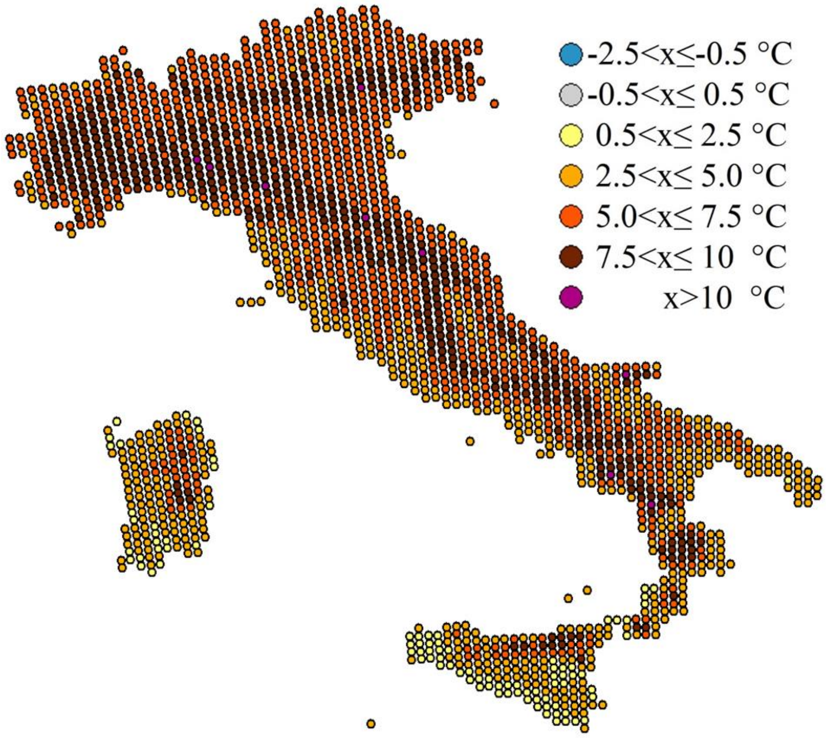


4.4 Estimated variations in T_{min} characteristic values

The corresponding calculations for the characteristic values of T_{min} are presented in ***Figure 10*** to ***Figure 13*** below.

Figure *10* illustrates the expected variation in T_{min} characteristic values as provided by the ensemble mean values, and allows to identify two elements: (i) the expected increase for the characteristic values of T_{min} is substantially higher (with a mean value equal to 6.2°C; a 25th percentile equal to 4.4°C and a 75th percentile equal to 7.5 °C) than the increase of the respective values for T_{max}; and (ii) spatial patterns are evident showing a higher increase in temperature mean values in Alps, Prealps and Apennine mountain chains (up to 10°C).

Figure 10. Expected variation in T_{min} characteristic values as provided by the ensemble mean of simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).



The growth trend in the minimum temperature values is eventually (or could be in the future) more consistent than in the maximum temperature values. This possibility has been widely investigated in the literature (Hartmann et al., 2013) and different explanations have been provided. In this perspective, the possibility that the minimum values are currently, or could be in the future, affected by growth trends is much more consistent than the maximum ones, has been widely investigated in the literature (Hartmann et al., 2013), and different explanations have been provided. Several studies indicate upward trends in the cloud cover (Dai et al., 1997, 1999) as the main element forcing increases in vegetation and soil moisture (Collatz et al., 2000). Urbanization processes and associated urban heat island effects are recognized to play a relevant role in the observation trends while, at the moment, they may hardly be taken into account in global or regional climate modelling (Easterling et al., 1997; Braganza et al., 2004).

Higher increases are also confirmed for the boundaries of the confidence intervals for the minimum temperature: for the lower boundary, the mean value is 2.7 °C (25th percentile equal to 1.7°C and 75th percentile equal to 3.5°C) while for the upper boundary, the mean value could attain, on average, a value equal to 9.5 °C (25th percentile equal to 6.7°C, 75th percentile equal to 11.5°C). Finally, regarding the square deviation, Δ, (see ***Figure 13***) for the characteristic values of minimum temperature, higher values were estimated for areas with high elevation. This is due to the higher disagreement among the climate simulation chains included in the EURO-CORDEX ensemble on areas characterized by complex geomorphological features.

Figure 11. Expected variation in T_{min} characteristic values computed by subtracting the square deviation to the ensemble mean, considering all available simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).

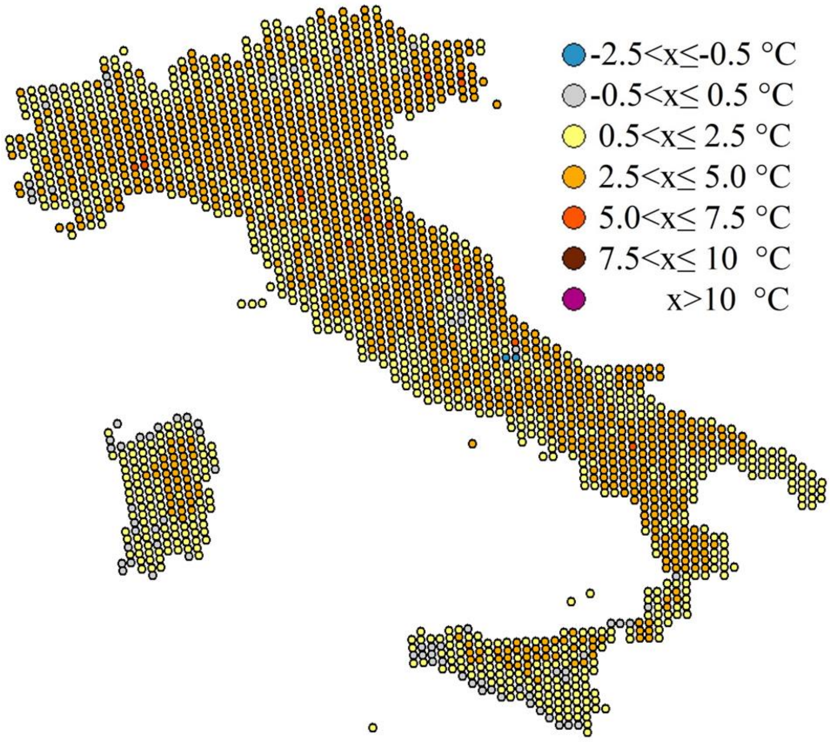


Figure 12. Expected variation in T_{min} characteristic values computed by adding the square deviation to the ensemble mean, considering all available simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).

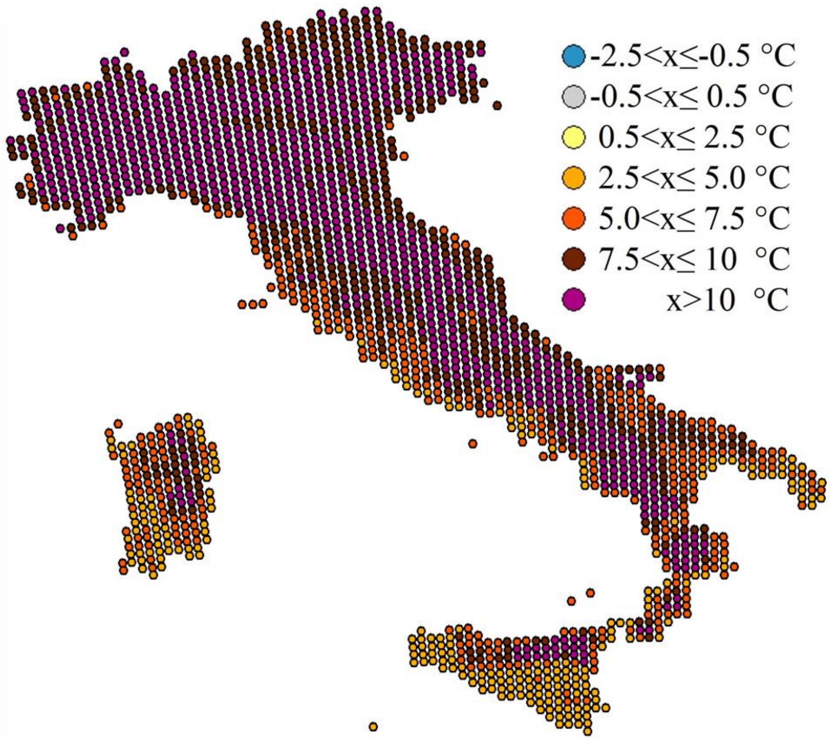
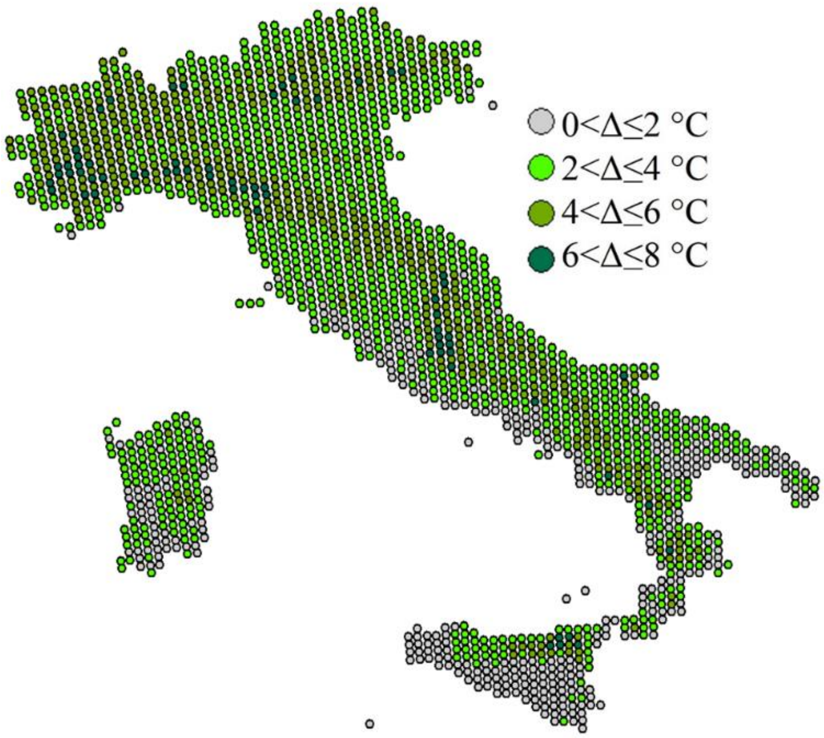


Figure 13. Expected variation in the square deviation Δ for T_{min} values by considering all available simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).



4.5 Estimated variations in Diurnal Temperature Range (DTR) characteristic values

The variation in the characteristic values of the Diurnal Temperature Range (DTR) are reported in ***Figure 14*** to **Figure *16***.

According to the ensemble mean of the simulations (see ***Figure 14***), no significant variations are expected in the characteristic values of DTR; on average, the variation is close to 0°C (-0.1°C) (with a 25th percentile equal to 0.5°C and a 75th percentile equal to 0.2 °C); nevertheless, on the Alpine Region, higher decreases of DTR (up to 5°C) were estimated.

