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Expected implications of climate change on the corrosion of structures

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Summary

The report presents the work of the Joint Research Centre (JRC) scientific network on adaptation of structural design to climate change addressing the expected implications of a changing climate on the corrosion of structures.

The work first outlines recent EU policies supporting the sustainability and climate resilience of infrastructure and buildings. It is highlighted how the construction sector is encouraged to adopt more sustainable and circular economic practices, extend the lifetime of buildings and strive for better performance of buildings and infrastructure throughout their life cycle. The ongoing action plan to adapt European standards to a changing climate is emphasised.

The report evaluates the expected variations in climatic factors causing corrosion, provides a state-of-the-art review on climate change induced corrosion of reinforced concrete and steel structures, and presents recent works on the corrosion impact, the costs and effectiveness of adaptation strategies. The effects of corrosion on the seismic performance of structures is addressed as well.

In conclusion, this report presents the scientific and technical background to study the expected implications of climate change on the corrosion of structures. The work intends to stimulate debate on the subject, identify further research needs, and serve as a basis for the development of further work relevant to the adaptation to climate change of European standards and policies.

Foreword

The construction sector 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), is the largest single economic activity and the biggest industrial employer in Europe, providing about 12 million direct jobs in 3.3 million companies[1].

Construction is a key element for the implementation of the European Single Market and for other relevant EU strategies. Ensuring more sustainable and climate resilient infrastructure and buildings are central priorities of the European Green Deal (COM(2019) 640[2,3]). The adaptation of the construction sector to 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[4]) and the launch a '*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 [5]) and the New Industrial Strategy for Europe (COM(2020) 102 final[6]) 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.

It is well known that standardization plays an important part in strengthening Europe's resilience to the impact of a changing climate. In fact, standardization is an important instrument to regulate the construction sector, in particular a major role is played by the Eurocodes[7] that are a set of European standards (EN 1990 to EN 1999) for structural design.

In the framework of Administrative Arrangements between the European Commission 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. This work goes beyond the developments within the Mandate M/515[8] EN for a detailed work programme for amending existing Eurocodes[9] and extending the scope of structural Eurocodes.

This report presents the scientific and technical background to study the expected implications of climate change on the corrosion of structures, intends to stimulate debate on the subject by identifying further research needs, and serve as a basis for the development of further work relevant to the adaptation to climate change of European standards and policies.

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[1] EUROSTAT 2018, Structural Business Statistics

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

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

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

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

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

[7] Eurocodes: Building the future (https://eurocodes.jrc.ec.europa.eu/)

[8] 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

[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/)

The editors and authors have sought to present useful and consistent information in this report. However, users of the 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).

June 2020

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Jana MARKOVA, Czech Technical University in Prague, Klokner Institute, Czech Republic

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Claus KONDRUP, Directorate-General for Climate Action (DG CLIMA)

Andras TOTH, Directorate-General for Climate Action (DG CLIMA)

1 Introduction

Climate change is happening, is a key message of *the European environment — state and outlook 2020* report, SOER 2020, published by the European Environment Agency.

Unfavourable climate change is associated with rising global temperature and sea level and, consequently, with increasing frequency, intensity, extent and duration of extreme weather and climate events throughout Europe and the world. Extreme events such as heat waves, severe storms, heavy rainfall and floods can affect the safety and service life of buildings and infrastructure, but also changes in the concentration of pollutants and in different climate variables like temperature, relative humidity, precipitation and wind patterns can have similar effects.

SOER 2020 claims that even if European global emission reductions and mitigation efforts succeed in the coming decades, the inevitability of climate change will require adaptation strategies. Typically, in climate change literature, "mitigation" focus on the source of climate change and refers to the reduction of greenhouse emissions and the enhancement of the sinks of such gases, while "adaptation" involves making adjustments to new climate conditions to minimize the adverse impact of climate change or explore beneficial opportunities that may arise (IPCC, 2013, SOER 2020, Batidas-Arteaga and Stewart, 2019).

In this context, state-of-the-art building standards, integrating recent scientific and engineering knowledge, play a major role preventing adverse consequences of climate change, especially when they have the capacity to update and adapt to evolving risks.

The Eurocodes are a set of 10 European standards that comply with the above-mentioned requirements. The Eurocodes provide common technical rules for design of buildings and other civil engineering works, checking their strength and stability against live extreme loads. 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 construction products.

EN 1991 "Eurocode 1: Actions on structures" provides 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.

The Safety and Security of Buildings Unit of the European Commission Joint Research Centre (JRC) conducts pre-normative research towards European standards for safety and security of the built environment, also addressing sustainability and efficiency issues. In the framework of Administrative Arrangements between the JRC and the Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs (DG GROW), that JRC Unit is working on establishing the needs for research, guidelines and standards to better address the adaptation of the design of buildings and infrastructure to a changing climate.

In this regard, the JRC has 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 network is participated by:

— The chairmen of two Subcommittees (SC) of CEN/TC250 "Structural Eurocodes"[10] relevant to the adaptation to climate change: "SC10 - Basis of Structural Design" and "SC1 Actions on Structures" and the convenor of the CEN/TC250 Horizontal Group (HG) "Bridges". The chairman of SC10 and the convenor of HG "Bridges" also represent the

[10] The European Standardization 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.

University of Pisa in Italy. Both have previously participated in the European Snow Load Research Project (ESLRP, 1998) that produced the European snow load map incorporated in the Annex C to EN 1991-1-3[11].

- The Project Team (PT) Leader of task SC1.T5 "Climate change", under Mandate M/515[12] 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, 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 DG JRC dealing with adaptation strategies to climate change, European standards, climate change projections and impact models.

Currently, the scientific network has already produced the following results:

- A pilot project on the definition of snow load for structural design taking into account recorded climatic data for Italy (daily temperatures and precipitation) and setting up an advanced harmonised approach for deriving characteristic snow loads considering climate change projections, and thus evaluating the future trends in the variation of snow loading. The main results of the pilot project were presented in a paper entitled "The snow load in Europe and the climate change", published in the Elsevier journal "Climate Risk Management (Croce et al., 2018).
- A report entitled "Towards new European snow map", (Croce et al., 2016) substantiating the need for a new European project to update the existing snow load maps in Annex C of EN 1991-1-3 and to help National Authorities to redraft their national snow load maps. The report recommends the procedure established in the pilot project for the definition of snow load from climate change projections, since it allows producing new national snow maps in a harmonised way, by using the best available knowledge and contributing to the reduction of inconsistencies at borders between neighbouring countries.
- A report entitled "Thermal design of structures and the changing climate" (JRC, 2020), explaining how thermal actions are addressed in the Eurocodes, illustrating the thermal maps in the National Annexes of the EU Member States and assessing the potential implications of thermal action changes in structural design. The report presents a case study on expected variations of climate factors that would directly affect the design values for thermal actions in the standards. A methodology for developing thermal maps for structural design given the influence of climate change is also presented.

The current report presents expected effects of climate change induced corrosion, which shall be further studied and if needed, addressed in the Europe's policies and long-term sustainability goals relevant to environmental and climate challenges, and in the European standards. The work provides a state-of-the-art review on the corrosion of reinforced concrete and steel structures due to climate change, and assesses the corrosion impact, costs and effectiveness of adaptation strategies. The effects of corrosion on the seismic performance of structures is also addressed. The last chapter presents the main conclusions of the report, and identifies further research needs regarding the impact of future climate change on the corrosion of buildings at the European level.

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

[12] 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

2 Policies and standards for climate adaptation

2.1 Policy background

2.1.1 The Green Deal

Environmental degradation, climate change, and respective consequences are increasingly being felt in Europe and around the world.

The Intergovernmental Panel on Climate Change (IPCC) claims with high confidence that global temperatures will continue to rise for the decades to come, largely due to greenhouse gases (GHG) produced by human activities (IPCC, 2018). Global warming gives rise to changes in the frequency, intensity, spatial extent and duration of weather and climate extremes, conceivably resulting in exceptional extreme events (Seneviratne et al., 2012).

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. The World Meteorological Organization (WMO)[13] 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 GHG, which are responsible for long-term climate change, since atmospheric carbon dioxide levels showed a rapid rise in the last century and carbon dioxide remains in the atmosphere for centuries and even longer in the oceans. Thus, the United Nations claim: "climate change is not on pause"[14], *i.e.*, climate patterns will continue to change, unless there are worldwide sustainable adjustments towards a more climate-friendly economy and individual practices.

In this respect, EU citizens benefit from some of the world's high-quality environmental standards, which seek to ensure the health and wellbeing of the European population, reduce various forms of pollution, protect natural resources and promote an environmentally-friendly and sustainable economy.

In December 2019, the European Commission launched an ambitious roadmap termed *European Green Deal* (COM(2019) 640[15]), to support a new sustainable growth strategy aiming to transform the EU into a modern, resource-efficient and competitive economy. The Green Deal is the first of the six headline ambitions the European Commission (EC) wants to deliver in its 2020 Work Programme (COM(2020) 37 final[16]). The Programme was adjusted in May 2020 (COM(2020 440 final[17]), as part of *Europe's Recovery Plan* (COM(2020) 456 final[18]) 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 after the COVID-19 crisis started.

The Green Deal is a package of measures aiming to make Europe the world's first climate-neutral continent by 2050, *i.e.* an economy with net-zero greenhouse gas emissions in line with the EU's commitment to global climate action under the Paris Agreement.

Figure 1 illustrates the set of eight policy areas that are part of a coherent strategy to achieve the Green Deal, and highlights, in blue, the financing pillars of the transition, *i.e.*, the *European Green Deal's Investment Plan* (EGDIP – COM(2020 [19,20]) 21 final), and a Proposal for Regulation establishing the *Just Transition Fund* (COM(2020) 22 final [21]). The Fund is part of the Investment Plan, but targeted to a socially-fair transition.

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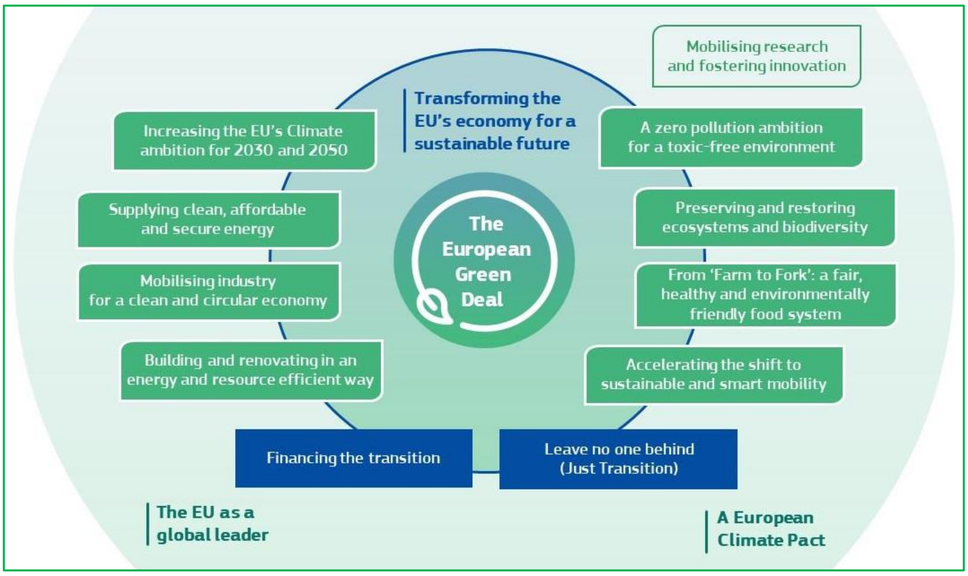
13 https://public.wmo.int/en/media/news/economic-slowdown-result-of-covid-no-substitute-climate-action
14 https://www.un.org/sustainabledevelopment/climate-change/
15 https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF
16 https://eur-lex.europa.eu/resource.html?uri=cellar%3A7ae642ea-4340-11ea-b81b-01aa75ed71a1.0002.02/DOC_1&format=PDF
17 https://ec.europa.eu/info/publications/2020-commission-work-programme-key-documents_en
18 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:456:FIN
19 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:21:FIN
20 https://ec.europa.eu/commission/presscorner/detail/en/qanda_20_24
21 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:22:FIN

Figure 1. The European Green Deal



2.1.2 Policy areas under the Green Deal

The current section addresses the policy areas and key actions under the Green Deal that are relevant to the adaptation of the construction sector to climate change.

Climate Action

The European Commission already in 2013 adopted *An EU Strategy on Adaptation to Climate Change* (COM(2013) 216[22]) to set out a framework and mechanisms to improve EU's preparedness for current and future climate impacts, anticipating the adverse effects of climate change. The strategy has been welcomed by the Member States and positively evaluated in 2018 (SWD(2018) 461 final[23]). Currently, all Member States adopted an adaptation strategy[24].

The EU Strategy on Adaptation to Climate Change was accompanied by a Commission staff working document *Adapting infrastructure to climate change* (SWD(2013) 137 final[25]), aiming the climate change adaptation of selected infrastructure sectors in EU, namely the energy and transport infrastructure, as well as buildings. Since many infrastructures and building have a long life expectancy and a high economic value, they need to adapt to, and be resilient to future impacts of a changing climate. The document recognised 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.

Relevant climate action initiatives under the Green Deal are:

- The first *European Climate Law* (COM(2020) 80 final[26]) with which the Commission proposed a legally obligatory target of net-zero greenhouse gas emissions by 2050 and the framework for action at EU and national level to meet the target.
- Interim targets for 2020 and 2030 to help realise the vision for a neutral EU by 2050 on greenhouse gas emissions (Eurostat, 2020).
- The *European Climate Pact*[27] that aims to engage citizens and all parts of society in concrete actions designed to mitigate and adapt to the impacts of climate change. The European Climate Pact will be launched in the last quarter of 2020.

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22 https://ec.europa.eu/clima/policies/adaptation/what_en#tab-0-1
23 https://ec.europa.eu/transparency/regdoc/rep/1/2013/EN/1-2013-216-EN-F1-1.Pdf
24 https://climate-adapt.eea.europa.eu/countries-regions/countries
25 https://ec.europa.eu/clima/sites/clima/files/adaptation/what/docs/swd_2013_137_en.pdf
26 https://ec.europa.eu/info/files/commission-proposal-regulation-european-climate-law_en
27 https://ec.europa.eu/clima/policies/eu-climate-action/pact_en

- A *New*, more ambitious *EU strategy on adaptation to climate change*. The background framework of the new strategy is presented in a blueprint document that accompanies the public consultation of the new EU strategy[28]. The new adaptation strategy is proposed to be in full synergy with the other strategic initiatives announced in the European Green Deal relevant to the construction sector such as, the Renovation Wave, or the Sustainable Industry described below.

Building and renovating

Building and renovating addresses the challenges of more efficient and affordable energy and resources throughout the life cycle of buildings, as summarized in Figure 2.

In this context, in the third quarter of 2020, the Commission will launch a *'Renovation Wave*' initiative in the buildings sector. Currently, only around 1% of buildings in the EU are renovated each year[29]. It is expected to at least double the current rates of renovation of existing building stock, addressing the referred twin challenges of energy efficiency and affordability.

In addition, the Commission will review the *Construction Products Regulation* (Regulation (EU) No 305/2011[30]) 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.

Sustainable industry

The *Sustainable industry* policy area also supports the Green Deal's climate and environmental objectives intending to accelerate the transition of the EU industry to a sustainable model based on the principles of a circular economy (Figure 3).

To achieve those objectives the Commission adopted, in March 2020, the *A New Industrial Strategy for Europe* (COM(2020) 102 final[31] - Figure 4) to address the twin challenge for a green and the digital industrial transformation.

As part of the actions to put the Industrial Strategy into effect, the New *Circular Economy Action Plan* (COM(2020)98 final[32] -see Figure 5) was adopted in March 2020. This plan aims to transform the current linear economy into a circular economy, in order to develop a cleaner and more competitive industry, reduce environmental impacts, alleviate competition for scarce resources and reduce production costs.

At the heart of the Circular Economy Action Plan is the new *Sustainable Product Policy framework*, that will present new initiatives along the entire life cycle of products, including legislation to ensure that products placed on the EU market will follow sustainability principles, are designed to last longer, are easier to reuse, repair and recycle, and incorporate as much as possible recycled material instead of primary raw material, ensuring less waste.

Concrete initiatives will be launched focusing on the sectors that use most resources and where the potential for circularity is high, such as the *Construction and buildings*. In fact, the built environment requires vast amounts of resources and accounts for about 50% of all extracted material. The construction sector is responsible for over 35% of the EU's total waste generation. GHG emissions from material extraction, manufacturing of construction products, construction and renovation of buildings are estimated at 5-12% of the total GHG national emissions. Greater material efficiency could save 80% of those emissions.