Regarding the lower boundary of the confidence interval, the higher variations can be identified again on high elevation land areas where characteristic values of the DTR may decrease up to 8°C; in this regard, further investigations are required to better understand the mechanisms driving such patterns. On the other hand, the temperature values at the boundary of the confidence interval do not show strong variations compared to the ensemble mean; only in the southern part of the country and at the Sardinia coast, a slight increase in the DTR is assessed with values up to 5°C.

Figure 14. Expected variation in DTR characteristic values as provided by the ensemble mean of simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).

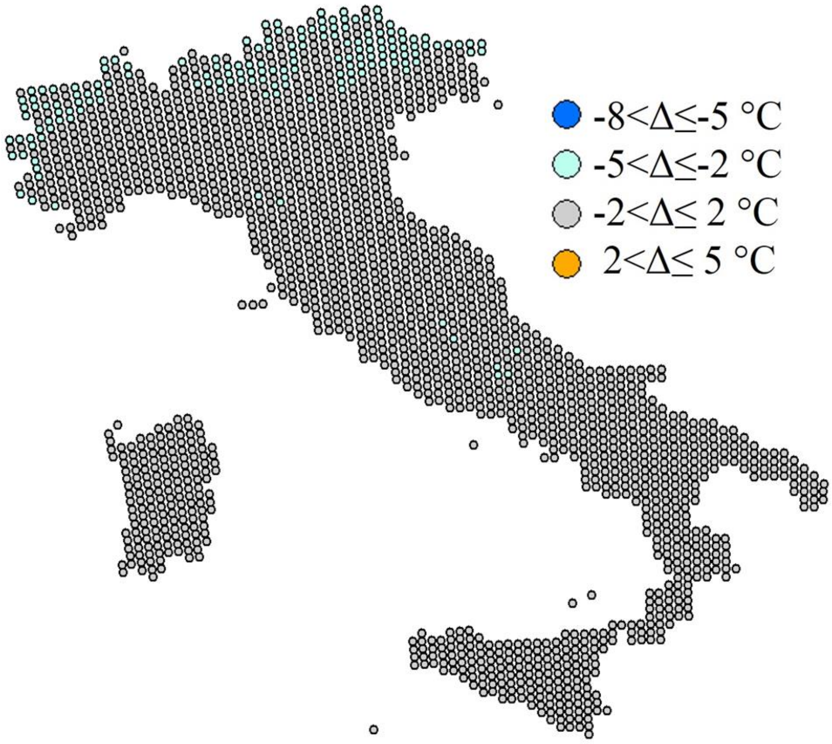


Figure 15. Expected variation in DTR characteristic values computed by subtracting the square deviation to the ensemble mean, considering all available simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).

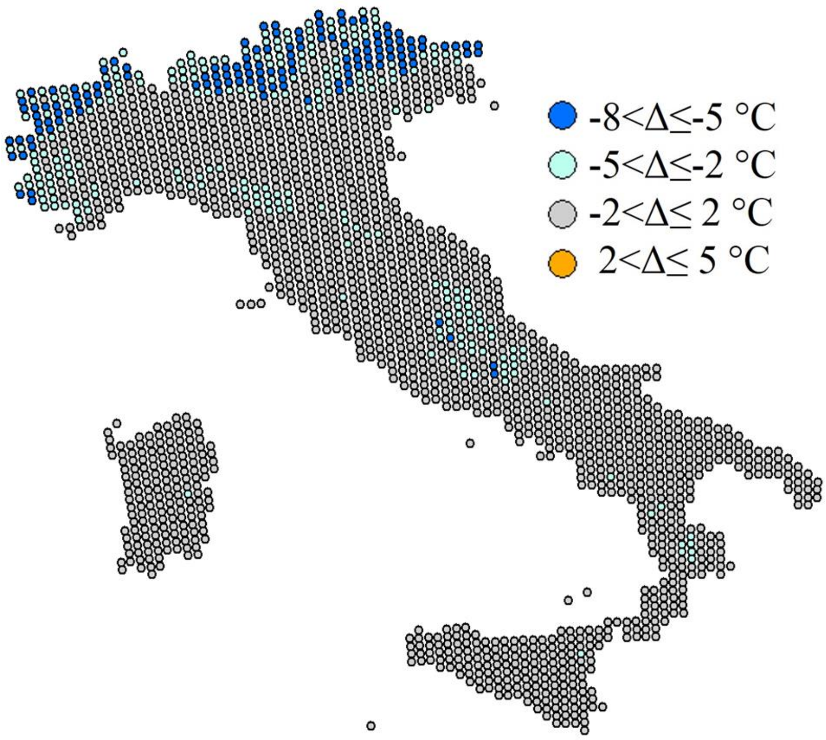
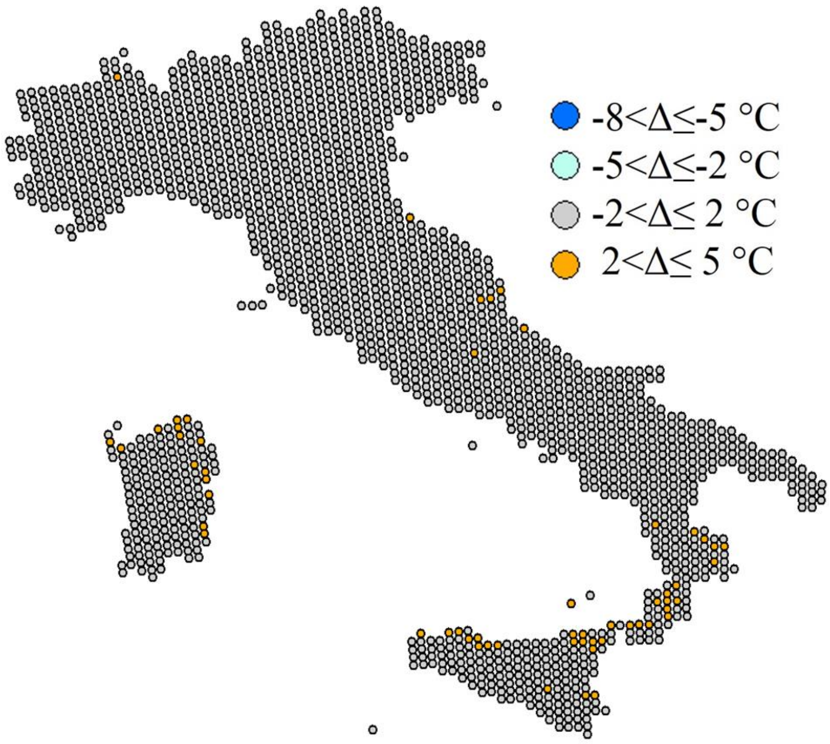


Figure 16. Expected variation in DTR characteristic values computed by adding the square deviation to the ensemble mean, considering all available simulations included in EURO-CORDEX 0.11° datasets (2056-2085 vs 1971-2000, RCP8.5).



4.6 Conclusions

The variations in the characteristic values of T_{max}, T_{min}, and Diurnal Temperature Range, were analysed taking into account a future Representative Concentration Pathway (RCP), RCP8.5 for Italy. The variations between the reference current period 1971-2000 and the future time span 2056-2085 considered illustrative of a midterm scenario 2070) show the following main trends:

— The increase in T_{max} and T_{min} characteristic values is evident throughout Italy.

— In average terms, an increase in T_{max} can be expected on the entire domain. A 4°C mean value is expected (with a 25th percentile equal to 3.7°C and a 75th percentile equal to 4.4°C). In spatial terms, no clear patterns are recognizable. The most remarkable variations are estimated in the North-West and the Alpine Region (up to 6°C). Such trends confirm how mountain regions could represent particularly sensitive areas to climate change.

— The expected increase in the characteristic values of T_{min} exhibits a mean value of 6.2°C (with a 25th percentile equal to 4.4°C and a 75th percentile equal to 7.5°C); spatial patterns are evident with higher increase (up to 10°C) in the Alps, Prealps and Apennine mountain chains.

— According to the ensemble mean, no significant changes are expected in the characteristic values of the Diurnal Temperature Range; on average, the variation is close to 0°C (-0.1°C) (with a 25th percentile equal to -0.5°C, and a 75th percentile equal to 0.2°C).

— The growth trend in the minimum temperature values seems (or could be in the future) more consistent than in the maximum temperature values. This possibility has been widely investigated in the literature (Hartmann et al., 2013) and different explanations have been provided. Several studies indicate upward trends in cloud cover as the main forcing; nevertheless, increases in vegetation and soil moisture, or in urbanization processes and associated urban heat island effects, are recognized as playing a relevant role in the observation trends.

5 Methodology for developing thermal design maps

5.1 General procedure

At present, thermal design maps, like maps for other climatic actions (for example snow maps), are usually developed according to a general procedure based on the following steps:

— Collection of annual extremes for a suitable period (40 or more years) for an appropriate number of weather stations over the considered region.
— Fitting of an extreme value probability distribution to the available data of each weather station, in order to derive the characteristic values of the thermal action with an assigned annual probability of exceedance.
— Identification of proper altitude-action relationship, in order to be able, if necessary, to transpose the characteristic values to the sea level.
— Drawing of isopleths over the considered region to plot the climatic map for a given annual probability of exceedance.

The aforementioned procedure relies on the assumption of a stationary climate; therefore, to take into account the influence of climate change in the development of thermal design maps, information about past climate based on observations should be combined with future climate projections derived from climate models.

When using climate projections, it should be considered that assessed temperature data are affected by uncertainty coming from three different sources (Hawkins & Sutton, 2009):

— Model uncertainty: starting from the same radiative forcing assumption, different climate models give different outcomes.
— Scenario uncertainty: radiative forcing and then climate evolution depends on future emissions of greenhouse gases which cannot be defined a priori.
— Internal variability of the climate system: even in the absence of any radiative forcing of the planet, climate is subject to natural fluctuations, in some cases neutralizing alterations associated with anthropogenic influences.

Moreover, a gap remains between the scale of the Regional Climate Model (RCM) projections and local scale observations even at the highest resolution of the RCMs, which currently is achieving 2 to 5 kilometres.

When assessing future trends in climate extremes, all these aspects should be duly taken into account.

The delta change approach, also known as "factor of change" approach, is the proposed approach to develop thermal design maps taking into account the influence of climate change. The factor of change approach has a long history in climate impact research and aims to bridge the gap between large scale model and local conditions, duly considering the aforesaid sources of uncertainty. Factors of changes can be derived from the analysis of an ensemble of different RCMs runs, according to different concentration scenarios (RCPs), while the internal variability of each climate model can be estimated by implementing suitable weather generators.

Weather generators are currently used as a statistical downscaling technique in climate change impact studies (Fowler et al., 2007) to generate time-series of climatic variables with statistical properties similar to the input ones.

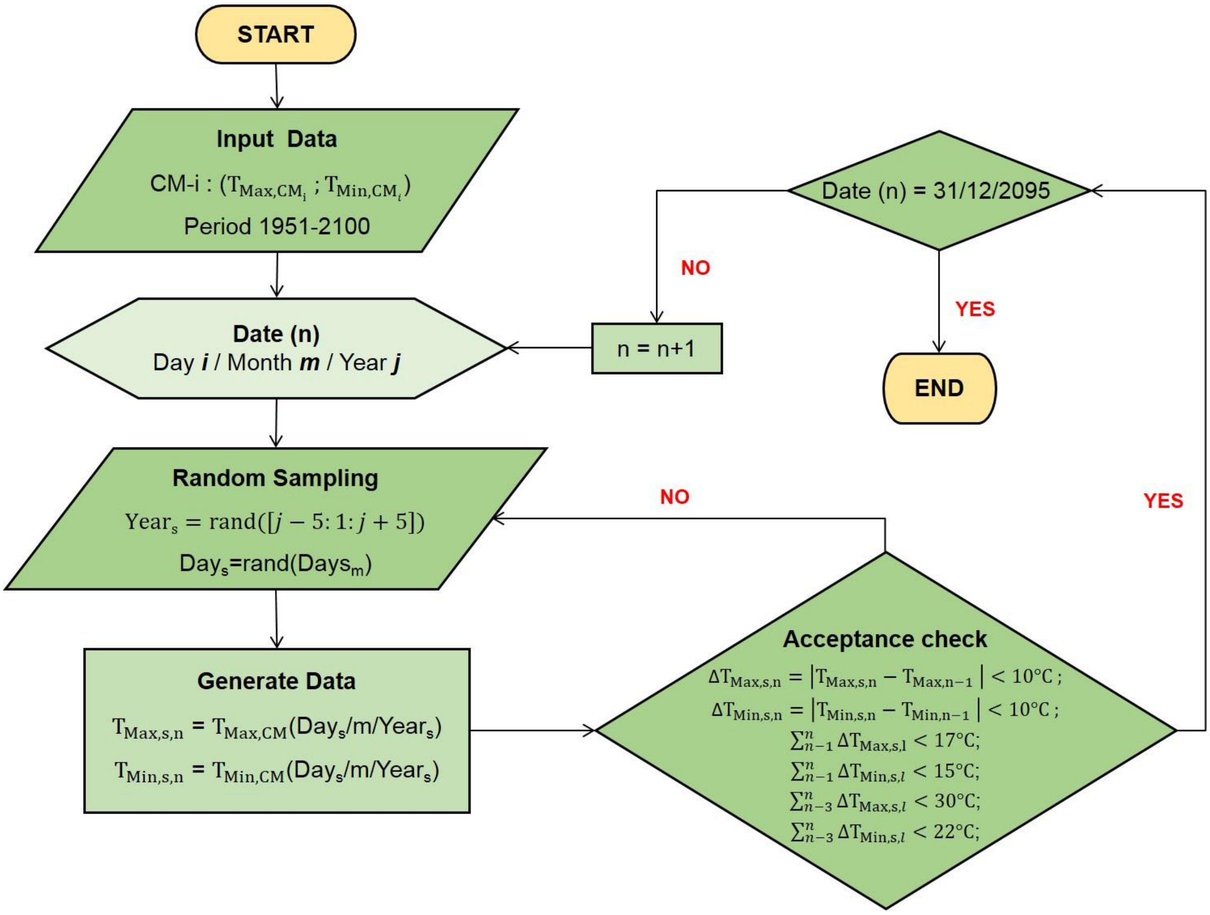
Weather generators are statistical models whose parameters are usually derived through regression analysis of daily climatic variables. In climate change studies, they are usually applied to generate future weather series from the observed climate statistics factored by a factor of change derived from analysing the climate model (CM) output. The basic assumption is that the climate model could better represent the change in the statistical properties of the climate variable, from the present to the future climate, than the absolute values of the variables.

The main steps of the procedure are:

- Collection of high-resolution climate projections for the period 1951-2100 (e.g. from the EURO-CORDEX ensemble) assuming different concentration scenarios (RCPs).
- Generation of weather series from each climate projection data series.
- Extreme value analysis of weather series corresponding to moving time windows of fixed length, in such a way that factors of change can be derived for thermal actions.
- Estimation of the variation of the characteristic value of the temperature, in the considered time interval, applying the suitable factor of change.
- Update of thermal design maps, adopting the maximum or minimum characteristic value of the temperature obtained in each site, in the considered time interval.

Based on climate projections data, future weather series can be generated according to the algorithm presented by Croce et al. (2017a; 2019a; 2019b; 2019c; 2019d), summarized in the flowchart reported in ***Figure 17***.

Figure 17. Flow chart of the weather generator algorithm (adapted from Croce et al. (2019a))



In the new approach presented in Croce et al. (2017a; 2019a), climate data series are directly generated by sampling the climate model outputs, instead of weather series being generated from the statistics of the climate variables. This approach leads to an improvement of the statistical representativeness of the climate model ensemble and, consequently, to a better estimation of the internal variability of climate models and the factors of change.

The input data of the algorithm presented in ***Figure 17*** are the climate series of daily maximum and minimum air temperatures, provided by the considered climate model.

Then, the generated daily data for the Date *n* (*i.e.*, Day *i* in Month *m* in Year *j*) is randomly sampled, (*s*) from the daily data of the climate variables at the same month, *m* in the period defined by the considered year plus and minus five years [*j*-5;*j*+5], and referred as

$T_{Max,s,n}$ *and* $T_{Min,s,n}$, respectively. The idea is to derive a representative sample of the daily data from the model outputs. The basic assumption is that weather parameters in a given day *i* in month *m* belong to a homogenous population composed of daily data predicted by the climate model for the given month *m* in a time window of eleven years, centred on the considered year. A time window of eleven years for the sampling interval is considered a good compromise to obtain a representative sample of daily data. In fact, this time window is relatively long, allowing to derive samples of reasonable size (around 330 elements), but short enough to exclude influences of climate change on the sample population of climate variables.

The random sampling procedure is implemented with some physical constraints, in order to avoid the generation of unrealistic weather data series. In particular, for each Day *i,* the algorithm imposes constraints for maximum and minimum temperatures in two, three and five consecutive days (see ***Figure 17***). In the ***Figure 17***, the summations are extended to all the relevant days considered in the corresponding step of the analysis.

Using these constraints, the methodology proposed by Croce et al. (2017b) generates consistent climate data series of daily maximum and minimum air temperature ($T_{Max,s}$ and $T_{Min,s}$) for the considered period (1956-2095 for the climate model ensemble). For a proper definition of non-stationary extremes, climate data series were analysed considering moving time windows. The considered time windows were 40 years long and two consecutive windows were shifted by 10 years (1956-1995, 1966-2005, 1976-2015,…., 2046-2085,2056-2095).

For each time window, an extreme value analysis was carried out according to the block maxima approach (Coles, 2001) to evaluate characteristic values, having a probability of exceedance of 2% in one year, in accordance to EN1990 concept for characteristic values. Following the procedure by Froli et al. (1994) for the elaboration of the current thermal maps in Italy, an extreme value distribution Type I (Gumbel) was assumed as the limiting distribution for the maxima.

Delta change factors are thus derived as the difference between the characteristic values $T_{Max,k}(t)$ and $T_{Min,k}(t)$ at each time window *t* and the corresponding one at the first time window (*t*=1), $T_{Max,k}(t = 1)$ and $T_{Min,k}(t = 1)$, respectively*:*

$$\Delta T_{Max,k}(t) = T_{Max,k}(t) - T_{Max,k}(t = 1) \quad (5.1)$$

$$\Delta T_{Min,k}(t) = T_{Min,k}(t) - T_{Min,k}(t = 1) \quad (5.2)$$

Subsequently, the expected delta factors of change and uncertainty interval can be computed combining the results obtained for each investigated series.

Finally, trends in characteristic temperature values ($T_{Max,k}(t)$) are computed for the whole region applying the derived delta changes ($\Delta T_{Max,k}(t)$) to the current characteristic values provided by thermal maps, which are based on the analysis of observations ($T_{Max,k,obs}$):

$$T_{Max,k}(t) = T_{Max,k,obs}(t = 1) + \Delta T_{Max,k}(t) \quad (5.3)$$

$$T_{Min,k}(t) = T_{Min,k,obs}(t = 1) + \Delta T_{Min,k}(t) \quad (5.4)$$

For example, in Italy, the characteristic values of T_{Max} and T_{Min} obtained by Froli et al. (1994) from the analysis of observations collected in the period 1951-1990 and reported in the thermal maps given in the Italian National Annex to EN1991-1-5 can be updated according to the estimated delta changes. Some relevant examples are reported in the next sub-section.

In this way, at each time window *t*, an updated value for the characteristic maximum and minimum temperature will be available.

5.2 Selected results for Italy

The general procedure described in the previous paragraph has been applied to an ensemble of daily climate projections of maximum and minimum temperatures (T_{Max} and T_{Min}) developed within the EURO-CORDEX initiative for the control period 1951-2005 (*Historical Experiment*) and for the future period 2006-2100 (RCP4.5 and RCP8.5 *Experiment*).

Table 2 reports the model specifications of the considered climate projections. The three columns report the institution carrying out the simulation, the adopted Earth System Model and the Regional Climate Model exploited for dynamical downscaling. The simulations were carried out with a horizontal resolution of 0.11° (about 12 km).

Table 2 . Summary of climate simulation chains provided by EURO-CORDEX ensemble, codes refer to Table 1 in Chapter 4.

Code	Institution	Driving model (ESM)	RCM
5	DMI	EC-EARTH	HIRHAM5_v1
18	CLMcom	CNRM-CM5_LR	CCLM4-8-17
6	CLMcom	EC-EARTH	CCLM4-8-17_v1
4	KNMI	EC-EARTH	RACMO22E_v1
14	MPI-CSC	MPI-ESM-LR_r1i1p1	REMO2009
8	IPSL-INERIS	IPSL-CM5A-MR_r1i1p1	WRF331F_v1

Future trends of T_{Max} and T_{Min} for a region in Italy have been assessed. The region studied is illustrated in ***Figure 18***, derived from Croce et al. (2019a, b and c). The region studied includes the Zones 3-4 of the Mediterranean climatic region in EN 1991-1-3 "Eurocode 1 - Actions on structures - Part 1-3: General actions -Snow loads" (as illustrated in Figure C.6 in EN 1991-1-3). ***Figure 18*** also presents the 272 cells of the EUR-11 grid (12.5 km x 12.5 km resolution) for which the climate projections were provided.

Implementing the procedure described in the previous section, delta changes and prediction intervals are derived for each cell in the investigated region. ***Figure 19*** shows an example of the evolution of the delta changes in $T_{\mathrm{Max,k}}$ for cell number 120 together with the prediction interval corresponding to the 25% and 75% percentiles. The intermediate emission scenario (RCP4.5), in blue, and the highest emission scenario (RCP8.5), in green, were considered.