[28] https://ec.europa.eu/info/law/better-regulation/have-your-say/initiatives/12381-EU-Strategy-on-Adaptation-to-Climate-Change/public-consultation

[29] https://www.europarl.europa.eu/legislative-train/theme-a-european-green-deal/file-renovation-wave

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

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

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

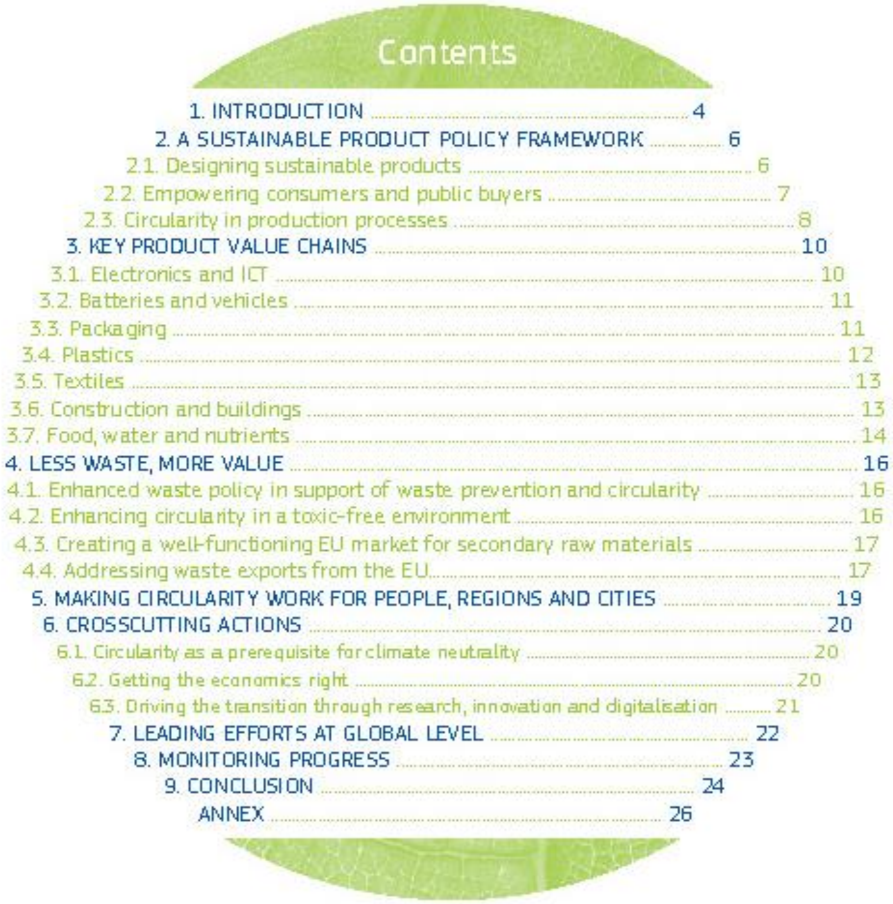
Figure 2. The *Building and renovating* policy area[33]

Figure 3. The *Sustainable industry* policy area[34]

Figure 4. The *new Industrial Strategy for Europe*[35]

[33] https://ec.europa.eu/commission/presscorner/detail/en/fs_19_6725
[34] https://ec.europa.eu/commission/presscorner/detail/en/fs_19_6724
[35] https://ec.europa.eu/commission/presscorner/detail/en/fs_20_425

Figure 5. Table of contents of the new *Circular Economy Action Plan*[36]



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To exploit the potential for increasing material efficiency and reducing climate impacts, the Commission will launch a new comprehensive *Strategy for a Sustainable Built Environment*. This Strategy will ensure coherence across the relevant policy areas, like climate, energy and resource efficiency, management of construction and demolition waste, accessibility, digitalisation and skills. As a prerequisite for climate neutrality, it will promote circularity principles throughout the lifecycle of buildings by:

— Addressing the sustainability performance of construction products in the context of the revision of the *Construction Product Regulation*, including the possible introduction of recycled content requirements for certain construction products.

— Promoting measures to improve the durability and adaptability of built assets in line with the *Circular economy - Principles for buildings design*[37], published in February 2020.

— Using Level(s)[38] (Dodd et al, 2017a, Dodd et al, 2017b), 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.

2.2 Adaptation of structural design standards to climate change

The publication of the European standards for structural design, the Eurocodes (EN 1990 to EN 1999), by the European Committee for Standardization (CEN) in May 2007, marked a major milestone in the European standardisation for construction. This set of standards

[36] https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf
[37] https://ec.europa.eu/docsroom/documents/39984
[38] https://ec.europa.eu/environment/eussd/buildings.htm

introduced common technical rules for the calculation of the mechanical and fire resistance, and the stability of constructions and construction products.

The Eurocodes are state-of-the-art reference design codes for buildings, infrastructures and civil engineering structures and meant to lead to more uniform levels of safety in construction in Europe. They are used in different regulatory systems due to their flexibility to adapt to each country's specific conditions and 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 Members[39], as stated in the report of the European Commission on the implementation of the Eurocodes (Dimova et al., 2015), and currently, there is a considerable interest in the use of the Eurocodes outside EU[40].

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, Section 1.5.2.8). 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[41]. In this way, structures designed in 2020 shall withstand climatic actions (snow, wind, thermal) and extreme events expected in the period 2020-2070, as for buildings, and in the period 2020-2120 as regards bridges and monumental buildings (Croce, 2018). Both new and existing infrastructures and buildings should be made more climate-resilient over their lifetime, also considering that the real lifetime of most structures is longer than their design working life, they are very sensitive to climate change implications.

Besides, it must be underlined that climatic data on which the current generation of the Eurocodes is based are mostly 10-15 years old, with some exceptions of recent updates of national data, e.g. the case of the new maps for climatic actions of the Czech Republic (Croce, 2018).

In 2012, DG GROW of the European Commission issued the Mandate M/515 for a detailed work programme for amending existing Eurocodes and extending the scope of structural Eurocodes. The work of CEN/Technical Committee (TC) 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. The Mandate includes standardization works relevant to climate change, namely:

— Publication in 2017 of the final report of the Project Team SC1.T5 (PT5) "Climate change"[42], analysing and providing guidance for potential amendments for Eurocodes concerning structural design addressing relevant impacts of future climate change (general and material specific).

— Revision and update of the Eurocodes Parts EN 1991-1-3 on snow loads, EN 1991-1-4 on wind actions, and EN 1991-1-5 on thermal actions, preparation of background documents.

— Conversion of ISO standards on actions from waves and currents, and on atmospheric icing to ISO-EN standards.

— Preparing a document with the probabilistic basis for determination of partial safety factors and load combination factors, taking into account the variability and interdependence of climatic actions.

[39] More information about CEN Members at https://www.cen.eu/about/community/pages/default.aspx

[40] https://eurocodes.jrc.ec.europa.eu/showpage.php?id=8

[41] EN 1990 gives indicative design working lives (in Table 2.1) for design purposes for various types of structures. Modified indicative design working lives for all/some of the categories maybe specified in the National Annex of a country implementing the Eurocodes. Moreover, EN 1990, Section 2.4(1) states that the structure shall be designed such that deterioration over its design working life does not impair the performance of the structure below that intended, having due regard to its environment and the anticipated level of maintenance.

[42] Project Team SC1.T5 "Climate Change" under Mandate M/515 (2017) Final Report to CEN/TC250, April 2017.

In 2014, the European Commission issued the Mandate M/526[43] requesting the European Standardisation 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, except the Eurocodes. The work performed under mandate M/526 encompassed:

— establishing the Adaptation to Climate Change Coordination Group (ACC-CG)[44] 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[45] 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 standardization 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)[46]. The Guide is designed specifically for writers of CEN-CENELEC infrastructure standards (and similar documents).

— identification of twelve standards as a 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.

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

2.3 Concluding remarks

To conclude, the European Union 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. Figure 6 summarises how the different elements fit together as part of the European Green Deal.

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. Adaptation to unavoidable impacts of climate change is a key aspect to take into account in the future evolution of standards.

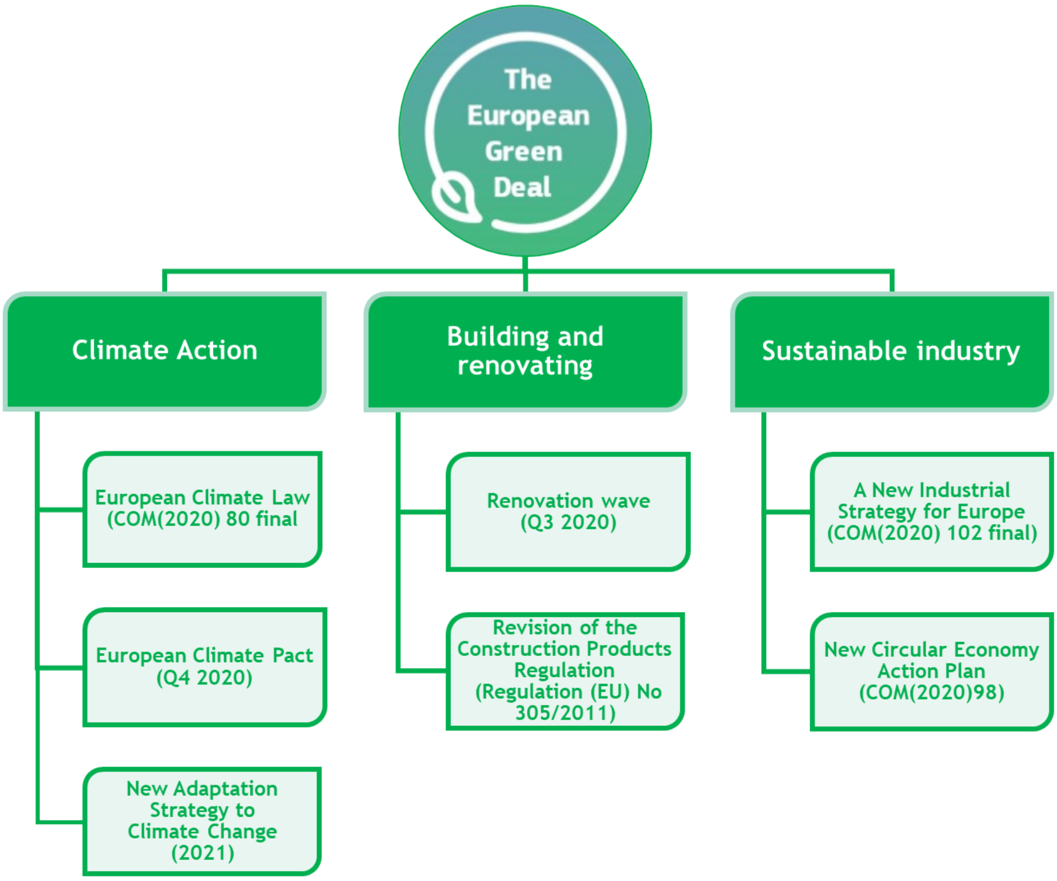
[43] M/526 Commission implementing decision C(2014) 3451 Final of 28.5.2014 on deciding to make a standardisation request to the European standardisation organisations pursuant to Article 10(1) of regulation(EU) No 1025/2012 of the European Parliament and of the Council in support of implementation of the EU Strategy on Adaptation to Climate Change [COM(2013) 216 FINAL] http://ec.europa.eu/growth/tools-databases/mandates/index.cfm?fuseaction=select_attachments.download&doc_id=1549

[44] https://www.cencenelec.eu/standards/Sectorsold/ClimateChange/Pages/default.aspx

[45] https://www.cencenelec.eu/standards/Guides/Pages/default.aspx

[46] https://www.nen.nl/Standardization/Adaptation-to-Climate-Change/Mandated-project-Adaptation-to-Climate-Change.htm

Figure 6. Policy areas and key actions relevant to the construction sector as part of the European Green Deal



3 Expected variations in temperatures and relative humidity in Europe due to climate change

3.1 Climate models

Air temperature and relative humidity are two weather variables recognized as effective proxy indicators for studying the effect of atmospheric dynamics on corrosion processes, which will be addressed in chapter 4. This section discusses the potential variations in air temperature and relative humidity that are expected due to climate change. The assessment adopts the ensemble of climate projections performed at a regional scale in Europe and included in the EURO-CORDEX initiative[47] (Giorgi and Gutowski, 2016; Kotlarski et al., 2014; Casanueva et al., 2016).

In summary, the simulation chain usually adopted for assessing variations in weather patterns at a regional scale and currently used for climate simulations comprises three main elements:

(i) *Representative Concentration Pathways (RCPs)*. Based on assumptions about future trends in socio-economic dynamics (economic growth, technological progress, demographic pressure), scenarios for future concentrations of greenhouse gases (GHG), aerosols and chemically active gases and variations in land use/cover are defined. The Intergovernmental Panel on Climate Change (IPCC) has selected four Representative Concentration Pathways[48] (RCPs) described by an estimated increase in the radiative forcing values in the year 2100 equal to 2.6, 4.5, 6.0 and 8.5 W/m^2 compared to the preindustrial era (see Figure 7). The lowest value (2.6 W/m^2) is associated to strong and effective mitigation efforts to reduce emissions, the two medium values (4.5 and 6.0 W/m^2) represent "mid-way" scenarios, while the highest value (8.5 W/m^2) is considered a pessimistic but "business as usual" scenario. Further explanations may be found in the IPCC report (IPCC, 2014b).

(ii) *Earth System Models (ESMs).* RCPs are used as boundary conditions to force Earth System Models that consists of mathematical models simulating the atmospheric and oceanic circulation dynamics at a global scale. The horizontal resolution currently permitted by the available computational resources is in the range of 100 kilometres (but hardly exceeding 70 km). Several studies (IPCC, 2013) report how ESMs reproduce the global response to concentration increases with higher reliability for some variables (temperature) and lower for others (precipitation). In this regard, the Coupled Model Intercomparison Project (CMIP), constituting the backbone for the assessment described in the IPCC reports, represents an international effort to advance climate models by comparing multiple ESMs simulations and improving the understanding about trends and associated uncertainties. Figure 8 illustrates the development of climate models since mid-1970s, showing how capabilities in modelling have improved over recent years. The fifth Coupled Model Intercomparison Project (CMIP5) was used to support the 5th IPCC assessment report (AR5, IPCC 2014b). On the other hand, the low horizontal resolutions of ESMs prevent to achieve proper estimations at a regional scale where aspects as distance from the sea and orography, play a crucial role even with respect to large-scale atmospheric circulation.

[47] Further details can be retrieved at: https://www.euro-cordex.net/060374/index.php.en

[48] "The name "representative concentration pathways" was chosen to emphasise the rationale behind their use. RCPs are referred to as pathways in order to emphasise that their primary purpose is to provide time-dependent projections of atmospheric greenhouse gas (GHG) concentrations. In addition, the term pathway is meant to emphasise that it is not only a specific long-term concentration or radiative forcing outcome, such as a stabilization level that is of interest, but also the trajectory that is taken over time to reach that outcome. They are representative in that they are one of several different scenarios that have similar radiative forcing and emissions characteristics". Source: IPCC Expert Meeting Report, Towards New Scenarios for Analysis of Emissions, Climate Change, Impacts, and Response Strategies, IPCC 2007

Figure 7. (a) Emissions of carbon dioxide (CO_2) alone in the Representative Concentration Pathways (RCPs) (lines) and the associated scenario categories used in IPCC Working Group III (coloured areas show 5 to 95% range). The WGIII scenario categories summarize the wide range of emission scenarios published in the scientific literature and are defined on the basis of CO_2-eq concentration levels (in ppm) in 2100. **(b)** Global mean surface temperature increase at the time global CO_2 emissions reach a given net cumulative total, plotted as a function of that total, from various lines of evidence. Coloured plume shows the spread of past and future projections from a hierarchy of climate carbon cycle models driven by historical emissions and the four RCPs over all times out to 2100, and fades with the decreasing number of available models. Ellipses show total anthropogenic warming in 2100 versus cumulative CO_2 emissions from 1870 to 2100 from a simple climate model (median climate response) under the scenario categories used in WGIII. The width of the ellipses in terms of temperature is caused by the impact of different scenarios for non- CO_2 climate drivers. The filled black ellipse shows observed emissions to 2005 and observed temperatures in the decade 2000–2009 with associated uncertainties (Figure SPM.5, page 9 in IPCC, 2014b)

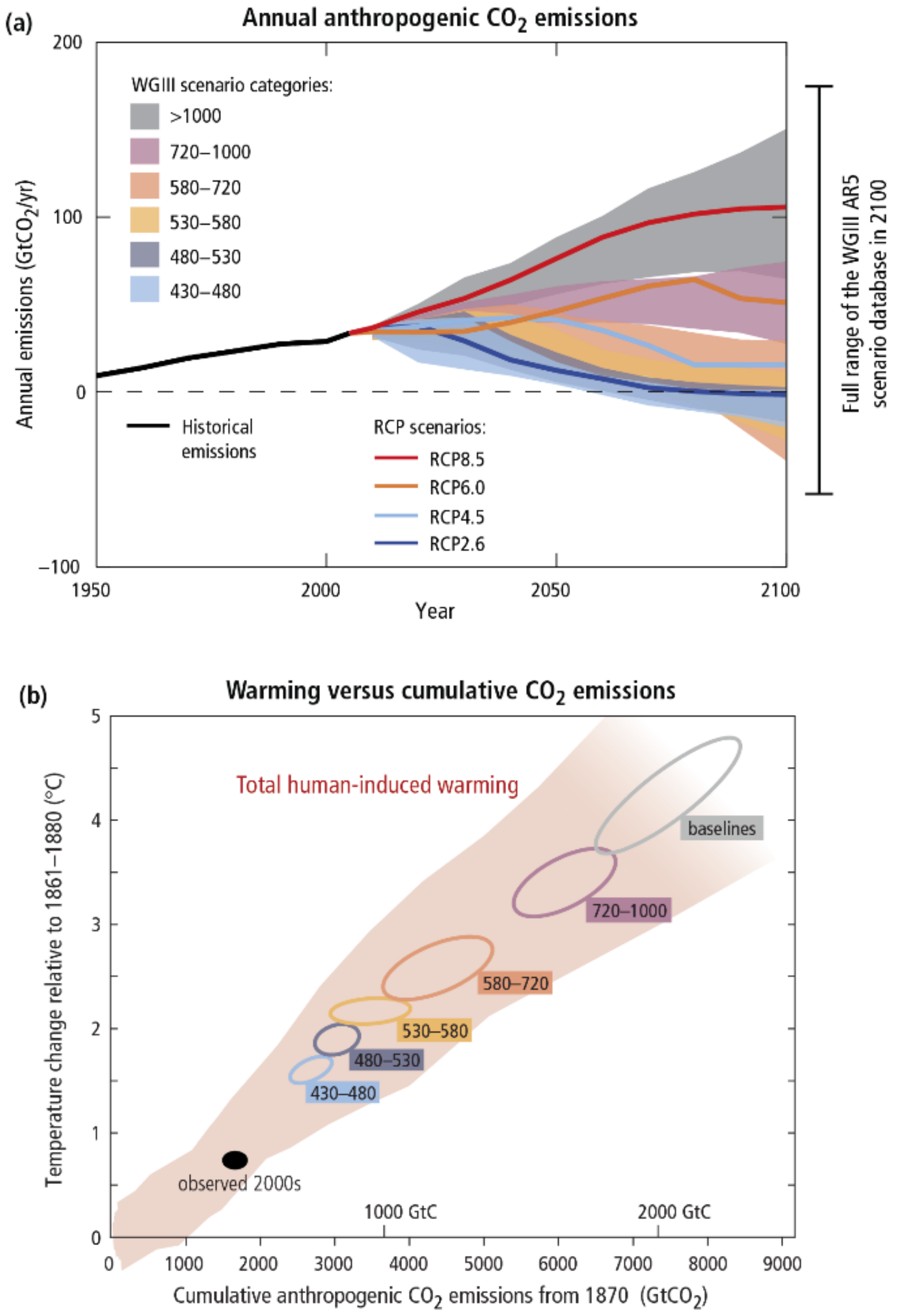
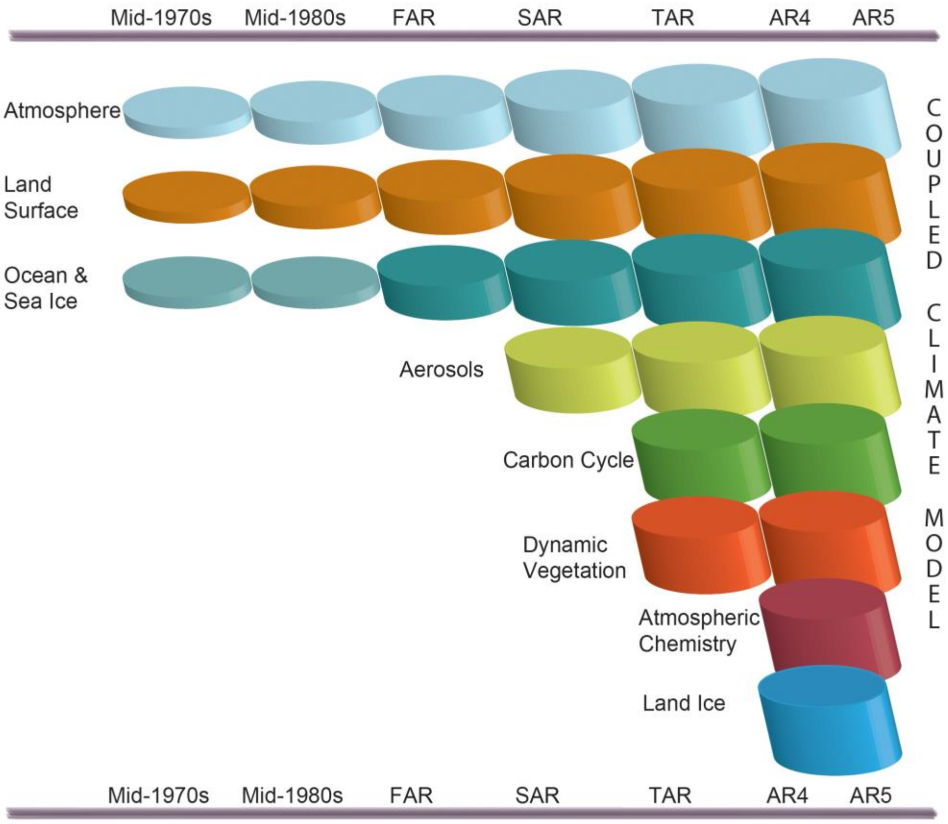