The results obtained in terms of delta factors of change for characteristic values of maximum and minimum air temperatures at each cell in the studied region are then summarized in ***Figure 20*** to ***Figure 23*** using bivariate colour maps (Teuling et al., 2011). In this way, two limit percentiles (25% and 75%) of the prediction interval are drawn for each cell of the maps obtaining a convenient representation of the evolution of extreme temperatures together with their uncertainty intervals.

In particular, uncertainty maps of the delta factor of change for the maximum temperature ($T_{\mathrm{Max,k}}$) considering RCP4.5 and RCP8.5 scenarios for time windows 1976-2015, 1996-2035, 2016-2055 and 2036-2075, are reported in ***Figure 20*** and ***Figure 21***, respectively. Similar maps regarding the uncertainty on the delta factor of change for the characteristic minimum temperature ($T_{Min,k}$) are shown in ***Figure 22*** and ***Figure 23***.

Figure 18. Investigated region in the Italian Mediterranean climatic area (adapted from Croce et al., 2019)

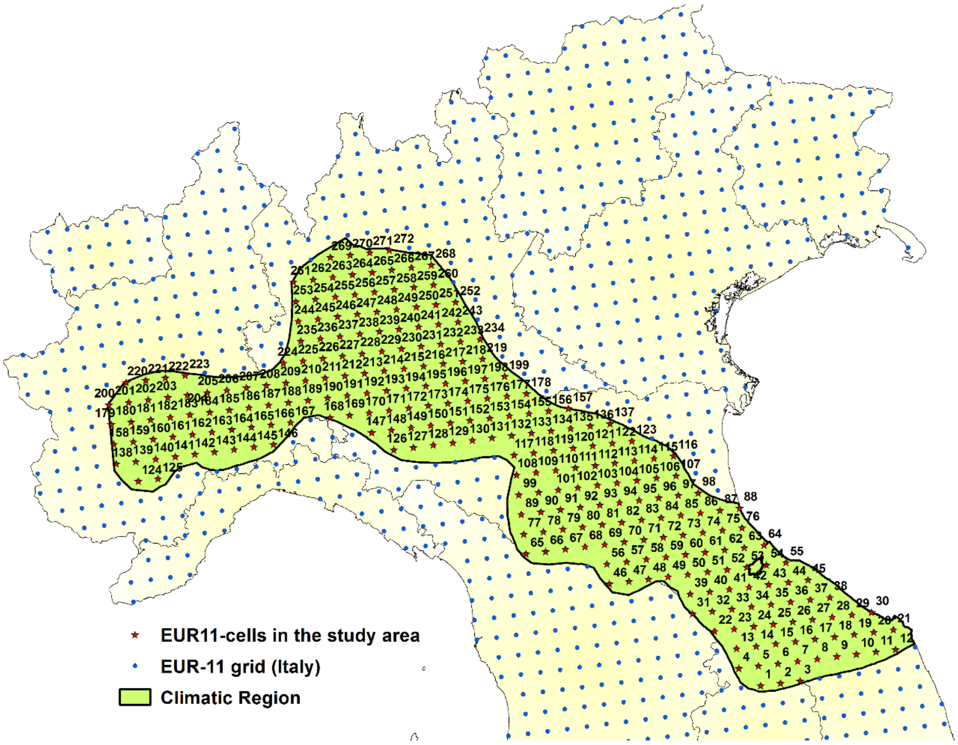


Figure 19. Median values of factor of change $\Delta T_{Max,k}(t)$ for an investigated cell according the RCP4.5 (in blue) and RCP8.5 (in green) scenarios together with the prediction interval [25%-75%].

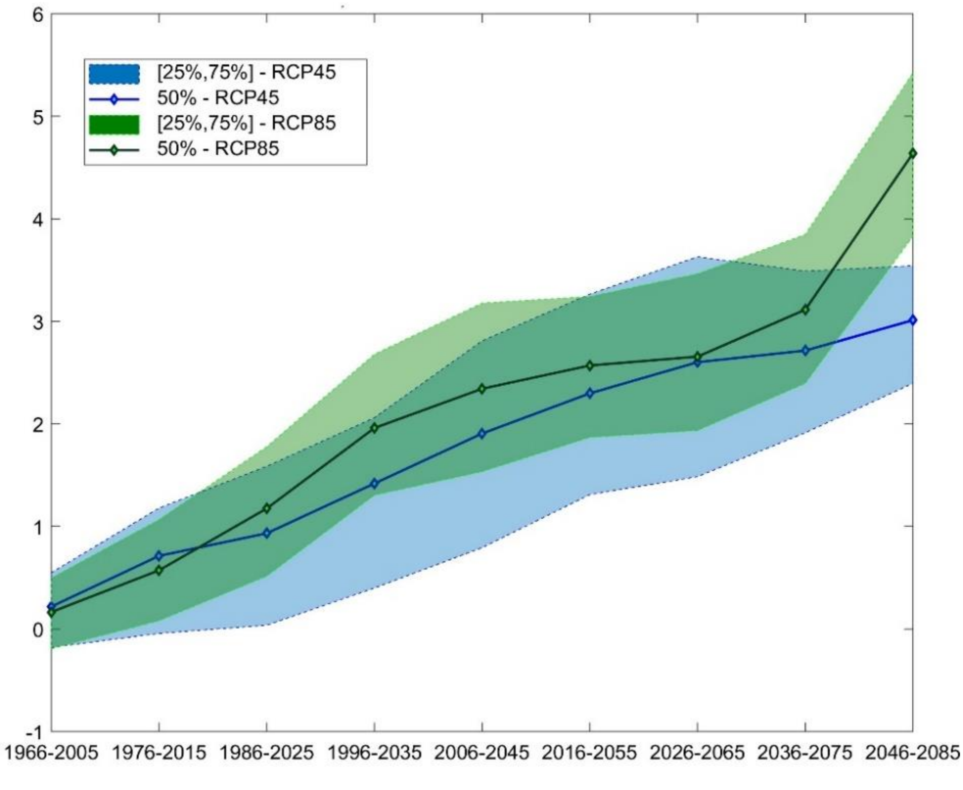


Figure 20. Delta changes [°C] uncertainty maps for $T_{Max,k}$ with respect to 1956-1995 – Prediction interval [25%-75%] map (RCP4.5).

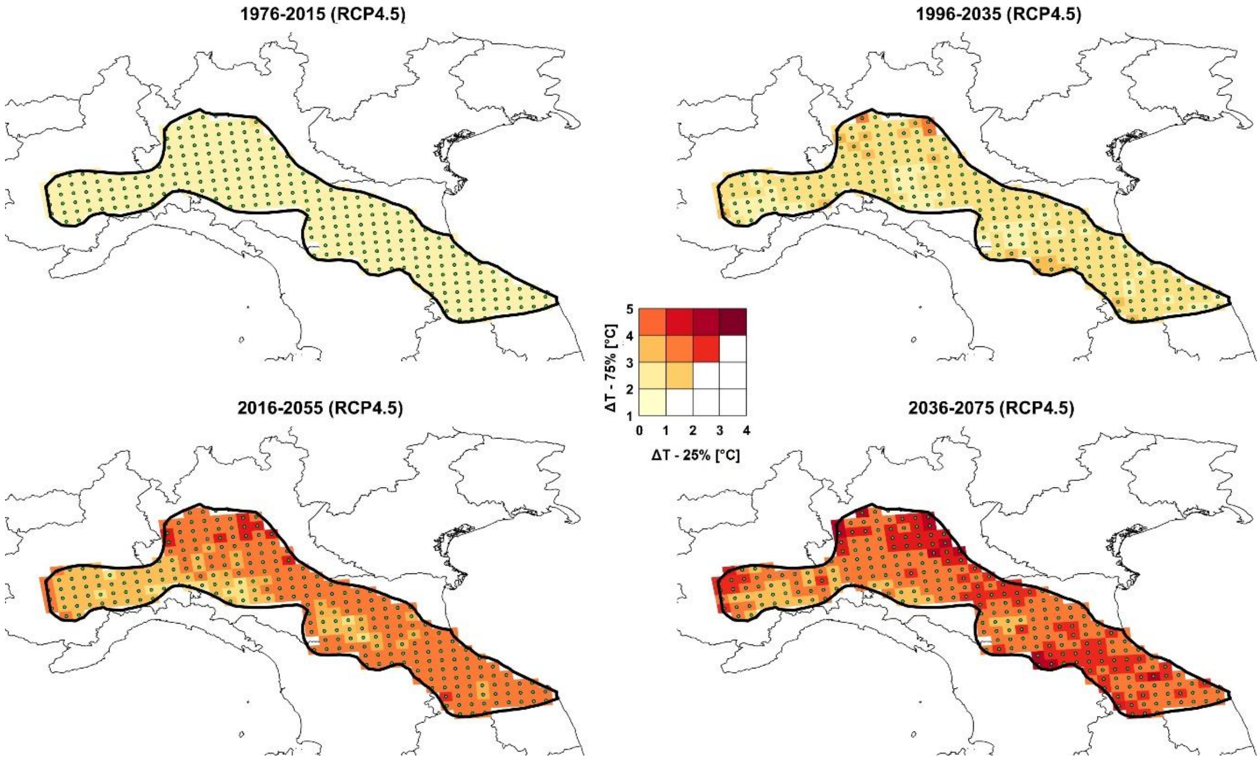


Figure 21. Delta changes [°C] uncertainty maps for $T_{Max,k}$ with respect to 1956-1995 – Prediction interval [25%-75%] map (RCP8.5).

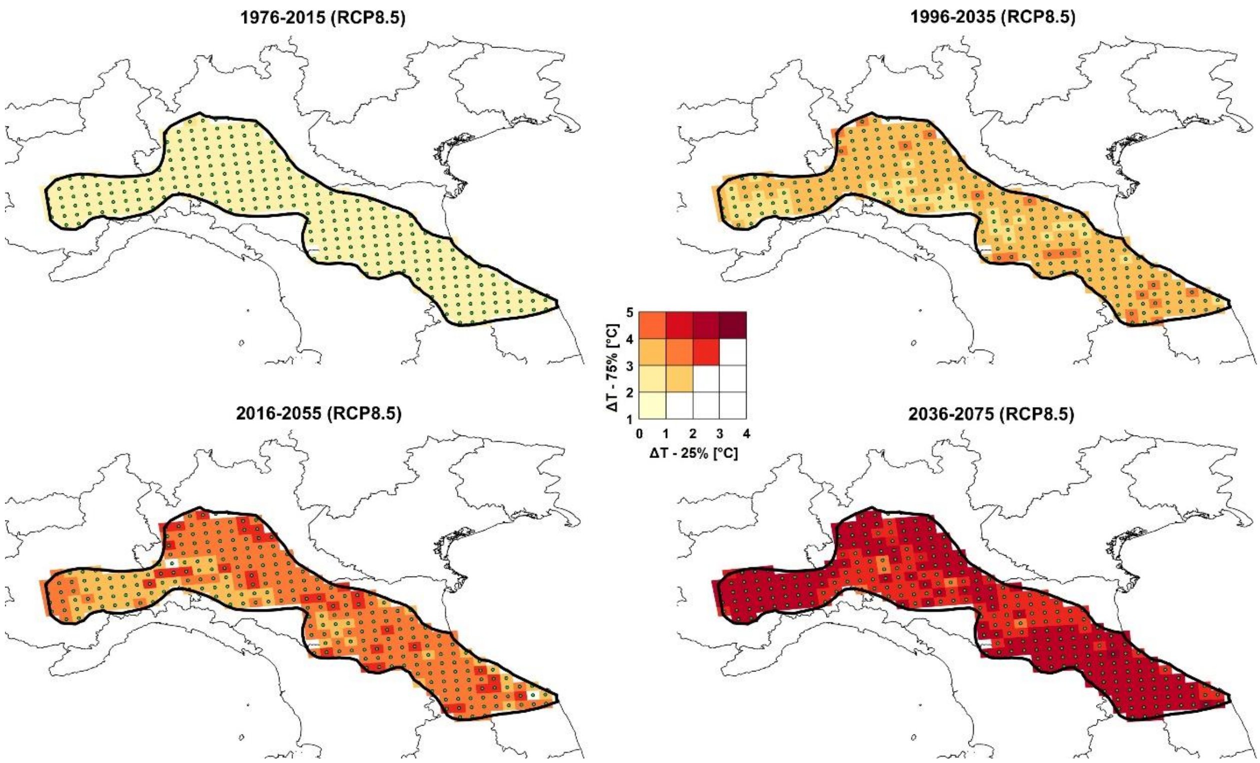


Figure 22. Delta changes [°C] uncertainty maps for $T_{Min,k}$ with respect to 1956-1995 – Prediction interval [25%-75%] map (RCP4.5).

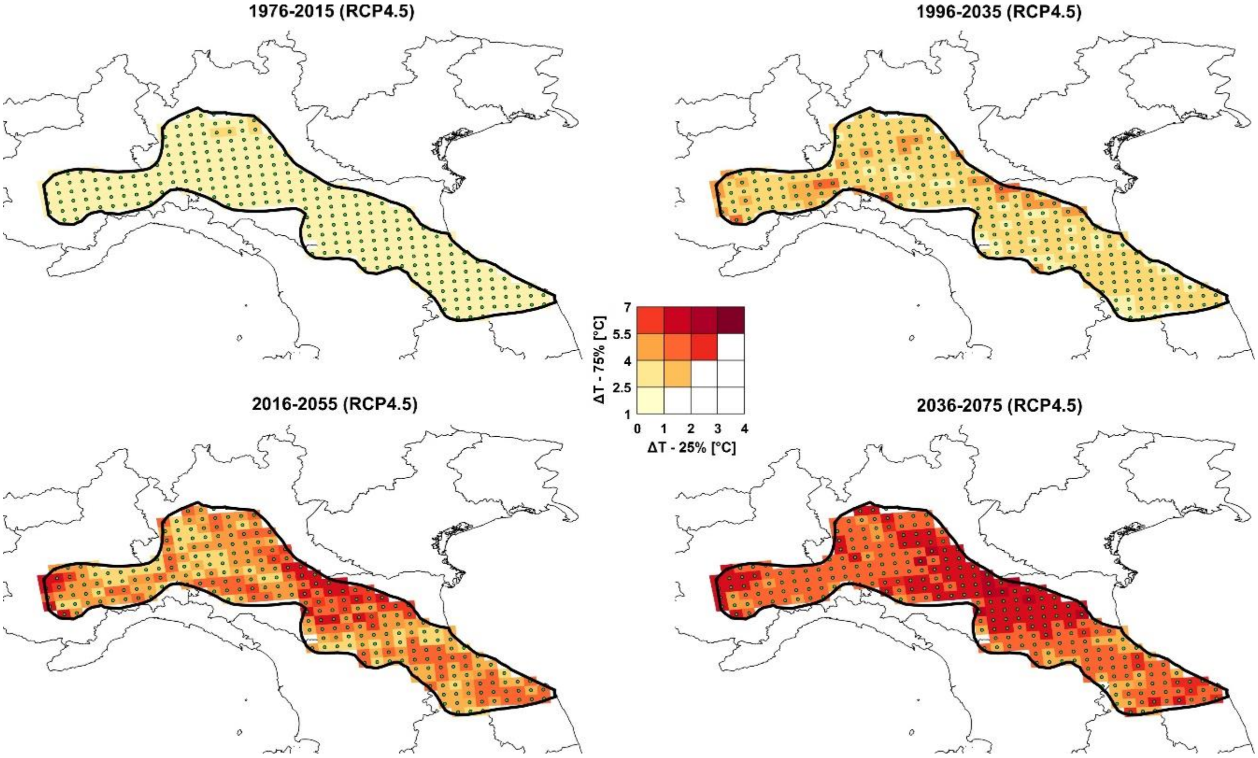
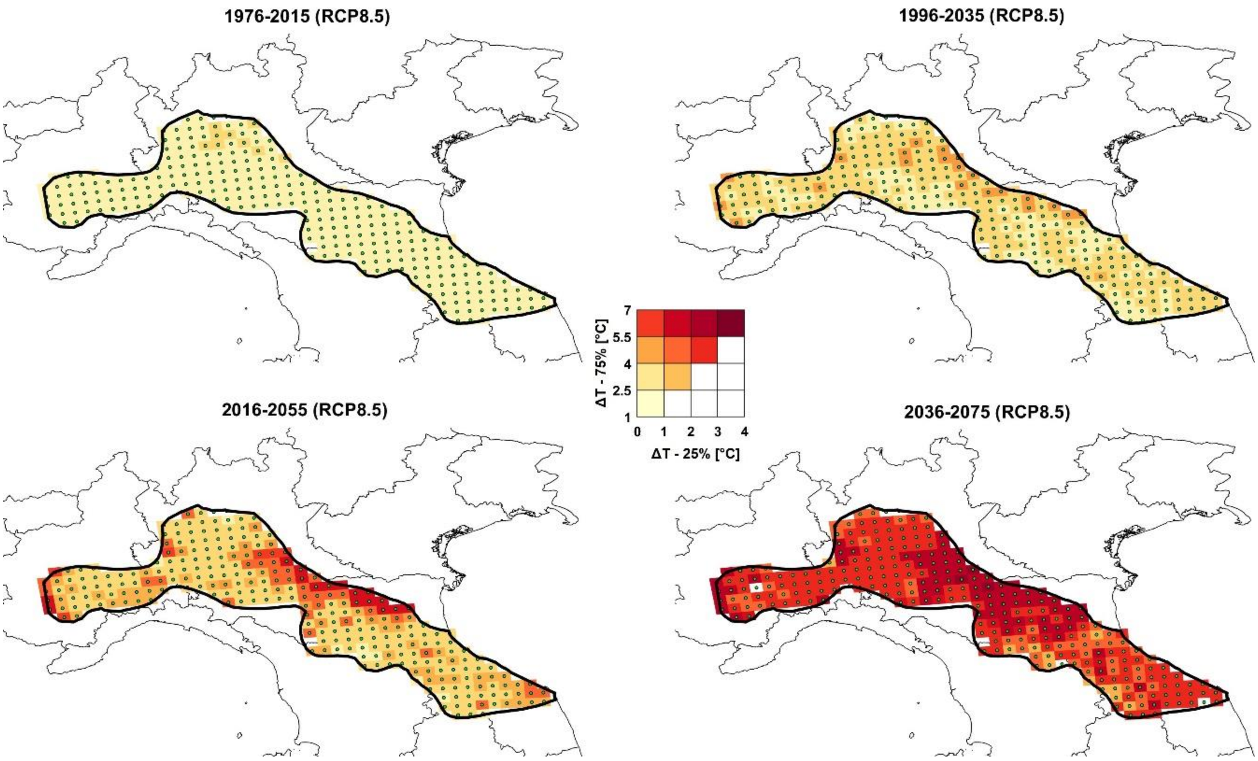


Figure 23. Delta changes [°C] uncertainty maps for $T_{Min,k}$ with respect to 1956-1995 – Prediction interval [25%-75%] map (RCP8.5).



Finally, ***Table 3*** and ***Table 4*** present the average values of factors of change percentiles (25%, 50%, 75%), obtained according to the two different scenarios for the region with reference to the first-time window 1956-1995, for the maximum and minimum temperature, respectively.

Table 3. Average of delta change for $T_{Max,k}$ [°C] for percentiles 25%, 50% and 75% in the considered region.

Time window	**RCP 4.5**			**RCP8.5**		
	25%	*50%*	*75%*	*25%*	*50%*	*75%*
1966-2005	0.04	**0.41**	0.82	0.03	**0.36**	0.72
1976-2015	0.31	**0.87**	1.42	0.35	**0.88**	1.42
1986-2025	0.45	**1.16**	1.87	0.81	**1.43**	2.06
1996-2035	0.65	**1.49**	2.25	1.26	**1.93**	2.67
2006-2045	0.89	**2.01**	3.10	1.44	**2.19**	2.85
2016-2055	1.33	**2.33**	3.31	1.77	**2.51**	3.19
2026-2065	1.58	**2.63**	3.63	2.00	**2.76**	3.54
2036-2075	1.87	**2.75**	3.55	2.47	**3.37**	4.17
2046-2085	2.18	**2.83**	3.67	3.93	**5.10**	6.08

Table 4. Average of delta changes for $T_{Min,k}$ [°C] for percentiles 25%, 50% and 75% in the studied region.

Time window	**RCP 4.5**			**RCP8.5**		
	25%	*50%*	*75%*	*25%*	*50%*	*75%*
1966-2005	-0.30	**0.14**	0.73	-0.28	**0.15**	0.73
1976-2015	-0.23	**0.56**	1.60	-0.16	**0.63**	1.66
1986-2025	-0.12	**0.98**	2.48	-0.29	**0.84**	2.44
1996-2035	0.31	**1.57**	3.16	-0.08	**1.23**	2.92
2006-2045	0.65	**2.01**	3.89	0.24	**1.63**	3.39
2016-2055	1.01	**2.59**	4.52	0.83	**2.13**	3.67
2026-2065	1.48	**3.03**	4.87	1.55	**2.75**	4.19
2036-2075	1.59	**3.18**	5.22	2.29	**3.52**	5.23
2046-2085	2.40	**3.81**	6.02	2.83	**4.42**	8.55

The results confirm that an increase in extreme temperatures will be significant in the near future with a high confidence level. For example, considering the time window 2036-2075, an increase is expected for $T_{Max,k}$ in the region, reaching a value of 2.75°C for RCP4.5 (with a 50% prediction interval between 1.87°C and 3.55°C) and 3.37°C for RCP8.5 (with a 50% prediction interval between 2.47°C and 4.17°C) . In the same time window, even an higher increase is expected for $T_{Min,k}$ reaching a value of 3.18°C for RCP4.5 (with a prediction interval between 1.59°C and 5.22°C) and 3.52°C for RCP8.5 (with a prediction interval between 2.29°C and 5.23°C).