Figure 8. The development of climate models over the last 35 years showing how the different components were coupled into comprehensive climate models over time. In each aspect (e.g., the atmosphere, which comprises a wide range of atmospheric processes) the complexity and range of processes has increased over time (illustrated by growing cylinders). Note that during the same time the horizontal and vertical resolution has increased considerably e.g., for spectral models from T21L9 (roughly 500 km horizontal resolution and 9 vertical levels) in the 1970s to T95L95 (roughly 100 km horizontal resolution and 95 vertical levels) at present, and that now ensembles with at least three independent experiments can be considered as standard (Cubasch et al., 2013, page 144, Figure 1.13). [FAR: First Assessment Report (Houghton et al., 1990); SAR: Second Assessment Report (Houghton et al., 1995); TAR: Third Assessment Report (IPCC, 2001); AR4: Fourth Assessment Report (2007); AR5 Fifth Assessment Report (IPCC, 2013)]



(iii) *Downscaling approaches*. To assess regional climate change and associated impacts, several "downscaling" approaches have been proposed over past years (Rummukainen, 2010). Specifically, two main approaches can be recognized: (a) a dynamical downscaling according to which a high-resolution model (Regional Climate Model, RCM) is nested on ESMs for the area of interest and (b) a statistical downscaling for which large- "predictors" and local- scales "predictand" are empirically linked through statistical and/or stochastic approaches. The first approach permits evaluating trends over large areas through physically based tools. The second one, generally performed at very local (point) scale, is characterized by a much lower computational burden, but at the same time, requires a large amount of observed data for proper calibration and validation phases. Concerning RCMs, spatial resolutions currently achievable (in the order of 10 km) permit to improve orography representation and solve a substantial fraction of the local atmospheric phenomena. Nevertheless, several issues in orography misrepresentation, land surface feedbacks and sub-grid processes may cause substantial bias in simulated regional climate compared to observations (Maraun, 2016; Maraun et al., 2015). Then, on one hand, under the assumption that for current and future conditions the simulations are affected by biases in a similar way, the projections are usually exploited in terms of absolute and/or relative variations between the future and reference current time spans. On the other hand, the adoption of climate model output as input for impact studies or evaluations in absolute terms, requires post-processing through approaches currently known as Bias Correction methods (Lafon et al., 2013; Teutschbein and Seibert, 2012). These methods are defined as statistical regression models calibrated for current periods in order to detect and correct biases, which are assumed to systematically affect the climate simulations. Bias Correction methods are currently required by practitioners for impact studies; their strengths and weaknesses have been outlined in recent studies (Ehret et al., 2012). In the past years, several consortiums have promoted "ensemble" initiatives to allow a straight comparison among the different realizations of climate simulation chains and then to evaluate the uncertainties associated to the projections. In particular, the WCRP[49] Coordinated Regional Downscaling Experiment (CORDEX) project (Giorgi et al., 2009) is aimed to produce high-resolution "downscaled" climate data based on the CMIP[50] simulations; to this purpose, common geographical domains and resolution, covering the majority of the populated land areas worldwide plus both the Arctic and Antarctic, facilitate the above mentioned comparison, aiming at supporting climate change impact assessments and the formulation of adaptation policies.

3.2 Climate projections in Europe

In this work, climate projections over the European domain (EURO-CORDEX[51]) are considered under the RCP4.5 and RCP8.5 scenarios with a horizontal resolution of 0.11° (about 12 km). The projections consider the midterm scenario for year 2070 (the central point of the interval 2056-2085) compared to the reference period 1971-2000. The estimations are reported in terms of anomalies given the extension of the considered area, the weaknesses recognized in existing gridded dataset for temperature (Hofstra et al., 2009; van der Schrier et al., 2013) and the unavailability of equivalent data for relative humidity preventing the adoption of bias correction approaches over the domain. By January 2018, 11 climate simulation chains provide data for temperature and relative humidity under RCP4.5 and RCP8.5 scenarios. In Table 1, the three columns report respectively the institution carrying out the simulation, the adopted Earth System Model (ESM) and the Regional Climate Model (RCM) exploited for dynamical downscaling.

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

	Institution	**Driving ESM**	**RCM**
1	CNRM	CNRM-CM5_r1i1p1	Aladin53
2	SMHI	CNRM-CM5_r1i1p1	RCA4_v1
3	KNMI	EC-EARTH	RACMO22E_v1
4	DMI	EC-EARTH	HIRHAM5_v1
5	SMHI	EC-EARTH	RCA4_v1
6	IPSL-INERIS	IPSL-CM5A-MR_r1i1p1	WRF331F_v1
7	SMHI	IPSL-CM5A-MR_r1i1p1	RCA4_v1
8	KNMI	HadGEM2-ES	RACMO22E_v1
9	SMHI	HadGEM2-ES	RCA4_v1
10	SMHI	MPI-ESM-LR_r1i1p1	RCA4_v1
11	DMI	NorESM1-M	HIRHAM5

[49] WCRP - World Climate Research Programme
[50] CMIP - Coupled Model Intercomparison Project
[51] https://www.euro-cordex.net/

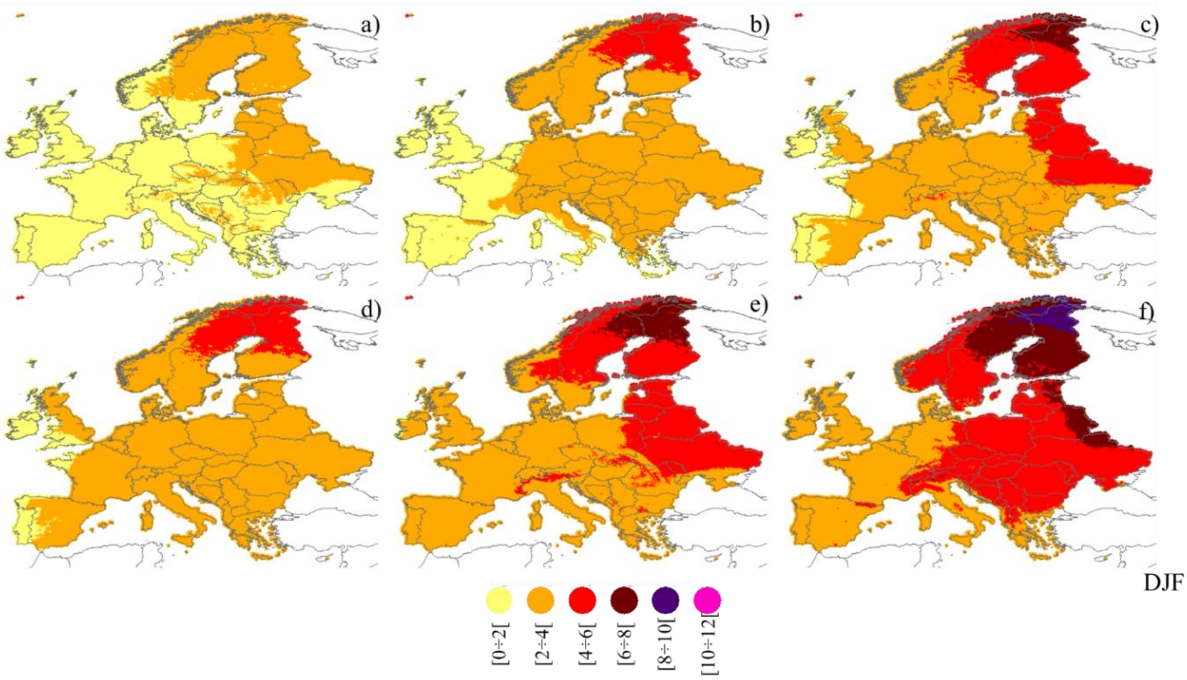
Figure 9 to Figure 12 show the variations in the seasonal mean temperature for the period 2056-2085 compared to the period 1971-2000 obtained by exploiting the EURO-CORDEX ensemble. The general outline for the maps presented in the Figures 9 to 12 is reported in Table 2. The central column of the figures presents the ensemble mean (EM) of the temperature variation. The first and third column of the figures illustrate the confidence intervals computed by respectively subtracting and adding to the ensemble mean the mean square deviation values, δ, provided by all available simulations.

Table 2. General outline for maps reported in Figure 9 to Figure 12

a) RCP4.5: EM- δ	b) RCP4.5: EM	c) RCP4.5: EM+δ
d) RCP8.5: EM- δ	e) RCP8.5: EM	f) RCP8.5: EM+δ

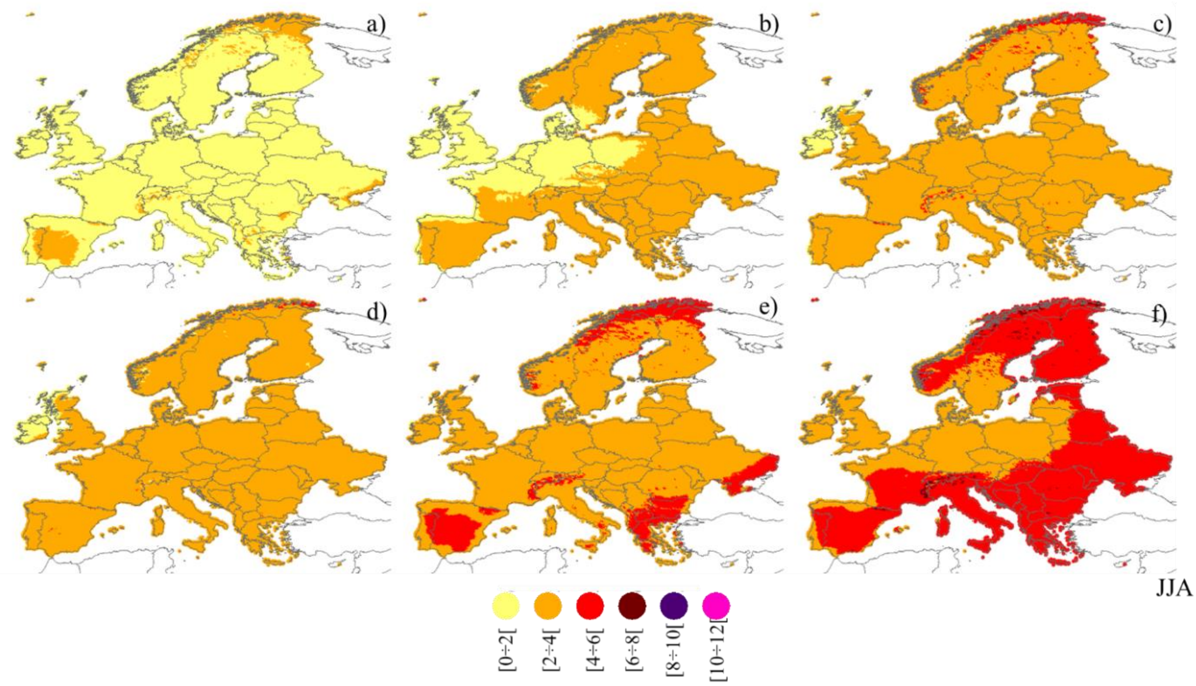
It is clear from the results presented in Figure 9 to 12 that the temperature increases in all seasons. Generally, it is the severity of the Representative Concentration Pathway (RCP) that regulates its magnitude; thus, under RCP4.5 scenario, the temperature variations are generally lower, ranging between 2° and 4°C, whereas according to the more pessimistic concentration scenario, RCP8.5, a large part of Europe could experience quite higher values with peaks up to 6-8 °C in terms of ensemble mean (up to 8-10°C in the EM+ δ configuration in Figure 9). In what regards the spatial structure of such increases, during the winter season (December-January-February noted as "DJF" in the figures), the north-eastern part of Europe could be affected by higher changes than during the summer season (June-July-August, noted as "JJA" in the figures). The Mediterranean countries are characterized by larger increases during the summer period compared to the winter period.

Figure 9. Mean temperature anomaly and confidence intervals for the season **DJF** under the concentration scenarios RCP4.5 (first row) and RCP8.5 (second row); 2056-2085 vs 1971-2000; further details in Table 2. Unit: °C.



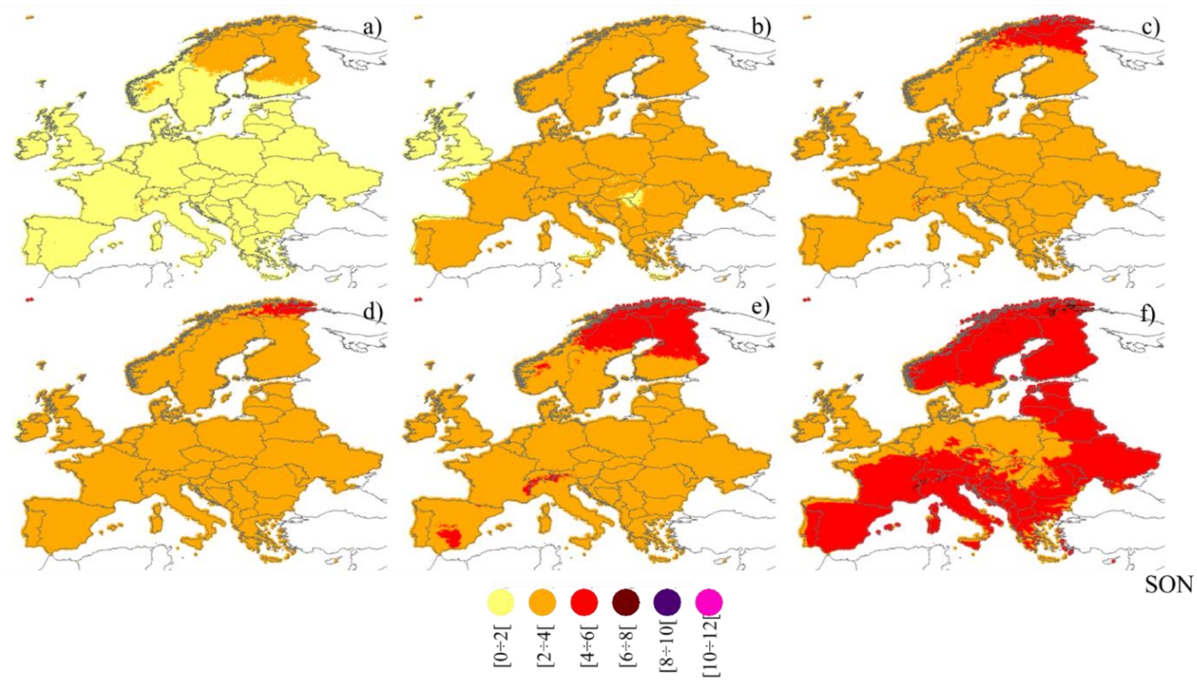
DJF - December-January-February

Figure 10. Mean temperature anomaly and confidence interval for the season **JJA** under the concentration scenarios RCP4.5 (first row) and RCP8.5 (second row); 2056-2085 vs 1971-2000; further details in Table 2. Unit: °C.