Comparing the obtained results with those provided in Chapter 4, it is clear that an increase for characteristic values of maximum and minimum temperatures is expected. However, under the fixed concentration scenario RCP8.5, the magnitude of such increases results slightly different. For maximum temperatures, the expected increase in values with 50-year return period is about 4°C while, exploiting statistical downscaling, it attains 5 °C. The last value is largely included in the prediction interval assessed considering all the climate projections available in EURO-CORDEX ensemble (at 2018).

On the other hand, as stressed in Chapter 4, the increase in the characteristic value for minimum temperature exceeds 6°C on the pilot area identified in Section 5.2, while using statistical downscaling, the increase stands at about 5°C. Also, in this case, such value is included in the prediction interval outlined by considering a larger set of climate projections (see **Figure *6*** to **Figure *9***). The discrepancies can be motivated by the differences in the used control period, 1971-2000 in Chapter 4 and 1956-1995 in Chapter 5, or the 30-years-long period taken into account in the first case and the 40-years-long in the second. Finally, in Chapter 5, the simulation chain coupling dynamical and statistical downscaling is carried out on a subset of climate projections used in Chapter 4. The inter-variability could be reduced and the obtained values could vary when considering a larger number of projections.

5.3 Recommendation for producing national thermal design maps

This chapter described the classical procedure to derive temperature design maps and a general procedure to consider the influence of climate change on the characteristic values of maximum and minimum temperatures, taking into account different sources of uncertainty in climate projections. A case study including an Italian region was carried out to illustrate the application of the procedure.

Maps of delta factors of change represent the starting point for the amendments of thermal maps in structural codes, taking a changing climate into consideration. It should be noted that the proposed procedure is susceptible to wider applications.

Since structures shall withstand climatic actions during their whole real life, which can be significantly greater than the design service life, the procedure for deriving the maps for thermal design from existing data needs further refinement to ensure the achievement of an adequate reliability level.

In brief, the characteristic values of the maximum and minimum temperature at each site should be evaluated enveloping the factors of change obtained for a given time interval t, as follow:

$$T_{Max,k} = T_{Max,k,obs} + \max\,(\Delta T_{Max,k}(t)) \quad (5.5)$$

$$T_{Min,k} = T_{Min,k,obs} + \min\,(\Delta T_{Min,k}(t)) \quad (5.6)$$

In this case, the updated thermal maps are obtained considering the maximum change for $\Delta T_{Max,k}$ in the investigated period and the minimum change for $\Delta T_{Min,k}$ and the isopleths over the region should be derived accordingly. It must be highlighted that in Eq. 5.6 the reference is obviously the minimum delta change, because in this way it is maximized the difference between $T_{Max,k}$ and $T_{Min,k}$.

6 Potential implications of changes in thermal actions on structural design

6.1 Preliminary note

Most of the material presented in this chapter incorporates relevant parts of the report "Climate change. Final report" by Fikke et al. (2017), prepared by the CEN/TC250 Project Team SC1.T5 working on the second generation of the Eurocodes. The author of the current chapter is also a co-author of the report by Fikke et al. (2017).

6.2 Background

An important task in the further development of the Eurocodes is to evaluate the potential impact of climate change on construction works, in particular on bridges and other structures with longer design life. It is important to analyse how the anticipated changes in the European climate could affect the assessment of the extremes and the design weather parameters, including the consideration of partial safety factors, based on knowledge gained from the projection models of the future climate in Europe.

In the framework of the activities of the Project Team SC1.T5 "Climate Change", Fikke et al. (2017) pointed out the biggest contributors to the inherent uncertainty in the estimation of climate projections. Some of these contributors are listed in the following:

- Uncertainties connected to the future emissions of greenhouse gases and other resources.
- Variations in climate due to solar activity and other natural contributors like volcanic forcing.
- Some essential properties of the climate models themselves, their spatial and temporal characteristics.

These uncertainties make it rather difficult to provide full set of recommendations concerning design parameters for actions on structures regarding climate change on a regional scale. However, the members of the Project Team SC1.T5 "Climate Change" also concluded that it is possible to indicate certain trends of selected basic variables, which influence the models of climatic actions on structures, environmental actions and the intensity of degradation of materials, e.g., the carbonation of concrete, steel corrosion, decay of wood.

6.3 Trends in temperature developments

6.3.1 Technical and research reports

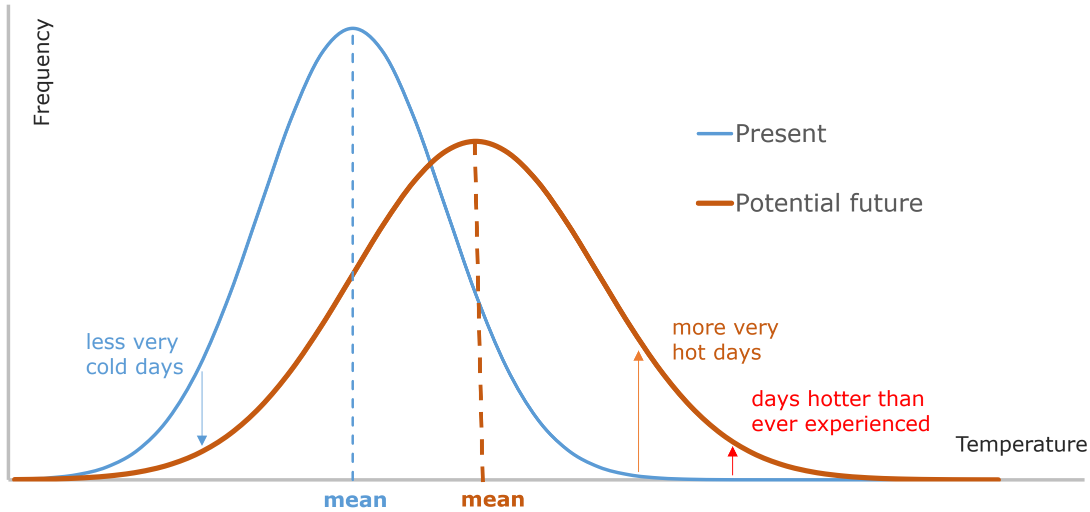
Several technical and research reports have been developed focused on prediction of future regional climate change, for instance, the IPCC Fifth Assessment Report (IPCC, 2014) revealed a high confidence in model projections of mean temperature within Europe stating that it is very likely that temperatures will continue to increase throughout the 21st century all over Europe and the Mediterranean region. The EASAC report[68] (Hov et al., 2013) examined trends in extreme weather events in Europe and implications for national and European Union adaptation strategies. The report highlights that most severe risks posed by climate change do not stem from changes in the mean of climate variables such as temperature, but rather from changes in the extremes of these variables.

Figure 24 illustrates the expected variations on average temperature distribution, showing how global warming can induce a shift in the distribution, but also a change in its shape.

[68] Report "*Extreme Events in Europe: preparing for climate change adaptation*" issued by the Norwegian Meteorological Institute and the Norwegian Academy of Sciences and Letters, in collaboration with the European Academies Science Advisory Council (EASAC)

The blue curve indicating the probability density in the figure represents the present situation that will be shifted to the orange curve in the future (Hov et al., 2013). A more flattened distribution with a higher average temperature indicates a higher variability and an increase of the frequency of "extreme" events, i.e., more very hot days. It is, thus, shown that the increase in the mean temperature will result in an increase of the frequency of hot days, and days hotter than ever are also likely to occur. The figure also indicates that there will be fewer days with the current average temperature and less very cold days relatively to today's distribution.

Figure 24. Possible changes in the mean value and variance in future temperatures, due to changes in the temperature probability density function (PDF) (adapted from: CH2011, Hov et al., 2013; Fikke et al., 2017)



According to Fikke et al. (2017) the winter mean temperature will rise more in Northern Europe than in Central Europe or Mediterranean, whereas summer warming will likely be less intense in Northern Europe. The trends in temperature were summarized as follows:

- Observations show a trend to fewer cold days over most parts of Europe since the mid-20th century.
- Increase frequency of hot days and heat waves.
- Most places in Europe will very likely experience more hot and fewer cold extremes as global temperature increases.
- The magnitude of hot extremes is expected to increase faster and more severely than mean temperatures over large parts of Europe.

6.3.2 Trends in temperature developments in the Czech Republic

The trends of average temperatures based on the measurements carried out by the oldest Czech meteorological station Klementinum in Prague in the past three 50-year periods is illustrated in ***Figure 25***. However, in this case, large scale variations potentially associated to global warming could be exacerbated by Urban Heat Island[69] dynamics induced by urbanization processes.

The increase of the mean shade air temperature in various regions in the Czech Republic in the year 2030 as assessed by the Czech Hydro-meteorological Institute (CHMI) is illustrated in ***Figure 26***. The projected near-term change in global mean surface air temperature will likely be in the range from 0.3 to 0.7°C (medium confidence). This projection assumes there will be no major volcanic eruptions or significant changes in total solar irradiance before 2035. It is expected that for the period 2016–2035, the global mean surface air temperature will increase not more than 1°C relative to 2016. In most land

[69] An urban heat island (UHI) is an urban area or metropolitan area that is significantly warmer than its surrounding rural areas due to human activities.

regions, the frequency of warm days and warm nights will likely increase in the next decades, while the number of cold days and cold nights will decrease. Also, in this case, increasing urban heat island phenomena, usually not explicitly taken into account in climate modelling, could be overlapped by local climate changes, thus enforcing the increases.

Figure 25. The trends of average temperatures based on the measurements in the meteorological station Klementinum in Prague (since 1861) (Figure from Climate change in CZ [Změna klimatu v ČR), ČHMÚ / CC BY-NC-ND 3.0 CZ])

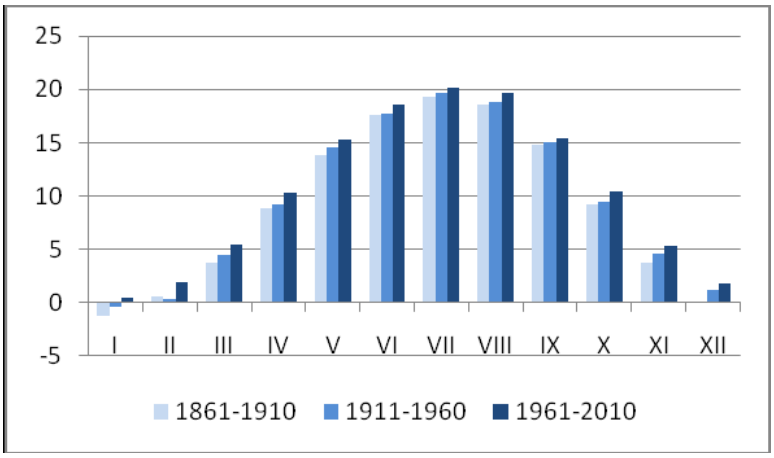
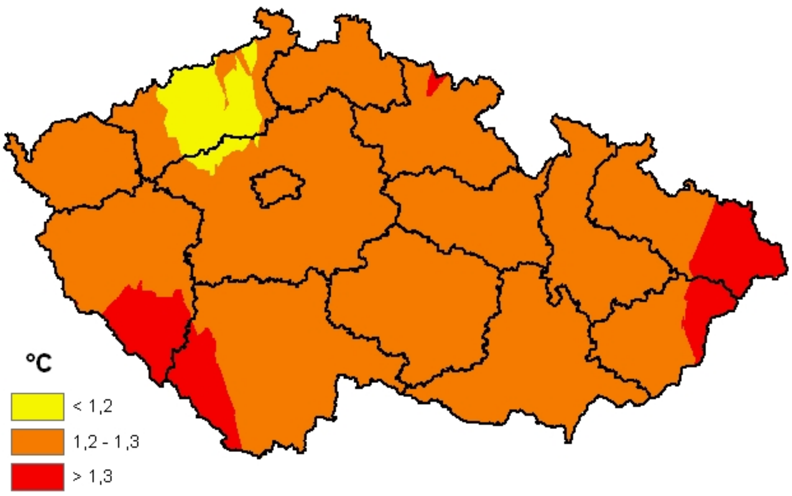


Figure 26. Projected increase of the mean shade air temperature in the Czech Republic (till the year 2035) relative to 2016 year (Figure from Climate change in CZ [Změna klimatu v ČR), ČHMÚ / CC BY-NC-ND 3.0 CZ])



Projections of temperature changes in the 'long term' show that global mean temperatures will continue to rise over the 21st century if greenhouse gas emissions continue unabated. The IPCC Fifth Assessment Report (IPCC, 2014) shows that the global mean surface temperatures for 2081–2100 will increase from 0.3°C - 1.7°C (RCP2.6[70]) up to 2.6°C – 4.8°C (RCP8.5), relative to 1986–2005.

Temperature changes will not be regionally uniform. There is very high confidence that globally averaged changes over land will exceed changes over the ocean at the end of the 21st century.

[70] The Representative Concentration Pathways (RCPs) are a set of pathways developed for the climate modelling community as a basis for long-term and near-term modelling experiments. Based on assumptions about future trends in socio-economic dynamics (economic growth, technological progress, demographic pressure) scenarios for future concentrations of greenhouse gases, aerosols, chemically active gases and variations in land use/cover, the Intergovernmental Panel on Climate Change (IPCC) has selected four RCPs characterized by an estimated increase in radiative forcing in year 2100 compared to pre-industrial era respectively equal to 2.6, 4.5, 6 and 8.5 W/m^2, i.e., RCP2.6, RCP4.5, RCP6.0 and RCP8.5.

6.4 Climate related parameters in the Eurocodes

6.4.1 Influence of climate change

Climate change might have influence on the design values of climatic and environmental actions leading to increase of:

- the mean value;
- the coefficient of variation due to uncertain development of the effects (aleatory uncertainty) and due to the limited knowledge and modelling of those effects (epistemic uncertainty).

Climate change might influence the probabilistic distribution of the extreme values of climatic actions. In addition, there exist uncertainties relating to how climate change will influence action effects on materials, structural components and construction systems. There might be needs for:

– changing the material composition of structures and their structural robustness to adapt to the expected changes in operating conditions, and
– an increase in maintenance to achieve the planned working life of structures or construction products.

Currently, the analytical models for determination of climatic actions in Eurocodes are based on the characteristic values of climatic actions and some conversion or influence factors for consideration of specific types, characteristics and location of buildings or civil engineering works. Uncertainties connected with possible impacts of climate change have not been considered in the Eurocodes till now.

6.4.2 Uncertainties of climatic actions dealt within the Eurocodes

EN 1990 "Basis of design"

Climatic actions are presently based on previously registered measurements of basic climate parameters. There can be observed changes in the natural variability of some climate parameters, some mixture between changing climate and natural variability, and therefore, various sources of uncertainty might arise in the determination of probabilistic models of climatic actions and estimation of a potential effect of climate change. Effects of non-climate related causes of change of the climatic actions might also arise in some regions due to changes in the built environment, e.g. increasing the area of buildings in urban areas and urban heat island effects.

The partial factor method is the basic method for the design of structures in the Eurocodes. This method makes it possible to take into account various types of uncertainties in modelling of actions, action effects and structural resistances. As explained in Chapter 3, in EN 1990, the main representative value of the action is its characteristic value. The characteristic value of a climatic action is based on the probability of 0.02 of its time-varying part being exceeded for a reference period of one year (equivalent to a mean return period of 50 years).

EN 1990 states that in some cases the character of the climatic action, or the selected design situation, could make another fractile or return period more appropriate. The possibility to apply a different fractile for a shorter time period is provided for short execution phases in EN 1991-1-6 "General actions - Actions during execution". Specific expressions for the characteristic values of snow, wind and thermal actions for different return periods, are given in relevant Parts of EN 1991 based on Gumbel or Weibull distributions.

The design value of an action effect given in EN 1990 is related to the characteristic value of the action, multiplied by partial factors γ_f and γ_{Sd}. The partial factor γ_f for the action takes account of the possibility of unfavourable deviations of the action values from the representative values. The factor γ_{Sd} takes account of uncertainties in modelling the actions or their effects (recommended in a range from 1.05 to 1.15 in EN 1990). The relationships between individual partial factors are given in EN 1990, Annex C. For all adverse climatic actions, a partial factor of 1.5 is currently recommended for the verification of structures in the Ultimate Limit States of type strength (STR) in EN 1990.

Similarly, for modelling the resistance of a structure, the partial factor γ_m for the material or product property takes account of the possibility of an unfavourable deviation of the property from its characteristic value, and of the random part of the conversion factor. Modelling uncertainty in structural resistance is considered by implementing the partial factor associated with the uncertainty of the resistance model γ_{Rd}.

Apart from the implementation of the partial factor method, which is still the main method for the design of structures in Eurocodes, probabilistic methods might be used under certain conditions as an alternative approach for structural design. Application of Normal distribution for self-weight and permanent actions and Lognormal or Weibull distributions for material and structural resistance, are recommended in Annex C of EN 1990. For variable actions, the possibility of application of extreme value distribution is noted.

Guidance on uncertainties in the modelling of the long-term course of climatic actions and predictions of their trends considering also climate change are not included in EN 1990.

Detailed information on probabilistic models of variable actions including climatic actions is not given in EN 1990, (Holicky and Markova, 2014). Other sources are available, e.g. ISO 2394:2015 and, more specifically, the Probabilistic Model Code (PMC) of the Joint Committee on Structural Safety (JCSS, 2014) where additional information on probabilistic methods, models of climatic actions and various climatic parameters are available. In some cases, these methods could also facilitate the description of different sources of uncertainties.

EN 1991-1-5 "Thermal actions"

a. Temperature components

Two basic temperature components are given in Eurocode EN 1991-1-5: the uniform temperature and the temperature difference components, in the vertical and the horizontal directions. The shade air temperature has considerable influence on the uniform temperature component, and the solar radiation on the temperature difference component.

The basic variables involved in the assessment of thermal actions on structures contain many uncertainties. Several factors influence the magnitude of resulting temperatures and their effects on structures: the structural materials, their thermal properties, the colours used, surfacing, geometry of the structure, the structure's sun exposure, shading by objects, air humidity, geographical and geomorphological position of site, etc. It is also necessary to consider the accuracy of measurements (selected cross-sections, instrumentation), time period and procedure of evaluation.

The daily temperatures (instantaneous part) and the seasonal temperatures (long-term part) influence the thermal course within the structure. The Weibull or three-parameter lognormal distributions could be preferably applied for modelling the temperature difference component.

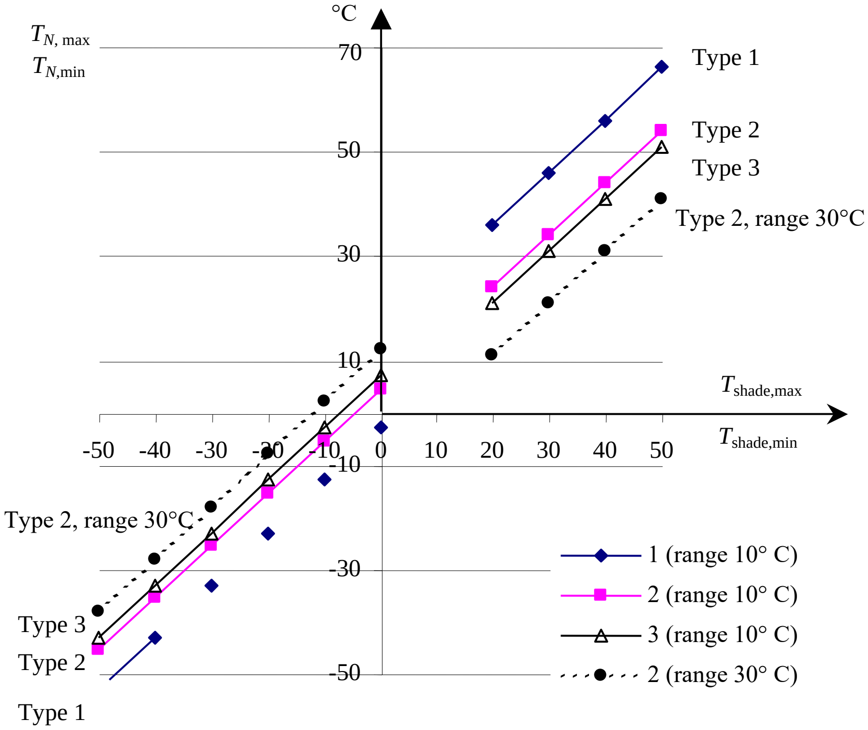
Increasing temperature demands should be considered in the design of structures or their parts subjected to temperature variations. The increase in frequency and magnitude of heat waves might have impacts on temperature sensitive structures and their members, e.g. on the bridges and their bearings, and on expansion joints.

The anticipated increase of shade air temperature due to climate change will lead to the augmentation of the uniform temperature component in structures. The increase of the uniform component will result in volume changes in unrestrained structures, e.g. elongation of a bridge, and in increase of stresses in restrained structures.

b. Design of bridges

EN 1991-1-5 provides a relationship for estimation of the uniform temperature component for bridges made from different materials, which is considered to be valid for a daily range of 10°C. The ranges of daily temperatures should be nationally checked for the potential updating of the relationship between the shade air temperature and the uniform temperature component for bridges (University of Pisa, 1999). The influence of different ranges of daily temperatures (10 °C and 30 °C) for composite steel-concrete bridges is illustrated as an example in ***Figure 27***.

Figure 27. Relationship between the shade air temperature and the uniform temperature component for steel bridges (Type 1), for composite steel concrete bridges (Type 2) and concrete bridges (Type 3). For composite bridges two different ranges of daily temperatures (10 and 30 °C) are illustrated. (Figure first published in Fikke et al., 2017. Data sources from EN 1991-1-5 [Fig. 6.1] and Konig et al. (1999) [Fig. 3.6.2 in p. 51]).



Currently, EN 1991-1-5 specifies that the initial bridge temperature T_0 should be taken as the "*temperature of a structural member at the relevant stage of its restraint (completion)*", i.e. it is the initial temperature when structural element is restrained. If no information is available, the recommended value T_0 = 10°C could be considered (NDP A.1(3) in EN 1991-1-5).