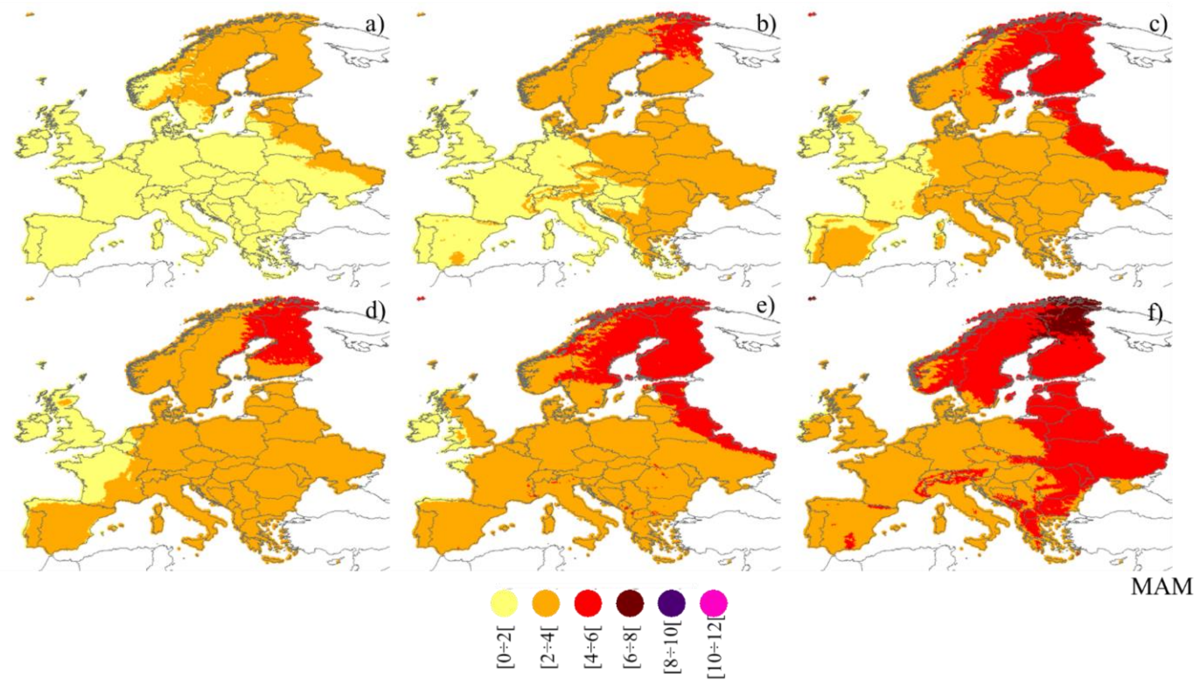
JJA – June-July-August

Figure 11. Mean temperature anomaly and confidence interval for the season SON under the concentration scenarios RCP4.5 (first row) and RCP8.5 (second row); 2056-2085 vs 1971-2000; further details in Table 2. Unit: °C.



SON – September – October - November

Figure 12. Mean temperature anomaly and confidence interval for the season **MAM** under the concentration scenarios RCP4.5 (first row) and RCP8.5 (second row); 2056-2085 vs 1971-2000; further details in Table 2. Unit: °C.

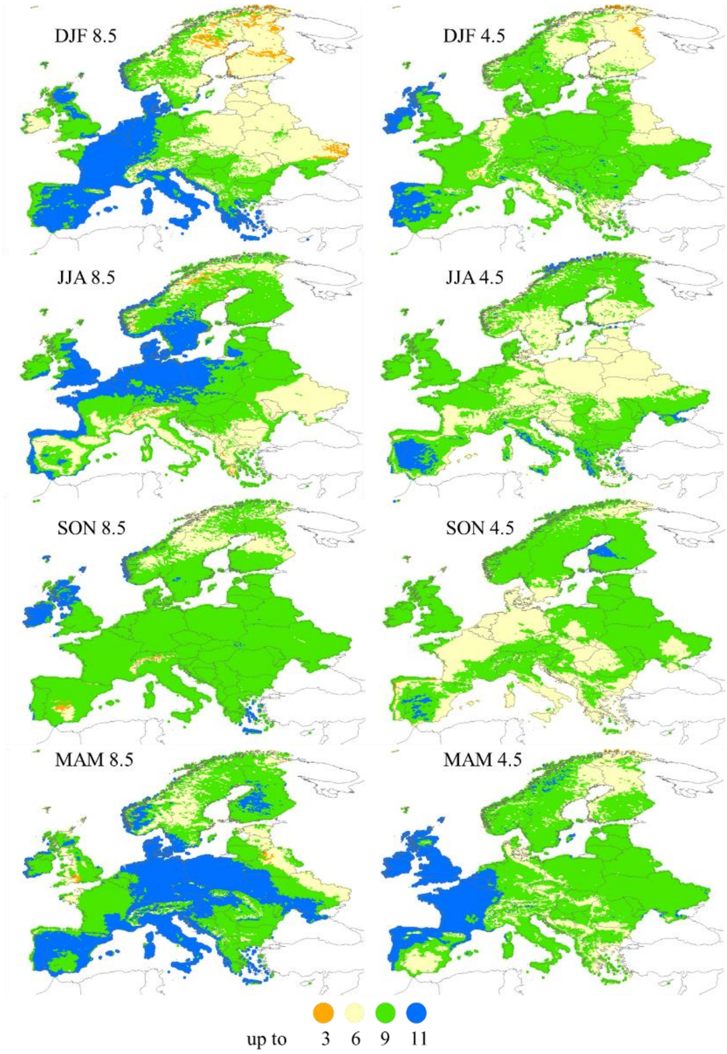


MAM – March – April - May

In Figure 13, the agreement among the models in returning the value displayed by the temperature variation ensemble mean maps (central rows in Figures 9-12) is reported. For every season and under the two RCPs scenarios considered, in each grid point is computed the number of models for which the anomaly is included in the range assessed by the classes adopted in Figure 9. The larger the number of models evaluating an anomaly within the class displayed above, the higher the agreement among the climate simulations is. Therefore, the spread of the model results compared to the ensemble mean value can be assumed low; on the other hand, when the number of models is small, the value returned by the ensemble mean represents an algebraic sum of climate simulation outputs characterized by high scattering.

For example, under the scenario RCP8.5 for the season DJF, the largest part of the domain for which the mean temperature anomaly does not exceed 4°C is generally characterized by a high agreement among the climate simulations, while higher temperature anomalies on north-east Europe are featured by a lower agreement. In this regard, such results can be also explained considering that for the actual anomaly, values close to the lower (higher) boundary of the class to which they pertain, a substantial number of models can be included in the preceding (following) class. A valuable example is represented by the scenario RCP4.5 for the season SON, where the ensemble mean value returns values ranging from 2°C to 4°C but with large areas (e.g. Central Europe) where the agreement is low. Similar patterns are also retrievable for other seasons (for example in the season MAM under RCP4.5 or JJA under RCP8.5). In general terms, the agreements in returning temperature growths appear more evident under the scenario RCP8.5 (for example in seasons DJF or MAM); nevertheless, no uncertainties arise about the increasing signal.

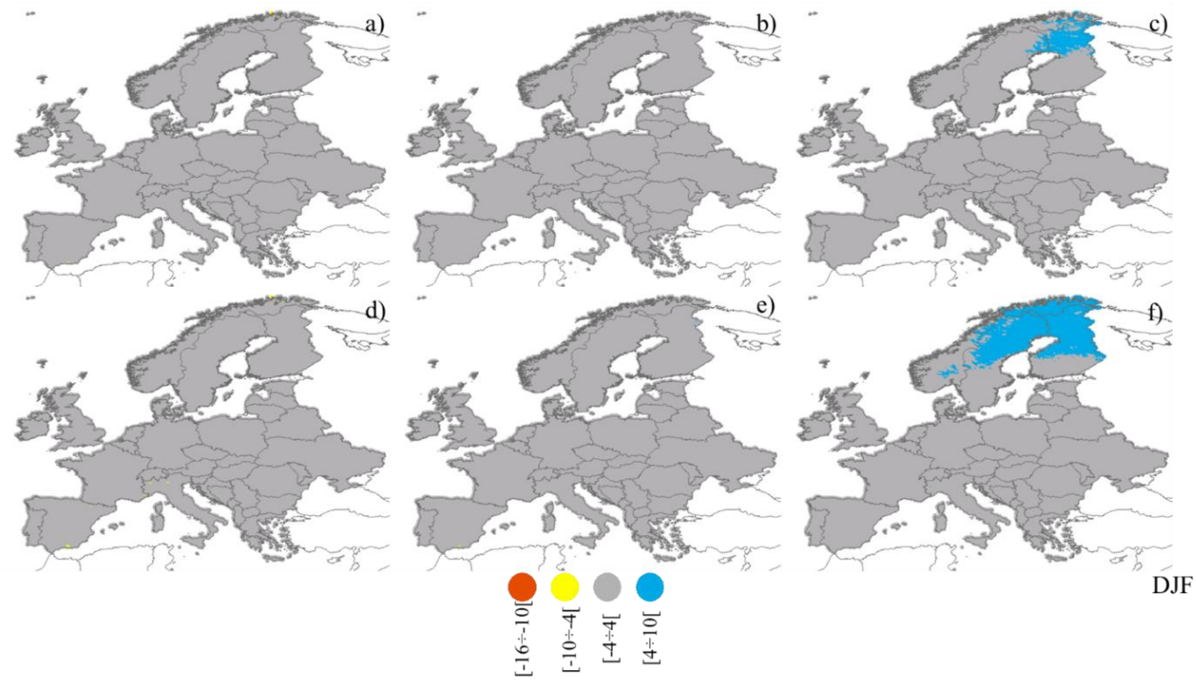
Figure 13. Agreement among climate simulations for mean temperature anomaly for the period 2056-2085 vs 1971-2000 under the RCP8.5 concentration scenario (first column) and RCP4.5 (second column) for the four seasons; Unit: n° of models.



Expected seasonal variations in relative humidity are reported in Figures 14 to 17. The changes assume values ranging between ±10%, which are fairly small in absolute terms but with varying tendencies according to the area and the season. In general, according to the IPCC Report (2014b), the observations available in the past 40 years show that relative humidity stayed almost constant at a global scale, albeit monitored temperature increased. For the future, the IPCC Report (2014b) states that "*on the planetary scale, relative humidity is projected to remain roughly constant, but specific humidity to increase in a warming climate*".

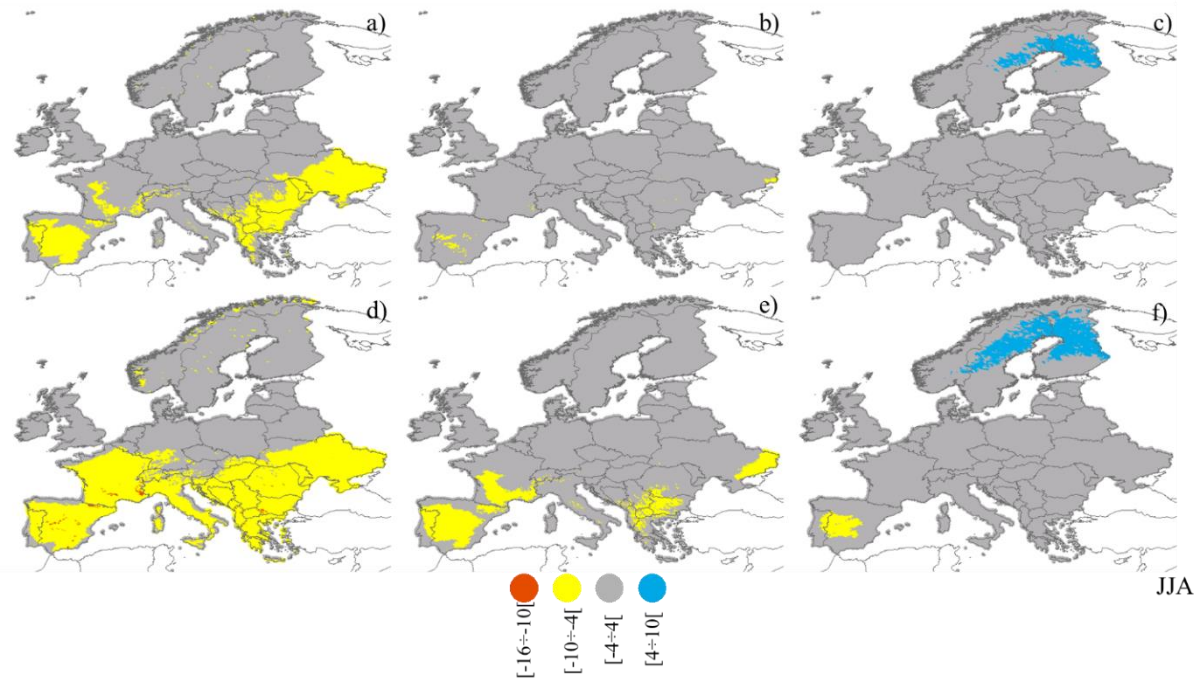
In recent years, several works investigated the large differences in expected variations on relative humidity between land and oceans (Sherwood et al., 2010; IPCC, 2014b; Byrne and O'Gorman, 2013, 2016) and showed a general decrease and increase, respectively. Several reasons may explain such differences; briefly, continents could warm more rapidly than oceans, but the higher atmospheric demand induced by the larger moisture retention capacity cannot be generally fulfilled by the soil moisture or the moisture transport by oceans. At the same time, changes in land use, and/or in stomatal conductance under elevated CO_2 concentrations, prevent the moisture transfer to the atmosphere, implying a drop in land relative humidity. In general, over Europe, the EURO-CORDEX ensemble returns slight variations in relative humidity with decreases in the Mediterranean area, probably induced by the above-reported dynamics, and increases in north Europe, probably due to lower reference starting values and higher soil water availability.

Figure 14. Mean relative humidity anomaly and confidence interval for the season **DJF** under the concentration scenarios RCP4.5 (first row) and RCP8.5 (second row); 2056-2085 vs 1971-2000; further details in Table 2. Unit: °C.



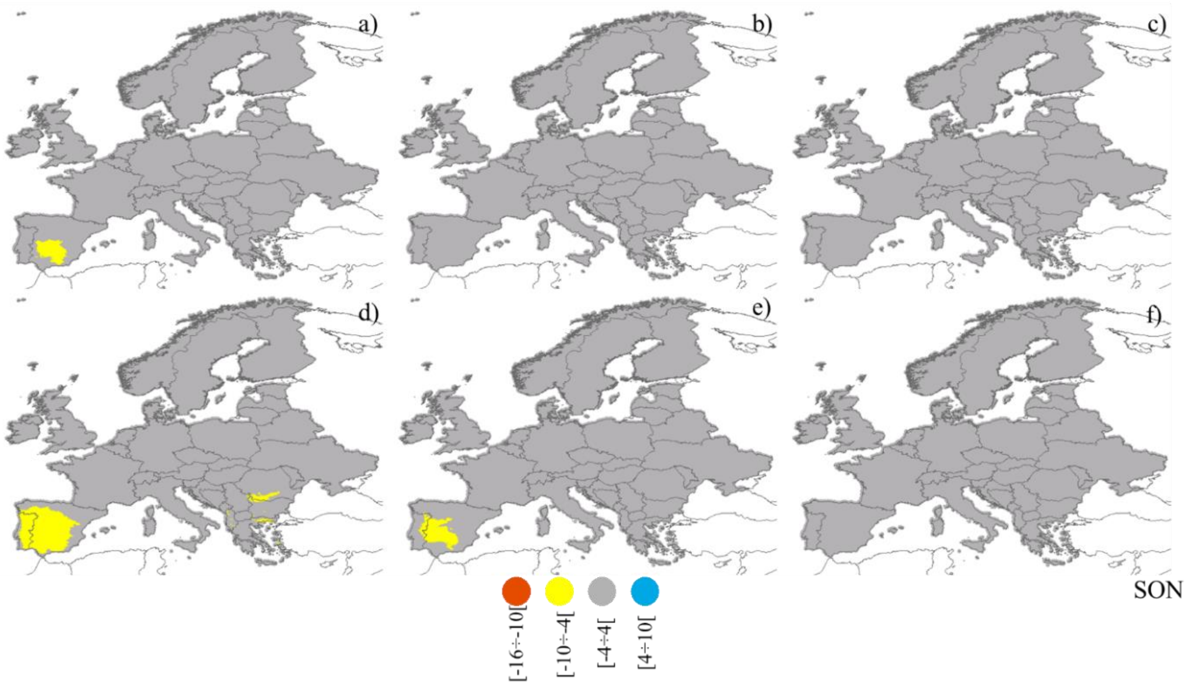
DJF - December-January-February

Figure 15. Mean relative humidity anomaly and confidence interval for the season **JJA** under the concentration scenarios RCP4.5 (first row) and RCP8.5 (second row); 2056-2085 vs 1971-2000; further details in Table 2. Unit: °C.



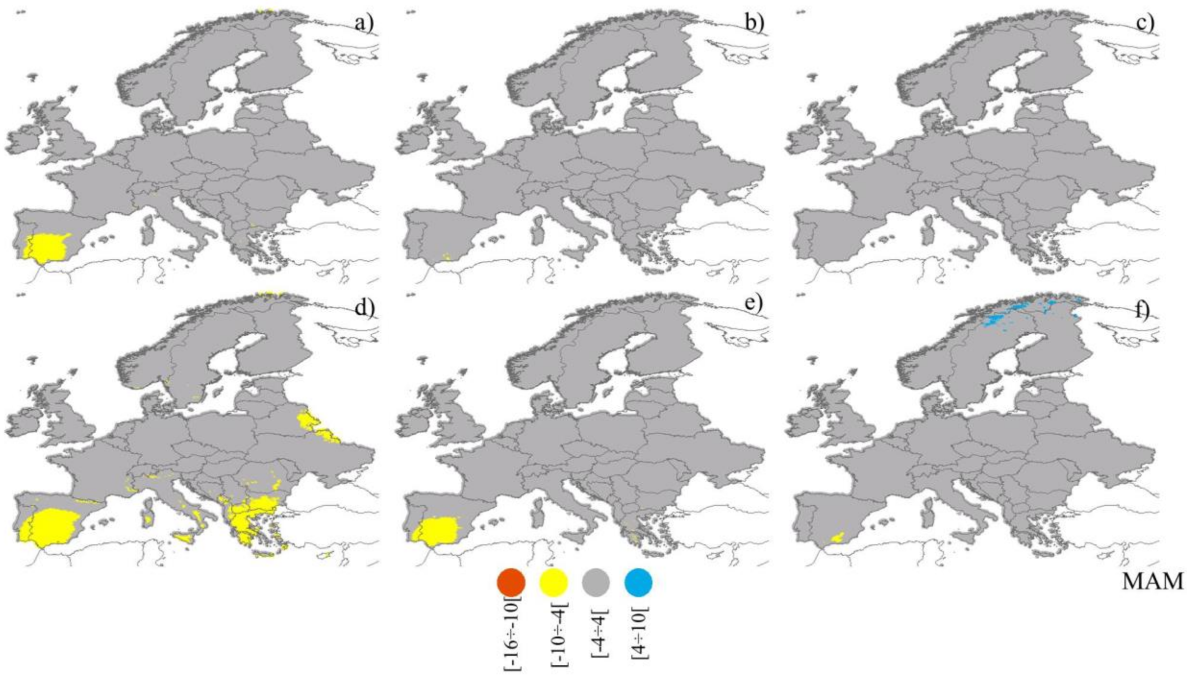
JJA – June-July-August

Figure 16. Mean relative humidity anomaly and confidence interval for the season **SON** under the concentration scenarios RCP4.5 (first row) and RCP8.5 (second row); 2056-2085 vs 1971-2000; further details in Table 2. Unit: °C.



SON – September – October - November

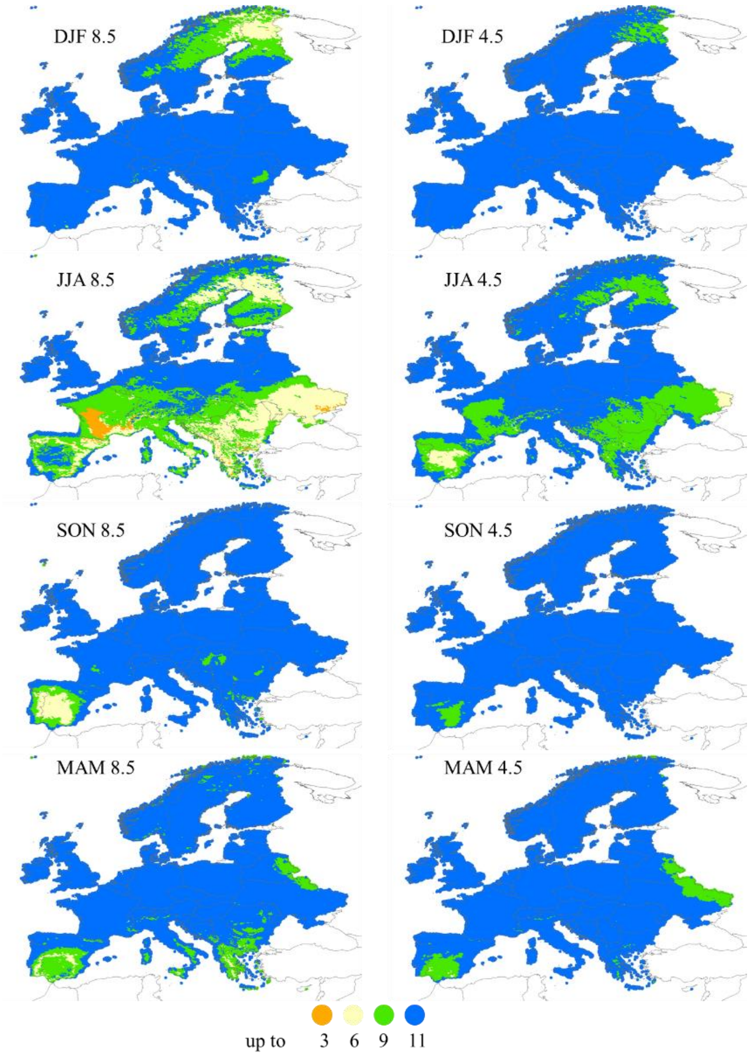
Figure 17. Mean relative humidity anomaly and confidence interval for the season **MOM** under the concentration scenarios RCP4.5 (first row) and RCP8.5 (second row); 2056-2085 vs 1971-2000; further details in Table 2. Unit: °C.



MAM – March – April - May

In Figure 18, the agreement among the models in returning the value displayed by the ensemble mean value of relative humidity is presented in a similar way to Figure 13.

Figure 18. Agreement among climate simulations for relative humidity anomaly 2056-2085 vs 1971-2000 under RCP8.5 concentration scenario (first column) and RCP4.5 (second column) for the four seasons; Unit: n° of models.



In this case, the data tend to substantially confirm the very low variations expected in Europe. In fact, the largest part of the climate simulations does not return significant variations. Furthermore, slight reductions in relative humidity that are expected under the scenario RCP8.5 in southern Europe (especially in season JJA presented Figure 15) are characterized by a low agreement among climate simulations.

Finally, Figure 19 and Figure 20 provide a brief overview of extreme values variations showing, respectively, the variation in the number of days with mean temperature higher than 25°C and daily relative humidity higher than 80%. Concerning the first case, a north-south gradient is clear in Figure 19 with larger variations under the RCP8.5 scenario, attaining increases in south Europe up to 50 more days per year with mean temperature higher than 25°C and peaks up to 80 days per year for EM+δ, mainly in the southern part of Greece (Figure 19f). At the same time, a large part of the Scandinavian Peninsula, Great Britain and Ireland are not affected by such increases. Regarding the variation in the number of days with relative humidity higher than 80%, reductions up to 40 days in Southern Europe and increases of comparable magnitude in Northern Europe (especially in Scandinavian Peninsula) may be observed in Figure 20.

Figure 19. Variation between 2056-2085 and 1971-2000 in the number of days with temperature higher than 25°C under the concentration scenario RCP4.5 (first row) and RCP8.5 (second row); further details in Table 2. Unit: days.

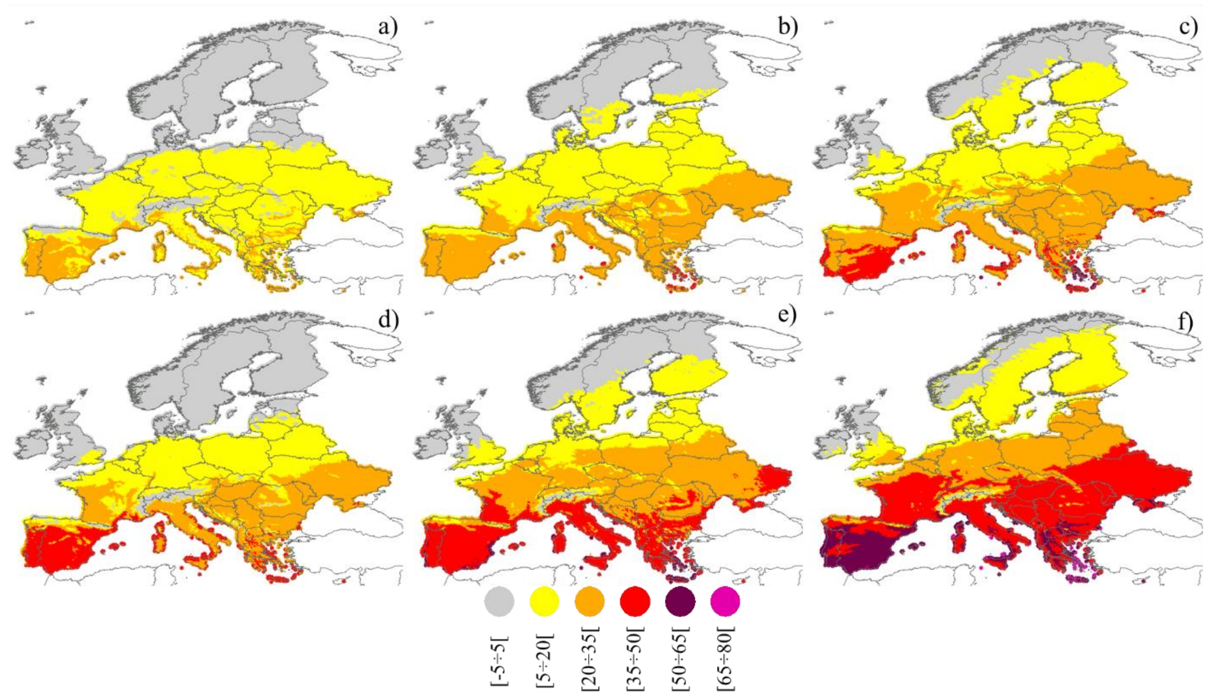
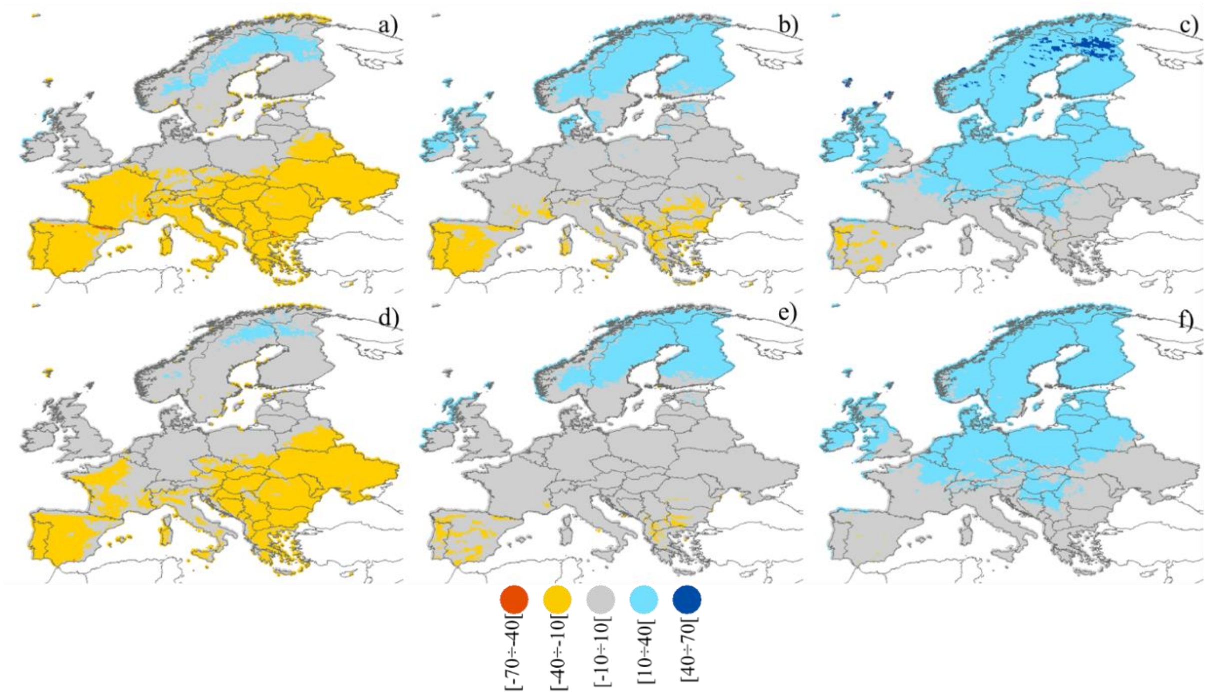


Figure 20. Variation between 2056-2085 and 1971-2000 in the number of days with relative humidity higher than 80% under the concentration scenario RCP4.5 (first row) and RCP8.5 (second row); further details in Table 2. Unit: days.



3.3 Concluding remarks

The Chapter presented the assessed variations in weather variables that are recognized as effective proxy indicators for studying the effect of atmospheric dynamics on corrosion processes.

The main findings provided by the ensemble of climate simulations included in EURO-CORDEX initiative, are summarized in the following. Climate simulations provide clear indications of an increase in the temperature over Europe. The severity of the concentration scenarios forcing the climate models plays a relevant role on the severity of such increases, while the spatial patterns of temperature vary according to the seasons. On the other hand, coherently with the state-of-art literature, less evident variations could occur in relative humidity all over Europe. In this regard, relative humidity variations are indirectly induced by temperature increases that regulate the maximum amount of water vapour that the air could sustain.

The following chapter presents specific impact models able to assess the effects of local atmospheric phenomena on corrosion processes. Those models use as input the weather variables studied above and their respective variation. On the other hand, the relevance of such changes on the corrosion dynamics should also take into account the current values of temperature and relative humidity on the area of interest.

4 State-of-the art of the research on corrosion of structures due to climate change

4.1 Effects on reinforced concrete structures

The durability of reinforced concrete (RC) structures is affected by climate change entailing variations in temperature and atmospheric humidity, and the increment of carbon dioxide (CO_2) concentration levels. In fact, these three parameters are the principal environmental drivers to increase concrete deterioration. The infiltration of harmful substances from the environment, such as chloride (chlorination) and carbon dioxide (carbonation) causes reinforcement corrosion. A raise in temperature and relative humidity will increase the rate of infiltration of these substances, with the corresponding increment of the steel corrosion rate (Bastidas-Arteaga et al., 2013).

Corrosion induced damage will affect serviceability and ultimate limit states of RC structures. Serviceability limit states (SLS) are related with corrosion initiation (due to carbonation or chlorination), cover cracking initiation or cover cracking propagation until a given threshold (Enevoldsen et al., 1994 and Neville, 1995). Ultimate limit states (ULS) are used to evaluate the probability of failure and account for applied loads and structural configuration (Bastidas-Arteaga et al. (2013). A larger number of studies focused on SLS where the main findings could be generalised without focusing on a given structure and could be useful for standardisation purposes.

4.1.1 Carbonation

Carbonation in concrete occurs because the calcium bearing phases present are attacked by the CO_2 and converted to calcium carbonate, thus reducing the pH of the concrete till values below the passivation threshold of steel. Changes in temperature due to the global warming will modify the diffusion coefficient of CO_2 to concrete, the rate of reaction between CO2 and $Ca(OH)_2$, and the rate of dissolution of CO_2 and $Ca(OH)_2$ in pore water (Saha and Eckelman, 2014).

In general terms, the carbonation depth will depend on (a) the diffusion coefficient, which is temperature- and time-dependent; (b) cement content, and calcium oxide content in cement, water–cement ratio w/c; (c) CO_2 levels in the environment (time-dependent); (d) time of exposure; and (e) relative humidity (RH) (e.g., annual frequency of wetting and drying cycles). Russell et al. (2001) and Al-Khaiat and Fattuhi (2002) reported the existence of a RH threshold (around 30%-50%) below which there is no carbonation reaction. Nevertheless, values of RH between 50% and 70% seem to be critical (Russell et al., 2001).

Yoon et al. (2007) analysed for the first time the relation between atmospheric CO_2 concentration and concrete carbonation depth. They proposed a simplified model based on the relationship between time and carbonation depth, but it fails to account for the influence of temperature change. Based on this first work, more complex models have been proposed where time-dependent CO_2, temperature and humidity, or a combination of them are considered. For instance, Talukdar et al. (2012a, b) presented a mathematical model to assess the depth of carbonation in non-pozzolanic, unloaded concrete structures, for time-varying concentrations of CO_2, temperature and humidity. De Larrard et al. (2014) also studied the effects of climate variations and global warming on the durability of RC structures subjected to carbonation. This study considered a carbonation finite element model into a comprehensive reliability framework and was applied to the probabilistic assessment of carbonation effects for several cities in France under various climate change scenarios. It was found that climate change and local relative humidity have a significant impact on corrosion initiation risks. In addition, some studies have focussed on specific type of concrete, such as Park and Wang (2017), who analysed the influence of the climate change on the carbonated-induced corrosion of high-volume fly ash (HVFA) concrete. HVFA, which contains more than 50% fly ash in the binder, is especially susceptible to carbonated-induced corrosion.

Table 3 shows a summary of different findings related to the effect of climate change on the RC structures, regarding the carbonation ingress process. It is noted that the location of the analysed cases is indicated in the second column. The reason is that, as highlighted by Talukdar and Banthia (2013), the results are very sensitive to local exposure conditions.

Table 3. Effect of climate change on RC structures, regarding the carbonation ingress process

Ref.	Location	Assumptions	Estimation		Scenarios	
			Target	**Value**	**Baseline**	**Target**
Park and Wang (2017)	Laboratory study	(a) increasing CO_2 concentration, and (b) increasing temperatures	service life of a HVFA concrete	reduction of almost 12%, more that 9% occurs during the initiation stage	year 2000	year 2100
Talukdar et al. (2012b)	Canada	(a) increasing mean yearly temperature, (b) increasing duration of the hot season, (c) constant RH over time, and (d) increasing concentration of CO_2	carbonation depths of non- pozzolanic, unloaded concrete structures	increment of 45%	year 2000 CO_2 level	A1FI, year 2100
Talukdar and Banthia (2013)	Mumbai, London, New York City, Sydney, Toronto, Vancouver (moderate humidity, higher temperatures)	(a) time dependent temperature	carbonation depths	increments between 27% and 45% (15 and 35 mm)	year 2000 CO_2 level	A1FI, year 2100
Saha and Eckelman (2014)	Boston metropolitan area	(a) increasing temperatures, (b) increasing concentrations of CO2	carbonation depths	increment of 40%	year 2000 CO_2 level	A1FI, year 2100
Peng and Stewart (2014)	China	(a) CO_2 concentration, (b) local temperature and (c) RH variable over time	carbonation depths	increment of 45%	year 2010 CO_2 level	RCP8.5, year 2100
Mizzi et al. (2018)	Malta	(a) increasing CO_2 concentration, and (b) increasing temperatures	carbonation depths for different concrete grades	increment up to 40%	RCP 2.6	RCP8.5, year 2070
De Larrard et al. (2014)	France (Nantes, Paris, Strasbourg, Clermont-Ferrand, Toulouse, Marseille)	(a) increasing CO_2 concentration, and (b) temperature and relative humidity changing locally depending on climate change scenarios (c) uncertainty on model parameters	reliability index concerning corrosion initiation	reliability indexes depending on specific weather conditions	year 2000 CO_2 level	A2, A1B, B1, year 2100

RCP8.5 scenario for the period 2081-2100 (mean=3.7 ºC & interval=[2.6-4.8]) and A1FI scenario for the period 2090-2099 (mean=4 ºC & interval=[2.4-6.4]) are comparable (Khatami and Shafei, 2017).