The analyses of 20 available National Annexes have shown that 13 countries accepted the recommended value, 3 countries adopted a value of 15°C, 3 countries adopted values of 20°C for the summer and 0°C for the winter, and 1 country adopted a value of 5°C.

The final draft of prEN 1991-1-5 of the second generation of the Eurocodes presently recommends to consider $T_{0,inf}$ for calculating contraction down to the minimum initial bridge temperature, and $T_{0,sup}$ for calculating expansion up to the maximum initial bridge temperature given as

$$T_{0,sup} = T_0 + \Delta T_0 \text{ and } T_{0,inf} = T_0 - \Delta T_0 \quad (6.1)$$

where ΔT_0 is a range of initial bridge temperature which can be set by the National Annex or defined on a project specific basis using local climatic data (see ***Figure 28***).

The values for $T_{0,inf}$ and $T_{0,sup}$ are clearly dependent on a variety of factors, such as geographical location and the local climate of the individual site, as well as the time of year during which any restraint may be imposed. Therefore, this consideration involves far too many variables to allow providing definitive, codified guidance on these values.

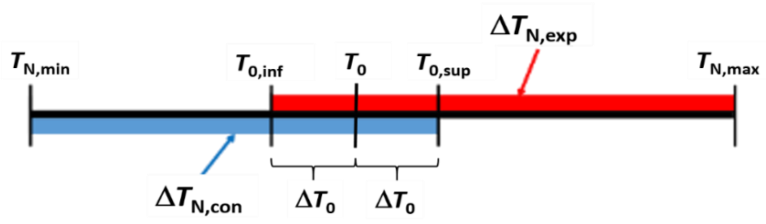
The characteristic value of the maximum contraction range of the uniform bridge temperature component, $\Delta T_{N,con}$, could be expressed as:

$$\Delta T_{N,con} = T_{0,sup} - T_{N,min} \quad (6.2)$$

and the characteristic value of the maximum expansion range of the uniform bridge temperature component, $\Delta T_{N,exp}$, could be expressed as:

$$\Delta T_{N,exp} = T_{N,max} - T_{0,inf} \quad (6.3)$$

Figure 28. Characteristic value of the maximum contraction ($\Delta T_{N,con}$) and expansion ($\Delta T_{N,exp}$) range of the uniform bridge temperature component



Currently, for the design of bearings and expansion joints, EN 1991-1-5 allows to specify in the National Annex the maximum expansion range of the uniform bridge temperature component, and the maximum contraction range of the uniform bridge temperature component, given that no other provisions are required. The recommended values are provided in NOTE 2 of NDP 6.1.3.3(3) of EN 1991-1-5.

c. Estimation of the influence of thermal changes for the Czech Republic

The IPCC Fifth Assessment Report (IPCC, 2014) predicts an increase of mean temperatures due to the climate change from 2 to 4 °C for 2100 for different representative concentration pathways. It might be assumed, for example, that the shade air temperature will increase 4°C. Based on the thermal models, the uniform (effective) temperature component will also increase, for the conditions in the Czech Republic, from the presently used uniform temperature component 56°C to 60°C for concrete bridges, from 44.5°C to 48.5°C for composite bridges and from 41.5 to 45.5°C for steel bridges. Therefore, the modification factor due to the climate change could be estimated to be about 1.07 for concrete bridges and 1.1 for composite and steel bridges. The recommended value of the partial factor for thermal actions in the Eurocodes is currently 1.5. This value could be reduced to about 1.3 in the second generation of Eurocodes. The application of the enhancement factor 1.1 would then result in a partial factor of about 1.4. Hence, the value of the partial factor 1.5 for the consideration of the uniform temperature component encompasses by itself some reserve for climate change for the Ultimate Limit States verifications.

However, for structures sensitive to thermal actions and having a long-term working life, a modification factor to the partial factor for thermal actions may be used for the design or verification with respect to the Serviceability Limit States.

6.5 Conclusions

The anticipated increase of the shade air temperature due to the climate change will lead to augmentation of the uniform temperature component of the thermal loading on structures. The increase of the uniform component will cause volume changes in unrestrained structures, e.g. elongation of a bridge. The increase of temperature will also impact (Fikke et al., 2017):

- the ranges of structural movements, which are important for the design of bearings and expansion joints;
- the effects of structural restraint leading to additional stresses;
- the additional stresses in structures and interaction of structures made of different materials in their joints;

- the interaction between a track and bridge for railway bridges.

The expected increase of solar radiation will lead mainly to the augmentation of the temperature difference component. This will influence temperature profiles in construction works, will cause additional stresses in structures, and interaction of structures made of different materials in their interface.

As referred in Chapter 3, the European maps for thermal design currently in use by countries are based on climatic data which, with some exceptions, is mostly 10 to 15 years old. These European maps ignore the potential effects of climate change and as a result, new maps should be developed using data better describing the future climate.

The partial factors for climatic actions should be further calibrated taking into account the changed characteristics of climatic actions. A modification factor considering the climate change should be specified to refine the relevant partial factor of a climatic action depending on the verified type of the limit state of the structure.

7 Conclusions and further developments

7.1 Rational and policy context synopsis

The European Green Deal is the roadmap for making the EU's economy sustainable by turning climate and environmental challenges into opportunities across all policy areas and making the transition just and inclusive for all. Within the Green Deal objectives, buildings and the construction sector as a whole are encouraged to adopt more sustainable and circular practices, extend the lifetime of buildings, strive for a better life-cycle performance of buildings and infrastructure and enhance the climate-proofing of buildings.

The assessment of the impact of climate change on the built environment and the identification of adaptation needs of infrastructure and buildings, are key aspects in defining adaptation strategies to climate change. In particular, extreme climatic events lead to variable loads on the buildings and construction works and changes in climate will have an effect on the design loads (i.e. wind, snow and temperature). Thus, building standards as a vital instrument for regulating the construction sector, should adapt to the new frequency and intensity of climate-related impacts in order to safeguard existing and new infrastructure and buildings, strengthening Europe's resilience to the impact of a changing climate.

In this context, the Eurocodes (EN 1990 – EN 1999), implemented in the EU Member States since 2010, play a major role as they are the common European standards for the structural design of buildings and other construction works. The users of the Eurocodes are obliged to use the maps for climatic actions specified in the National Annexes to the Eurocodes of the country, on whose territory is situated the structure to design. As explained in Chapter 3, the **European maps for thermal design currently in use by the EU countries, are based on climatic data that are mostly 10 to 15 years old** and also ignore the potential effects of climate change.

The Mandate M/515 of the European Commission to CEN requested the assessment of the climate change implications for the Eurocodes. In parallel, Mandate M/526 by the European Commission invited the European Standards Organisations to contribute to building and maintaining a more climate resilient infrastructure throughout the EU in the three priority sectors: transport infrastructure, energy infrastructure, and buildings/construction but not addressing the Eurocodes. However, under the ongoing standardisation works under the two mandates, the development of maps of climatic actions for design with the Eurocodes taking into account the implications of climate change is not planned.

7.2 Conclusions and recommendations

The national implementation of the Eurocodes in the EU Member States as regards the choice of Nationally Determined Parameters (NDPs) relevant to the definition of thermal actions (maximum and minimum shade air temperature) shows a good level of harmonisation. There are good examples of harmonisation in border values of the thermal action maps for neighbouring countries. However, the **thermal maps present dissimilar layouts and reveal discontinuities at countries borderlines**, mainly in the level of the minimum shade air temperatures, making it difficult to harmonise the use of Eurocodes in neighbouring areas of different EU Member States.

To proceed with the adaptation of structural design to the implications of climate change, **the expected changes in the climatic actions shall be assessed in terms of the Eurocodes concept** for the characteristic values of the variable climatic actions. Thus, updated European maps for the definition of thermal loading taking into account the climate change are necessary. Such maps can be published in informative annexes in the respective Eurocodes Parts of the second generation of the Eurocodes, as is currently the case of the European scale snow load map, which is incorporated in Annex C to EN 1991-1-3. The production of updated thermal design maps taking into account the climate change will help National Competent Authorities to redraft their national thermal action design maps in a harmonised way by using the best available knowledge, and reduce inconsistencies at the borders between neighbouring countries.

The analysis for the expected variations due to climate change in the characteristic values of T_{max}, T_{min} and Diurnal Temperature Range for the case study of Italy, taking into account a future Representative Concentration Pathway (RCP), RCP8.5, was presented in this report. The variations between the reference current period 1971-2000 and the future time span 2056-2085 (considered illustrative of a midterm scenario 2070) showed that the **increase in T_{max} and T_{min} characteristic values is evident throughout Italy**, highlighting the need to revise and update the thermal design maps based on climatic data that take into account the climate change.

In particular, in average terms, **an increase in T_{max} can be expected on the entire domain in Italy**. A 4°C mean value is expected and the most remarkable variations are estimated in the North-West and Alpine Region (up to 6°C) of Italy. Such trends confirm how **mountain regions could represent particularly sensitive areas to climate change**. Moreover, the expected increase in the characteristic values of T_{min} exhibits a mean value of 6.2°C; spatial patterns are evident with higher increase (up to 10°C) in the Alps, Prealps and Apennine mountain chains of Italy. According to the ensemble mean, no significant changes are expected in the characteristic values of the Diurnal Temperature Range.

In support of the development of updated European climatic action maps, the authors present a **proposal for a procedure to derive thermal design maps considering the influence of climate change** on the characteristic values of maximum and minimum temperatures and taking into account different sources of uncertainty in climate projections. A case study including an Italian region was carried out to illustrate the application of the procedure. The case study analysis confirmed that **an increase in extreme temperatures will be significant in the near future with a high confidence level**.

Maps of delta factors of change represent the starting point for the amendments of thermal maps in structural codes having a changing climate into consideration. The proposed procedure for deriving thermal design maps taking into account the changing climate is susceptible to wider applications. Since structures shall withstand climatic actions during their whole real life, which can be significantly greater than the design service life, the procedure for deriving the maps for thermal design from existing data needs further refinement to ensure the achievement of an adequate reliability level.

The study of CEN/TC250 Project Team SC1.T5 "Climate Change" working under Mandate M/515 concluded that the anticipated increase of the shade air temperature due to the climate change will lead to augmentation of the uniform temperature component of the thermal loading on structures. This increase will cause volume changes in unrestrained structures, e.g. elongation of a bridge. Such **augmentation influences temperature profiles in construction works**, leading to **additional stresses in structures**, and affecting the interaction of structures made of different materials in their interface (Fikke et al., 2017).

Moreover, the final report of the Project Team on SC1.T5 recommended that bridges and other structures influenced by stresses from extreme temperatures should be designed for temperature amplitudes justified from climate projections for the actual region. It highlighted that the models used for extreme value calculations of basic variables should be updated based on new knowledge on variation of climate parameters, both with respect to traditional input data as well as model data and analysing tools. In addition, estimates of characteristic values of climatic actions should be updated with intervals no longer than ten years.

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