4.1.2 Chlorination

Chloride ingress occurs through the release of bound chloride in the hardened concrete, resulting in a reduction of the alkalinity and potentially increasing the risk of corrosion (Neville, 1995). Chlorination of concrete can penetrate concrete by diffusion, convection, migration, absorption, permeation, and thermo-diffusion (Nguyen et al., 2017), and it is highly affected by the temperature and humidity. It is present in environments affected by de-icing salt and in coastal regions, allowing four different scenarios, which are, submerged, tidal, splash and salt spray. The content of chlorides in the concrete mixing is usually neglected when comparing with the one coming from outside, if chloride content is controlled in the concrete constituents.

The chloride concentration at a given depth mainly depends on (a) concrete diffusivity, which is mainly temperature-, relative humidity-, and time-dependent; it also depends on concrete properties related to its composition (water to cement ratio, type of cement, etc.) and manufacturing (vibration, curation, etc.); (b) surface chloride concentration that depends on the exposed conditions and whose variability over time is not determined yet, and some authors, such Stewart et al. (2011), stated that it does not seem to change significantly over time; and (c) loading conditions that would induce concrete cracks that would facilitate the chloride propagation, Wang et al. (2018) report that static or fatigue loading could induce significant lifetime reductions.

Recent studies addressing the impact of climate change on the chloride-induced corrosion in different geographical locations have been conducted. For instance, Khatami and Shafei (2017) analysed the impact of the climate change effects on the chloride-induced corrosion of bridges in the U.S. Midwest region due to the de-icing salts, modelling also the increment of the consumption of the de-icing salts (doubled in 25 years) as a consequence of the climate change. For all the scenarios considered, they observed an increasing trend of chloride content at the rebar level. Using the RCP2.6 scenario as a baseline, scenarios RCP4.5 and RCP8.5 show values 16% and 37% larger by the end of the century. Nguyen et al. (2017) proposed a thermo-hydro-chemical model to estimate the long-term life of RC structures in France based on the chloride ingress under different climatic scenarios and exposure conditions. They found that, in tidal zones with large immersion time, models based on seasonal variations can be used to estimate the risk of chloride-induced corrosion. In other cases, the selection of the climate models is a sensitive aspect.

Based on the findings summarised in Table 4, the effect of climate change on the RC structures affected by chlorination-induced corrosion seems to be lower than in the case of carbonation, but still considerable. The effects could be larger if ULS are considered.

Despite of the evidence suggesting the synergistic effect of chlorination and carbonation, there are few models able to evaluate it (Zhou et al., 2015, Achour et al., 2018). However, such studies do not evaluate the potential effect of climate change.

Table 4. Effect of climate change on RC structures, regarding the chlorine ion ingress process

Ref.	Location	Assumptions	Estimation		Scenarios	
			Target	Value	Baseline	Target
Xie et al. (2018)	China	(a) increasing temperatures	chloride concentration at the rebar level of offshore RC bridges	increments of 6%-15%	year 2000	RCP8.5, year 2100
Khatami and Shafei (2017)	U.S. Midwest region	(a) increasing temperatures, (b) decreasing, constant and increasing RH, and (c) increasing surface chloride concentration	chloride concentration at the rebar level	increment of 37%	RCP2.6, year 2100	RCP8.5, year 2100
Saha and Eckelman (2014)	Boston metropolitan area	(a) increasing temperatures, (b) increasing concentrations of CO_2	chloride penetration depths	increment of 12%	year 2000 CO_2 level	A1FI, year 2100
Bastidas-Arteaga et al. (2010)	Continental, oceanic and tropical environments	(a) increasing temperatures and length of hot periods, and (b) increasing RH	probabilistic lifetime assessment until corrosion initiation	lifetime reductions ranging from 2% to 18%	year 2000	year 2000

RCP8.5 scenario for the period 2081-2100 (mean=3.7°C & interval=[2.6-4.8]) and A1FI scenario for the period 2090-2099 (mean=4°C & interval=[2.4-6.4]) are comparable (Khatami and Shafei, 2017).

4.1.3 Stages in the corrosion process

The corrosion process can be split into two stages; the corrosion initiation stage, between the penetration initiation of chloride ion and the CO_2 into concrete cover and the initiation of the reinforcement corrosion; and the corrosion propagation stage, characterized by a loss of cross-sectional area of reinforcing steel. The latter will eventually produce the cover cracking and spalling, and final loss of concrete-steel bond.

The initiation stage is assessed by means of the carbonation depth and chloride concentration at the cover depth, which depend on the parameters previously referred.

The corrosion propagation will mainly depend on the following variables; (a) bar diameter and steel properties; (b) thickness of concrete cover; (c) concrete properties, such as Young modulus, creep coefficient, Poisson's ratio and tensile strength; (d) current corrosion density, which might be time-, relative humidity- and temperature-dependent; and (e) width of the porous zone.

Concerning SLS after corrosion initiation, Enevoldsen et al. (1994) and Neville (1995) have reported the existence of a RH threshold (50%) below which the carbonation- and chloride-induced corrosion rate is negligible, whereas the maximum corrosion rate occurs when RH is around 70%-80% (Neville, 1995).

Stewart et al. (2011), focusing on both carbonation and chlorination, studied the relative change in corrosion initiation and damage risks in Australia, due to enhanced CO_2 levels, temperature and humidity for different exposure classifications of the Australian code AS3600 (2009). The scenarios considered are A1B, A1FI[52], and the baseline scenario assumes year-2000 CO_2 levels. They conclude that, in Australia, carbonation-induced damage risks can increase by over 400% by 2100 for inland arid or temperate climates. Damage risks for chloride-induced corrosion can increase by no more than 15%.

Accordingly, Xie et al. (2018) analysed the effect of climate change on the reliability of the offshore RC structure designed following the Chinese code MOHURD (2008). They conclude that for 2100, the chloride concentration at the level of reinforcement increases around 6%-15% (RCP4.5 and RCP8.5) compared against the control scenario established in the year 2000. The structural reliability during the initiation stage of the chloride-induced corrosion seems to be smaller than during the propagation stage. Once the latter is reached, the concrete spalling might occur in a short period of time (no more than 1 year) in such an aggressive environment.

A study applied to cold climate regions, specifically to the building stock in Finland (Pakkala et al., 2019), showed that the corrosion propagation phase mainly depends on the geographical location and on the direction in which the structure faces, since corrosion propagation is influenced by solar radiation and by the amount of wind-driven rain, the latter being largely influenced by climate change in the region. The average corrosion rates during winter in the coastal region are estimated to be twice larger by 2100. In order to reduce this impact, drying conditions and constructions details were found to be relevant.

With respect to ULS after corrosion initiation, Bastidas-Arteaga et al. (2013) evaluated the effects of climate change on the failure probability of bridge girders subjected to chloride ingress and climate change. The results indicated that global warming can reduce the time to failure by up to 31%, or shorten service life by up to 15 years for moderate levels of aggressiveness. More recently, Bastidas-Arteaga (2018) assessed the reliability of reinforced concrete structures subjected to corrosion-fatigue and climate change. The overall results showed that climate change effect induces lifetime reductions ranging

[52] The Special Report on Emissions Scenarios (SRES) released by IPCC in 2000 (Nakicenovic et al., 2000) defines six potential greenhouse gas emissions scenarios accounting for different economic and societal trends. Within them, scenario A1FI relates to rapid economic growth in a more integrated world, with a strong dependence on fossil fuels. A more moderate scenario is considered by A1B, with a world balancing fossil and non-fossil energy sources.

between 1.4% and 2.3% if fatigue load is neglected. Under cyclic loading, total lifetime reduction increases up to 7%.

4.1.4 Impact and adaptation

The corrosion risk caused by the future CO_2-emission levels and climate change will depend on a number of factors, such as the geographical conditions, standards used for the structural design, construction and repair materials, age of the structure, and inspection and maintenance strategies.

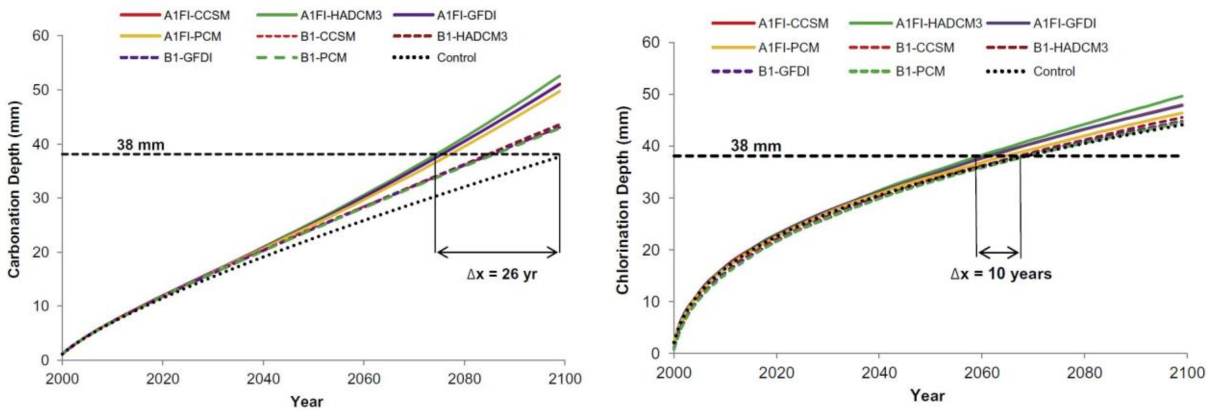
Saha and Eckelman (2014) studied the susceptibility to corrosion phenomena induced by carbonation and chlorination under the new climatic conditions of the building stock in the Boston metropolitan area infrastructure. The findings are shown in Figure 21. It is observed that, comparing the worst-case scenario with the case of control, the values of the cover thickness prescribed in the existing codes (i.e., ACI (2011)) are compromised 26 and 10 years earlier, respectively. The penetration depths in almost 60% of existing buildings in this area will exceed the code recommended cover thickness by 2050.

Stewart et al. (2011) found that the temporal and spatial effects of a changing climate can increase current predictions of carbonation-induced damage risks by more than 16%, which means that one in six structures will experience additional and costly corrosion damage by 2100 in Australia and presumably elsewhere. In addition, Bastidas-Arteaga et al. (2010) and Bastidas-Arteaga and Stewart (2015) noted that climate change can lead to lifetime reductions ranging from 2 to 18% for RC structures in France subjected to continental, tropical and oceanic weather conditions.

According to Saha and Eckelman (2014), concrete buildings in coastal locations should be designed with extra concrete cover (from 3-5 mm for the optimistic scenario, and up to 5-12 mm for the worst-case scenario), or using higher grade concrete or reinforcement, such as low carbon steel, stainless steel, galvanized steel or other methods of cathodic protection, or glass-fibre reinforced polymer rebars. For the existing buildings, it is also possible the use of protective surface coatings. Stewart et al. (2012) noted that the carbonation depths can be reduced by 10–65% by applying acrylic-based surface coatings. Critical structures may require more expensive interventions, such as the electro-chemical chloride extraction chlorination.

Stewart et al. (2012) considered the effect of climate adaptation strategies including increases in cover thickness, improved quality of concrete, and coatings and barriers on damage risks.

Figure 21. Left: Estimated carbonation depth (mm), and Right: estimated chlorination depth (mm), in Boston Metropolitan Area for a building constructed in 2000, under the emission scenarios IPCC A1FI (high) and B1 (low), and considering different atmospheric-oceanographic global climate models, *i.e.*, Community Climate System Model (CCSM), Hadley Climate model (HADCM3), Geophysical Fluid Dynamics Institute Model (GFDI) and Parallel Climate Model (PCM). The control scenario considers C02 and temperature constant over time (Saha and Eckelman, 2014).



It was found that increases in design cover ameliorate the RC durability under a changing climate. The increment of cost when increasing design cover by up to 8 mm or increasing concrete compressive strength by one grade is roughly estimated at 2-4%.

Given that the current annual cost of corrosion worldwide is estimated to exceed $1.8 trillion, which translates to 3% to 4% of the Gross Domestic Product (GDP) of industrialised countries (Schmitt et al., 2009), it can be foreseen that the increased maintenance and repair costs resulting from the acceleration of the corrosion process due to climate change might be of hundreds of billions of dollars annually (Bastidas-Arteaga and Stewart, 2015).

On the other hand, none of those studies includes cost-benefit assessment of climate adaptation strategies as recommended by Stewart et al. (2014). Bastidas-Arteaga and Stewart (2016) studied, in several locations of France, to which extent increasing the design cover by 5 or 10 mm is cost-effective when compared to the cost of repairing the corrosion damage by the technique of patch repair. They conclude that the cost-benefit of the different strategies will depend on the type of structural component and also the specific location (see Section 4.3 for further details). This fact highlights the importance of including the local climate conditions (i.e., the specific exposure) when updating the current standards. In addition, other aspects such as the type of structural element (applying adaptation strategies to smaller elements is less interesting in terms of cost-benefit) can be also considered.

Other strategies, such as the improvement of concrete mixes and application of coatings have not been extensively studied yet.

Certain types of blended and alkali-activated (AA) cements are likely to perform better than standard Portland cement (PC) when protecting steel reinforcement from corrosion. It is widely acknowledged that the use of certain types of blended cements improves the durability of concrete (e.g. the corrosion rate of steel reinforcement is significantly lower in slag-cement[53] concretes). In addition, some alkali-activated (AA) materials (e.g., AA slag cements) show very high corrosion resistance (Provis and van Deventer, 2014). Due to the high density of their matrices, AA cements tend to be highly impermeable, and can result in an excellent performance holding the steel bars in a passive state. Furthermore, AA cements are produced by the reaction of an alkali metal source and a silicate powder. Silicate powders coming from some locally produced waste (Alelweet and Pavia, 2019), are being investigated to produce low-cost, sustainable AA cements. These materials have a lower embodied energy and lower carbon and greenhouse gas emissions than PC, and can provide a sustainable alternative to PC. Slag cement was incorporated into concrete projects in the U.S.A. one century ago to improve durability, whereas AA cements have more tradition in Russia. Nevertheless, the feasibility of replacing PC binders in specific engineering applications should be further explored.

4.1.5 Concluding remarks

Despite the evident effort of recent years to understand and assess the impact of climate change on the European RC structures, important questions still remain open. Among them, the following are the most relevant in the context of this document;

(a) *Determining the reliability of the existing structure and building stock in the face of the changing climate*.
In this case, an extensive database of the European building stock is needed including aspects such as the age of construction, structural layout, materials, and structural type of the different structures and buildings.

(b) *Determining the evolution of corrosion associated with the future climate conditions and CO_2 levels.*
Accurate mathematical models accounting for the changing CO_2 levels and temperature and humidity variation are needed to determine the structural degradation process. In this

[53] In slag-cements, slag substitutes part of the Portland cement.

regard, it is recalled that combined carbonation and chlorination processes have not been modelled yet.

(c) *Determining the most cost-effective strategies to tackle the climate change-induced corrosion of both the existing and the new structures and buildings, with a global perspective.*
That is, the strategies should not be case-specific, but generalised accounting for typology, use, environmental conditions, geolocation, orientation, etc. In this regard, the focus should be put on the SLS that is linked with the initiation stage dominating the structural service life, rather than the ULS, linked to the propagation stage occurring during the last 1-10 years of the structural life. In addition, mapping the impact of climate change on temperature and humidity is mandatory in this context. It is noted that forecasting the evolution of the corrosion drivers in an accurate manner is challenging. As seen in the first part of this report, there are some *certainties* in terms of the climate evolution, nevertheless, there is also an important level of uncertainty given by the global economic and societal evolution. As a consequence, structural standards (codes) should include design-related adaptation measures addressing the "certain" climate change impact in a cost-effective manner. To tackle the uncertainty related to climate change, a sound measure is to prescribe specific maintenance activities in the structural standards (codes). That is, part of the adaptation investment should be put in place only if needed.

4.2 Effects on steel structures

Corrosion of metallic materials is defined as the destructive attack on a metal by chemical or electrochemical reactions with the environment (Revie, 2011). For corrosion to take place, two main elements are required: moisture and oxygen. Corrosion tends to cause the production of materials with much lower strength and thus significantly reduces the capacity of metallic elements. This is particularly true for steel elements, where Iron (Fe) oxidizes into iron oxides, which are much weaker than steel.

The detrimental effect of corrosion in steel structures is the loss of thickness of the cross-sections, thus affecting the structural performance in terms of strength, stiffness and ductility. In some cases, the stability of the structure could be affected by the local failure of components and, in case of cyclic loads, corrosion may lead to a significant reduction of the fatigue strength. In fact, corrosion is one of the main reasons, beside fatigue problems, for the failure of steel and composite structures.

The effects of climate change, including the change of temperature and RH, the increase in pollutant concentrations, the change in precipitation and wind patterns, etc., can have a significant impact on the service life of infrastructures (Cole and Paterson, 2010).

In the following paragraphs, the main factors controlling the degradation of metals are firstly described. Then, a brief discussion on the projected performance of steel structures is provided, based on the potential changes of these factors due to climate change.

4.2.1 Corrosion of metals and alloys

Corrosion is, combined with fatigue, the main deterioration mechanism of metallic structures and metallic structural components (e.g. bolts in timber structure, external steel plates in precast concrete construction).

Steel is the most common structural metal in the construction industry; zinc is frequently used as a protective system for steel. Due to the importance of steel to the construction industry, the following discussion is mainly devoted to this material.

The corrosion phenomena of metals and alloys is complex, and a range of corrosion processes can lead to the deterioration of structures. Considering the corrosive environment, degradation mechanics are classified into (Landolfo et al., 2010): (i) microbial and bacterial corrosion, (ii) gaseous corrosion, (iii) marine corrosion, (iv) underground corrosion, and (v) atmospheric corrosion.

Most metallic structural components, and in particular buildings and bridges are not exposed to particularly aggressive environmental, like those associated with gaseous, marine and underground corrosion. For these, atmospheric corrosion, associated with oxidation of metals exposed to the ambient air is critical. This form of corrosion occurs during unsheltered exposure to rain or in rain-sheltered exposure indoors and outdoors (Leygraf et al., 2016).

The initial stage of atmospheric corrosion is characterized by the formation of a layer of thin-film electrolyte (see Figure 22). This layer can be formed by rain, dew, and condensation of high RH (Revie, 2011). In moderate climates, this film is formed due to condensation, which typically occurs in the morning, when the metal surface is cooler than the surrounding air and the relative humidity goes above a certain threshold. For uncontaminated water, this threshold is designated *dew point* and evolves with air and surface temperate as shown in Figure 23.

Figure 22. Schematic representation of atmospheric corrosion of steel

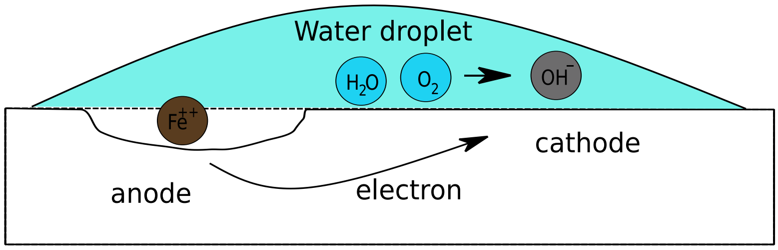
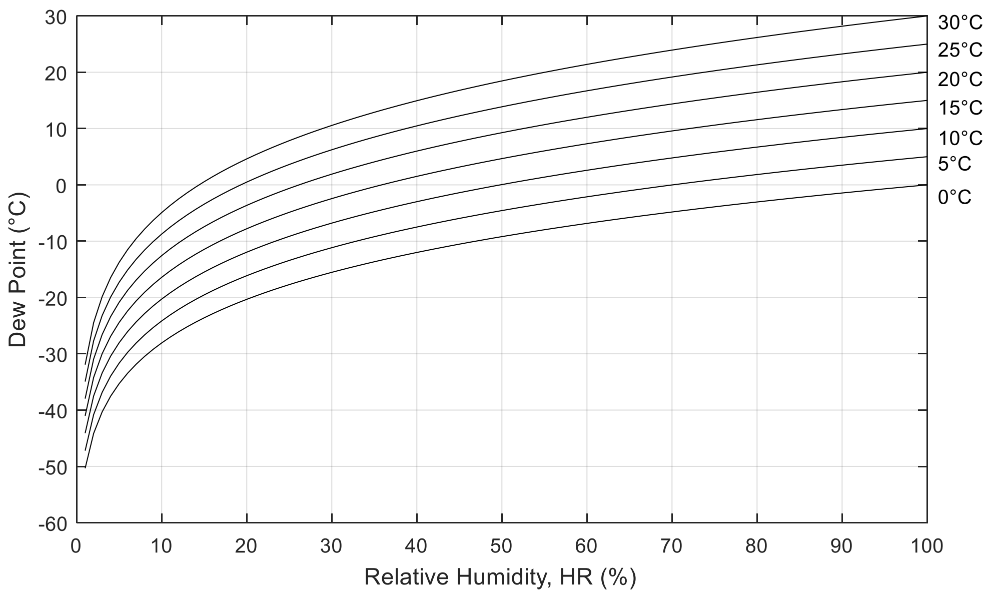


Figure 23. Relation between dew point temperature, relative humidity and metal surface temperature



A simplified indicator of the potential for formation of this film is the Time of Wetness (TOW) defined as the period of time when the relative humidity is above 80% and the temperature is over 0°C.

The progress of corrosion is also strongly influenced by the composition and contamination of this film. For example, the presence of chloride, typically originating from sea salt, can increase the time of wetness by reducing the required RH by up to 77%, but also the conductivity of the electrolyte, and thus accelerate corrosion. On the other hand, sulphur dioxide will be oxidized into sulphate ions in the water, producing hydrogen ions which rise the acidity of the electrolyte, increasing the corrosion rate.

The key factors affecting the atmospheric corrosion of steel structures, and the rate at which this type of corrosion occurs are (Infosteel, 2012):

- the relative humidity (RH) of the air where the metallic structure or component is located,
- the risk of condensation (depending on the relative humidity, the temperature of the metallic surface, the speed at which the air is moving, and the concentration of NaCl at the surface),
- the concentration of corrosion pollutants (gases, solids or liquids), such as sulphur dioxide, acids, alkalis or salts.

All these factors are potentially impacted by climate changes, often in conflicting ways and varying from location to location.

The cumulative impact of all these changes is still extremely complex to predict, and in the following each relevant potential impact of climate change on atmospheric corrosion will be discussed, based on the works of Cole and Paterson (2010), and its relevance in the European context will be evaluated.

i) Relative humidity (RH)

A fundamental requirement for atmospheric corrosion is the presence of a thin film electrolyte that can form on metallic surfaces (Nguyen et al., 2013). Longer presence of the film means longer periods of active corrosion and, consequently, greater average corrosion rates. For temperate climates, the fraction of time this film is present is mostly a consequence of the relative humidity, even if influenced by other parameters like temperature and presence of pollutants. For most of the European region, changes in RH are a critical factor affecting the impact of climate changes on corrosion.

ii) Temperature

As discussed above, atmospheric corrosion occurs when an electrolyte film is present. The presence of this film can be estimated based on the time of wetness described as the fraction of time humidity is above 80% and temperature is above 0°C. Consequently, increases in average temperature can impact the corrosion rate, particularly in cold areas. Although high temperatures generally increase the velocity of chemical reactions and thus of corrosion, most researchers found this variation to be of secondary importance in relation to the variation of the other parameters (Ben et al., 2017; Cole and Peterson, 2010).

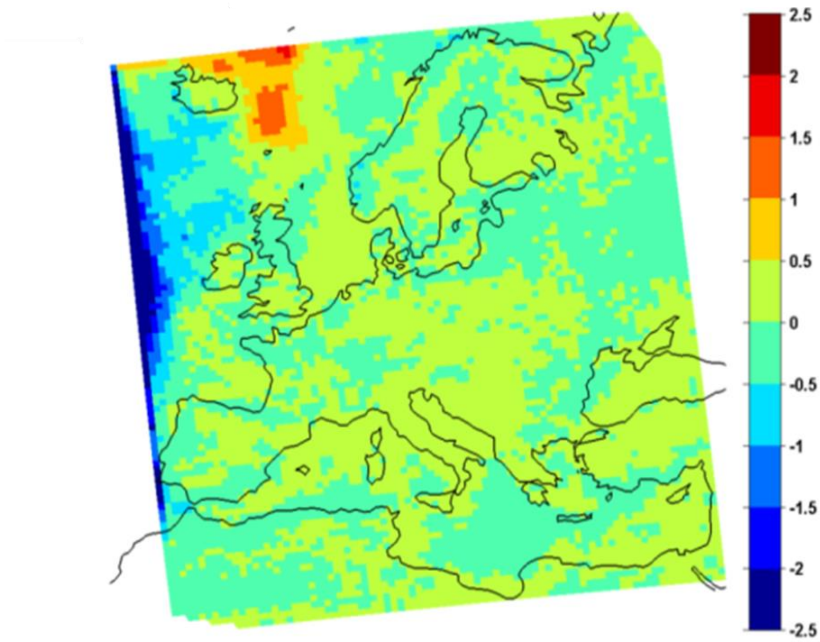
iii) Pollutants

As discussed, the electrolyte film can present very high levels of contamination, due to the presence of salt or pollutants. As described by Cole and Peterson (2010) these can accelerate the corrosion process. However, environmental policies aiming at mitigating climate changes are likely to reduce the emissions of other pollutants and, consequently, might reduce the presence of pollutants in the air over the life of structures. On the other hand, changes in wind patterns might change the dispersion of pollutants. Both of these effects are associated with very large uncertainty, as the first depends on long term policies, technological evolution and economic driver. The dispersion of pollutants will depend on local wind patterns for which, at this time, there are no reliable models.

iv) Salt

Chlorides are potentially the most critical non-human induced pollutant to corrosion. It usually originates from sea spray produced my mixing of air and sea water in whitecaps. Changes in temperature and wind patterns will change the production of surf in the sea and the transport of this to land. The consequent changes in concentration of salt deposited on metal surfaces has the potential to change the corrosion rate. This is a particularly complex aspect of the impact of climate changes on atmospheric corrosion as it depends not only on the climate changes on the location of interest, but also on the oceanic areas where surf is created, both at high sea and near the coast. In fact, as discussed in Cole et al. (2003), salt aerosols may be produced by whitecaps out in the ocean, or from the surf closer to the coast. The latter produces much higher concentrations of salt, but is only relevant for locations very close to the sea (<1km). Although oceanic whitecaps do not produce such high salt aerosol concentrations as surf, these aerosols may impact a wider area. Given the right circumstances they can travel up to 50km through the air. Cole and Paterson (2004) also found that wind is a crucial climatic parameter influencing the concentration of salt aerosol, but the relative humidity and rainfall also play a role on the generation of ocean aerosol. Reduction in rainfall and humidity increases the potential for transport of salt. A prediction of future evolution of the deposition of salt over Europe is presented in Figure 24, showing that some areas might experience increase in salt deposition while others will experience a decrease. This overall impact of salt on the evolution of corrosion is a combination of the changes in deposited salt and salt washing associated with rainfall patters.

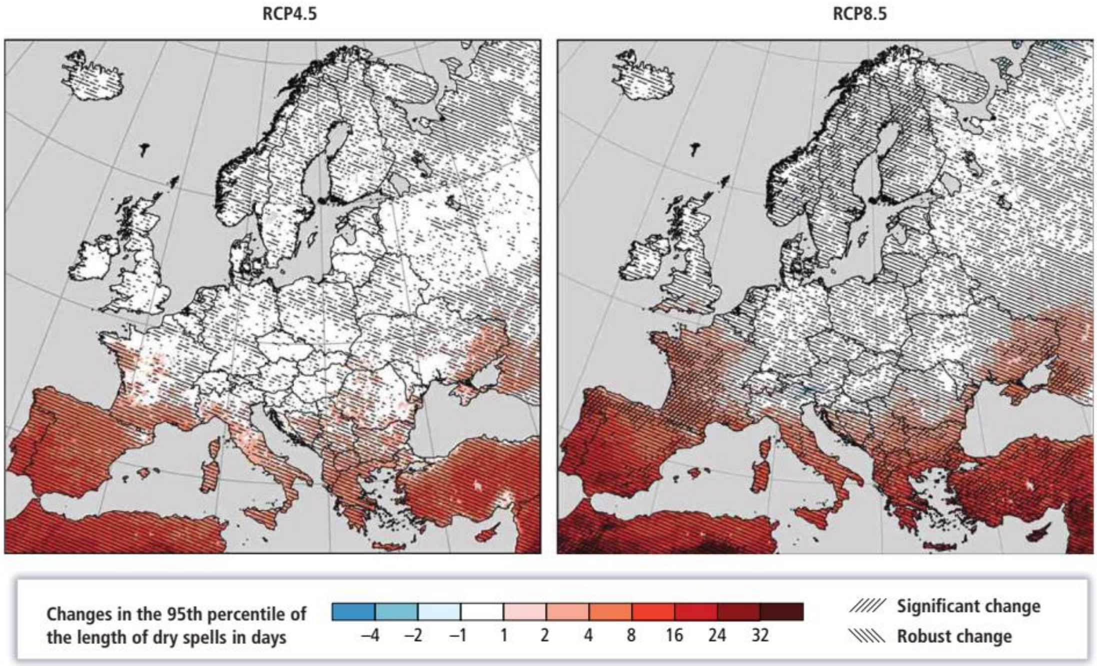
Figure 24. Variation of sea salt deposition (mgPM$_{10}$ m^{-2}): absolute difference between the future (2040–2059) and past periods (1990-2009) based on SILAM model (Sofiev et al., 2011). Figure source: in Soares et al., 2016



v) Rainfall patterns

As discussed above, the concentration of pollutants and salt on the metallic surface is critical for the corrosion initiation and rate of progress. Rainfall has usually a beneficial effect by washing out the atmospheric pollutants that are deposited on exposed surfaces thus reducing the risk of corrosion. Hence, in locations where projections indicate lower rainfall frequency, the cleaning effect may be reduced (Cole and Peterson, 2010). As shown in Figure 25, there is a high increase in the duration of extreme dry spells in Southern Europe, which will have a significant impact on the concentration of pollutants and salt on the metallic surface.

Figure 25. Changes in the 95th percentile of the length of dry spells: 2071–2100 compared to 1971–2000 (Figure source: Figure 23-2(d) (pp. 1278) in IPCC, 2014a)



4.2.2 Modelling atmospheric corrosion

To prevent the harmful process of corrosion on steel structures, a proper design and detailing of the structure should be provided ensuring adequate drainage. In addition, the atmospheric oxidation may be prevented by the use of a barrier (e.g. use of surface coatings, stainless steel or weathering steel) avoiding the contact between the steel surface and the atmosphere. The choice of the protection method is governed by environmental conditions and economic constraints.

The Eurocodes provide general protective measures or barriers, and structural redundancy. No predictive models are provided for the estimation of the corrosion depth of steel members.

However, different models are available in the literature for the estimation of the damage produced by atmospheric corrosion.

Most models describe the corrosion depth as a function of time, as expressed by (Wang et al. 2013):

$$C(t) = A \cdot t^{B} \tag{1}$$

where, $C(t)$ is the corrosion depth [μm]; t is the time length of exposure [year]; A is the corrosion rate in the first year of exposure, affected mainly by the initial condition of the environment; and B is related to the corrosion development with time.

Constants A and B are determined experimentally and are dependent on the material and environment. The estimation of corrosion may be inaccurate when the environmental conditions differ from those in which the models were calibrated (Landolfo et al., 2010).

Expression (1) has been found, in the past, to be reasonably accurate for exposures of up to 20 years' duration (ISO 9224, 2012). However, it does not take into account the independent variation of each environmental parameter. Under climatic changes scenarios, the environmental conditions are not constant over time, and will generally differ from those of the first year of exposure. This can cause inaccuracy examining a longer time profile.

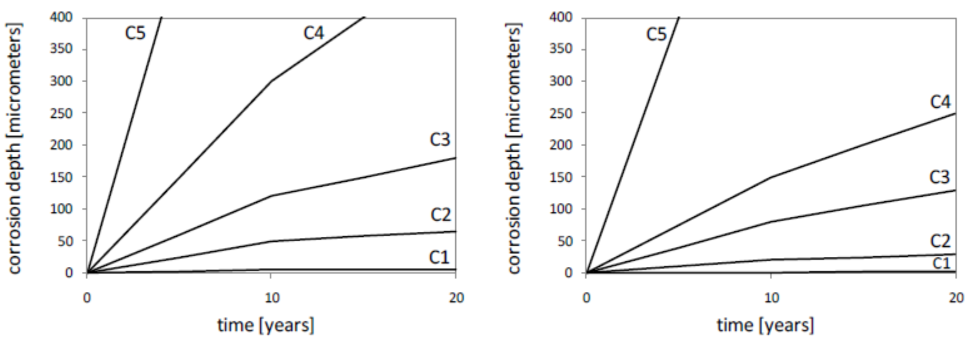
A more general model was provided by ISO 9224 (2012), in which the long-term corrosion rates of structural materials depend on the corresponding corrosivity class. In this document, five different corrosivity classes are considered, from C1, corresponding to a very low corrosive environment typical of indoor environments with insignificant pollution, or very low pollution and time of wetness, to C5, a very high corrosive environment, present in temperate and subtropical regions with very high pollution or significant presence of chlorides. ISO 9224 (2012) also considers an additional category CX, correspondent to extreme corrosivity, associated with very high pollution or chloride content in tropical or subtropical regions and very high time of wetness. It is recommended that one-year corrosion losses are used to predict future corrosion.

The standard (ISO 9223, 2012) provides guidelines to decide about the corrosivity categories depending on the measurable environmental parameters, such as:

- Time of Wetness (TOW),
- SO_2 concentration,
- Cl^- deposition rate.

The general model provided by ISO 9224 indicates that the average corrosion rate follows a bi-linear law. According to this model, for the first 10 years, the corrosion depth is dependent on the average corrosion rate; while, after 10 years of exposure, the corrosion rate is assumed to be constant with time. Taking into account the rates of corrosion provided by the standard for carbon steel and weathering steel, the corrosion depths for both types of steels are indicated in Figure 26.

Figure 26. Thickness loss as a function of time according to ISO 9224 and different corrosiveness classes: for carbon steel (left) and weathering steel (right) (Landolfo et al., 2010).



Other possibility to model the corrosion rate over time are the Dose Response Functions (DRF), which involve environmental parameters (climatic and pollutants) directly; hence, their independent changes can also be tracked. In the case of carbon steel, the corrosion rate is (ISO 9223, 2012):

$$r_{\text{corr}} = 1.77 \cdot P_d^{0.52} \cdot e^{0.020RH + f_{St}} + 0.102\, S_d^{0.62}\, e^{0.033RH + 0.040\,T} \qquad (2)$$

where

$$f_{St} = \begin{cases} 0.15(T-10) & \text{if} \quad T \le 10°C \\ -0.054(T-10) & \text{otherwise} \end{cases} \qquad (3)$$

and r_{corr} is first-year corrosion rate of metal [μm/a], T is the annual average temperature [°C], RH is the annual average relative humidity [%], P_d is the annual average SO_2 deposition [mg/(m^2.d)], and S_d is the annual average Cl^- deposition [mg/(m^2.d)].

However, at this point in time, there is no conclusive information regarding the impact of these environmental factors on corrosion, and a range of different models can be found in the literature (Benarie and Lipfert, 1986; Dean and Reiser, 1998, 2000, Tidblad et al., 2000, Feliu, et al., 1993a,b). All these are fundamentally regression models applied to experimental data, based on Time of Wetness, SO_2 and Cl contamination, and acidity of water.

4.2.3 Protection systems

A range of protection systems are used to delay the onset of corrosion on metallic structures. Of these, paint and galvanization are the most common. The first is widely used for larger profiles while the second is frequent in elements of small thickness.

The durability of these protection systems is critical to the durability and safety of steel structures. If, on one hand, there is significant work on the deterioration of zinc and galvanized steel (Cole, 2017), there is no work on a global view of the impact of climate changes on the deterioration of coatings. This might have several causes. Firstly, anticorrosive coating systems are very complex systems, composed of binders, pigments, solvents extenders and additives. As a consequence, the durability of anticorrosive coatings depends of a range of factors, including the type of substrate, curing, coating thickness, adhesion and external environmental factors (Sørensen et al. 2009). This variety of factors makes disaggregating causes of deterioration extremely complex. Moreover, the range of coatings available in the market, as well as their constant evolution, makes a general analysis very difficult. Lastly, most research on durability of steel coating systems is produced by private companies producing these systems, and thus, rarely published in scientific literature.

Nguyen et al. (2013) evaluated the effect of climate change on the rate of corrosion of zinc in Australia. The overall conclusion is that the factors influencing the corrosion of zinc are similar to those in steel, and consequently the impacts of climate changes will be similar.

4.2.4 Impact and adaptation

The availability of studies on the impact of climate change on the corrosion of steel structures, and particularly on quantitative assessment, is limited.

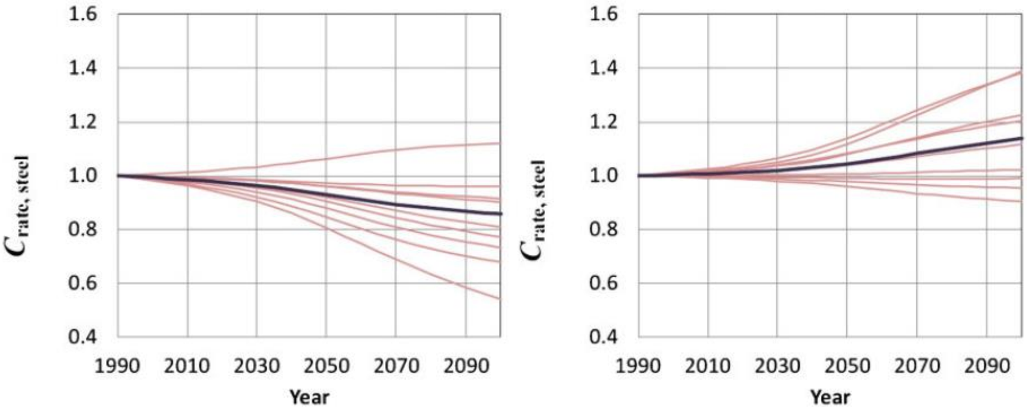
As described in Section 4.1, the effects of climate change on reinforced concrete structures suggest that the carbonation rate tends to increase with the increase of the temperature and CO_2 concentrations.

On the other hand, the effects of climate change on steel structures are somehow more difficult to be estimated due to the complexity of the meteorological phenomena that needs to be taken into account in modelling atmospheric corrosion, as described in the above paragraphs.

Projected future climate change potentially affect atmospheric corrosion of steel structures. Although some authors argue that it is currently very difficult to quantify the effects of climate change on atmospheric corrosion of steel structures, it is beneficial to assess the magnitude and uncertainties associated with corrosion estimates based on projected climate change models.

Based on a model developed in Australia, Nguyen et al. (2013) evaluated the estimated change in the corrosion rates of steel structures, due to climate change, in two different coastal cities: Melbourne and Brisbane. Based on the A1FI scenario of IPCC (IPCC, 2014b) and on several circulation models, the projected corrosion rates were found to decrease in the case of Melbourne and increase in the case of Brisbane, as illustrated in Figure 27.

Figure 27. Effects of climate change on corrosion rates for two cities: Melbourne (left) and Brisbane (right) (Nguyen et al., 2013).



In the above study, the most influential parameters were found to be the projected change in the RH, for the case of Melbourne, and the projected monthly wind speed, which affects the airborne salinity, for the case of Brisbane. In both cases, the effect of temperature change was found to be negligible.

A different study, carried out in Australia, aimed to assess the impact of climate change on corrosion rates in coastal and inland locations (Trivedi et al., 2014). The projections were made for the year 2070, considering different global warming scenarios and climate models. However, the main conclusions were taken for the A1F1 emission scenario and two climate models, representing the most severe and the most likely weather conditions for future years. In general, corrosion rates increased for coastal locations; while as for inland locations, a decrease of the corrosion rate was observed in all locations. In inland locations, the low airborne salinity and the reduced RH were pointed out as the main reasons for the decrease of the corrosion rate. On the other hand, in coastal locations, the main factor affecting the projected rates were the seasonal variation and intensity of rainfall. For instance, taking into account the most likely weather model, the increase in the corrosion rate for Brisbane was much higher than for Sydney, although they are both coastal cities. The main reason for this difference was the projected reduction of rainfall events, which was about 46% for Brisbane and about 9% for Sydney.

A reliability-based procedure for the time-dependent risk assessment of corroding metallic bridges, considering explicitly the influence of environmental and atmospheric parameters (e.g. RH, T, SO_2, Cl), was proposed by Kallias and Boulent (2013). In this case, the potential effect of climate change on risk and reliability assessment of bridges was quantified for a steel railway bridge. Results were provided for the moment capacity limit state for a number of different scenarios. These indicated that for the examined bridge type and location, climate change had a beneficial (although relatively small) effect on the long-term reliability and risk because of the decrease of the relative humidity and the respective decrease in the rate of corrosion.

More recently, the effects of variations in SO_2 concentrations and relative humidity due to climate change on steel structures were assessed using Dose Response Functions, for three different locations: rural, urban an industrial (Ben et al., 2017). The Dose Response Functions consider climate data such as temperature, RH, gaseous emissions (SO_2, NO_3 and O_3) and precipitation.

The study focussed on a steel railway bridge in UK and projections were made until year 2090. Taking into account the spatial variation of parameters, it was observed that the pollutants in each location greatly affected the loss of materials. Keeping the RH constant and varying the SO_2, the results for rural ($2<SO_2<15$), urban ($5<SO_2<100$) and industrial ($50<SO_2<400$) locations led to corrosion rates of 1.17 μm/year, 2.58 μm/year and 5.68 μm/year, respectively. In relation to the performance of the bridge, the moment resistance showed a decrease of 0.3% for the rural area, 0.9% for the urban area and 3%

for the industrial environment. In terms of shear resistance, decreases of 1.1%, 1.8% and 4.6% were observed for rural, urban and industrial areas, respectively (Ben et al., 2017).

4.2.5 Concluding remarks

Climate change variations can significantly affect the degradation of steel structures, depending on geographic and climatic conditions.

Considering the available information and the climate projections described in Chapter 3, climate changes can have contradictory consequences in Europe. On one hand, an increase in temperature in Northern Europe will increase the TOW, while a decrease in relative humidity in southern Europe will have the opposite effect.

Coastal locations generally showed higher corrosion rates than inland locations, strongly influenced by the salt deposition on the surfaces of metal. This in turn is correlated to salt levels in the atmosphere and cleaning of the surfaces. The effects of climate changes on salt production are far from being fully understood, in terms of production of surf and transport of salt over larger distances. However, in locations where the projected rainfall patterns decrease, the corrosion rate is expected to increase due to a reduction in the cleaning of pollutant on metallic surfaces. On the other hand, in inland locations, the main factor is the variation of the RH. An increase of the temperature leads to a reduced RH and therefore to a lower corrosion rate (Trivedi et al., 2014).

In relation to the variation of factors affecting air quality, the impact of climate change was observed to be more important in locations where the presence of pollutants resulting from industrial activities (such as SO_2) and other anthropogenic emissions are higher (Ben et al., 2017). There is the expectation that growing concerns regarding climate changes and environmental impact of industrial activities will lead to changes in policies reducing pollution. This has the potential to decrease the corrosion potential, particularly near industrial and urban areas.

The above conclusions were drawn based on a very limited number of research works and are relative to very specific geographic regions. Further research is thus needed to map the variations of climate change effects in other locations. Moreover, there is very little understanding of the impact of climate changes on protection systems, in particular, coatings. Considering that adaptation to climate changes will, in most cases, be associated with changes in coatings, there is an urgent need to study these interactions.

4.3 Assessment of cost-effectiveness of adaptation strategies

4.3.1 Cost-benefit analysis

Evaluating costs and effectiveness of adaptation strategies is a challenging task. Bastidas and Stewart (2019) identified three complementary criteria that may be considered to assess the cost-effectiveness of climate adaptation strategies: net-present value, benefit-to-cost ratio and probability of cost-effectiveness.

Cost-benefit analysis in a probabilistic context could be applied to determine the benefit-to-cost ratio and probability of cost-effectiveness for adaptation strategies applied to both new and existing structures. The 'benefit' of an adaptation measure is the reduction in damages associated with the adaptation strategy, and the 'cost' is the cost of the adaptation strategy. The benefit-to-cost ratio BCR(T_t) over the service life period T_t is:

$$\mathrm{BCR}\left(T_t\right)=\frac{\mathrm{E}_{\text{d-BAU}}\left(T_t\right)\Delta\mathrm{R}\left(T_t\right)}{\mathrm{E}_{\mathrm{a}}(T_t)}, \qquad \Delta\mathrm{R}\left(T_t\right)=\frac{\mathrm{E}_{\text{d-BAU}}\left(T_t\right)-\mathrm{E}_{\text{d-adapt}}\left(T_t\right)}{\mathrm{E}_{\text{d-BAU}}\left(T_t\right)} \tag{4}$$

where $\mathrm{E}_{\mathrm{a}}(T_t)$ is the adaptation cost, $\mathrm{E}_{\text{d-BAU}}(T_t)$ and $\mathrm{E}_{\text{d-adapt}}(T_t)$ are the cumulative expected damage cost (economic risk) for no adaptation measures (business as usual BAU, or existing practice) and considering adaptation measures, respectively; $\Delta\mathrm{R}(T_t)$ represents the proportional reduction in expected repair costs due to an adaptation measure. $E_a(T_t)$, $E_{d\text{-}BAU}(T_t)$, $E_{d\text{-}adapt}(T_t)$ and $\Delta R(T_t)$ may be computed from comprehensive models that take into account the effects of climate change on the deterioration processes (Stewart and Bastidas-Arteaga 2019).

An adaptation strategy is cost-effective if the benefit-to-cost ratio is larger than one – i.e., $BCR(T_t) > 1$. In addition, if probabilistic tools are used to propagate uncertainties in the cost-benefit analysis, it is possible to estimate the mean value of $BCR(T_t) > 1$, as well as the probability that an adaptation measure be cost-effective, $Pr(BCR(T_t)) > 1$. These indicators are very useful to estimate the risk of the adaptation investments under several climate change scenarios (Bastidas-Arteaga and Stewart, 2015, 2016).

4.3.2 Cost-effectiveness of adaptation strategies for RC structures subjected to chlorination

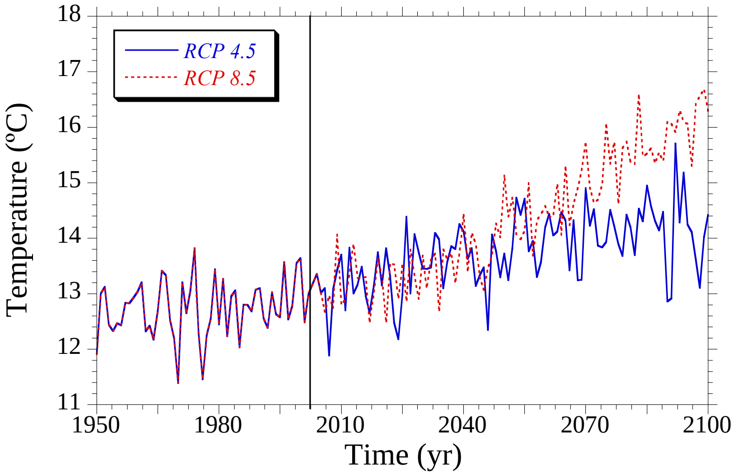
Bastidas-Arteaga and Stewart (2016) evaluated the cost-effectiveness of adaptation strategies for existing RC structures located in Saint-Nazaire (France) under a splash and tidal exposure and designed according to different design standards. Table 5 presents the mean BCR for slabs built in different years under RCP4.5 and RCP8.5 future concentration scenarios. The adaptation strategies consisted on increasing the design concrete cover (c_a) by Δc_a=5mm or Δc_a=10mm for repairs carried out after the adaptation time t_a=2020. The adaptation time is the year after which repairs account for the extra concrete cover Δc_a. The service life period considered is T_t=100 years.

In Table 5, it is noted that the mean $BCR(T_t)$ is less than one (1.0) for older structures and greater than one (1.0) for more recent ones, i.e. built in 1990 and 2010. A $BCR(T_t)$ less than 1.0 implies that the adaptation measure is not cost-effective for old structures, built in 1970. Recent standards recommend larger design concrete covers and are therefore more cost-effective during the service life period. The increase of $BCR(T_t)$ for recent structures is due, on the one hand, to the larger concrete cover recommended by the standards (Table 5) and/or considered by the adaptation measures. This means that a larger concrete cover is more effective for this splash and tidal exposure in Saint-Nazaire. On the other hand, larger $BCR(T_t)$ values are also related to the increase of climate change effects on chloride ingress rates (see Section 4.1.2) that justify the implementation of adaptation measures. Table 5 also shows that higher values of the mean $BCR(T_t)$ are expected for the RCP8.5 scenario that imply more severe changes with respect to the actual climate. The differences between the $BCR(T_t)$ for both scenarios are slightly larger for recent structures because they will be exposed to larger climate variations that are more pronounced after 2050 for the RCP8.5 scenario (e.g. Figure 28). These climate variations will induce more corrosion damage, so the cost-effectiveness of adaptation strategies will also increase. In all cases, increasing cover by 10 mm is less cost-effective than a 5 mm increase in cover. Even if the risk reduction, $\Delta R(T_t)$, should be higher for Δc_a=10 mm, the costs associated to this adaptation strategy are larger and thus reduce the mean $BCR(T_t)$.

Table 5. Mean $BCR(T_t)$ for slabs built in different years and t_a=2020

Construction year	Design concrete cover (c_a)	RCP4.5		RCP8.5	
		Δc_a=5mm	Δc_a=10mm	Δc_a=5mm	Δc_a=10mm
1970	40mm	0.8	0.7	0.8	0.7
1990	50mm	3.8	3.4	3.9	3.6
2010	55mm	4.6	4.3	4.7	4.5

Figure 28. Yearly temperature projections for Saint-Nazaire.



The effect of the time of adaptation on the mean BCR(T_t) and the probability that BCR(T_t) exceeds unity (Pr(BCR(T_t)>1)) for slabs, concrete cover increase Δc_a=5 mm and the RCP4.5 scenario is shown in Table 6. Note that the closer the adaptation year is to the end of the service life period, the lower the mean BCR and Pr(BCR(T_t)>1) are. Of interest is that Pr(BCR>1) only reaches a value of 59% when the mean BCR exceeds 4. This illustrates the high variability of damage risks caused by uncertainties of climate change projections, and variability of design parameters and deterioration processes. Bastidas-Arteaga and Stewart (2015) found that for new reinforced concrete structures, the increase of the concrete strength grade is generally more cost-effective than the increase of design concrete cover. However, it is important to highlight that these findings were obtained for specific environmental conditions and different conclusions could be drawn under other exposures and climate conditions.

These results could be used by owners of a given structure or building, and other stakeholders to evaluate the benefits and risks of implementing adaptation strategies at various years. For example, it is observed that the mean BCR(T_t) and Pr(BCR(T_t)>1) are small for older structures and therefore owners and stakeholders could prioritise investments in adaptation measures for more recent ones. These results could also be used to evaluate the impact of the adaptation year. For example, for structures built in 1990, if the owner or stakeholder decides to postpone the adaptation actions until 2040, the mean BCR(T_t) is about 1.4, which is still beneficial. However, the Pr(BCR(T_t)>1) for this adaptation time is less than 11% indicating that the risks of having no benefits are high.

Table 6. Mean BCR and Pr(BCR>1) (within brackets) for slabs for various t_a, RCP 4.5 scenario and Δc_a=5 mm

Construction year	**Adaptation year (t_a)**			
	2020	2040	2060	2080
1970	0.8 (6.1%)	0.05 (0.2%)	0 (0.0%)	-
1990	3.6 (43.5%)	1.4 (10.2%)	0.2 (0.7%)	0 (0.0%)
2010	4.6 (59.0%)	3.9 (44.7%)	1.7 (13.1%)	0.3 (0.9%)

4.3.3 Concluding remarks

Cost-benefit analysis is a very useful tool to evaluate the cost-effectiveness of adaptation strategies for new or existing structures. Cost-benefit analysis should be supported by comprehensive models to account for the effects of climate change on the deterioration processes in a probabilistic context. The outcomes of this analysis provide valuable information to estimate the potential benefits and risk of climate adaptation investments. For the considered example, the cost-effectiveness of the adaptation strategies depends on the age of the structure, climate change scenario and adaptation year. In a more general context, it also depends on specific weather conditions (Bastidas-Arteaga and Stewart, 2016) and varies with the adaptation techniques (e.g., use of more durable repair material). Thus, the cost-benefit analysis could be used to find technical adaptation solutions that minimize costs and mitigate climate change effects in a rational way.

5 Effects of corrosion on seismic performance of RC structures

5.1 Introduction

Corrosion of reinforced concrete (RC) elements and structures has been widely investigated. This chapter presents a review of analytical and numerical studies on the impact of corrosion on the seismic performance of RC buildings and bridges (see respectively Section 5.2 and 5.3) and provides preliminary insights on how climate change may affect the corrosion of RC buildings (Section 5.4).

As explained in Section 4.1, carbonation-induced corrosion causes cracking of concrete, whereas chloride-induced corrosion causes reduction of the diameter of steel rebars. Consequently, the concrete-steel bond strength, concrete confinement and concrete strength, as well as the yield and ultimate deformation of steel rebars, are reduced. Experimental results from monotonic tests show a large scatter in the values of steel properties and bond strength after corrosion (Andisheh et al., 2016). At the level of structural elements, corrosion may reduce the load-bearing and deformation capacity, and the energy dissipation. At the structure level, corrosion may alter a number of parameters that are important for seismic performance, such as the dynamic properties, base shear capacity, ductility, cyclic response and collapse mechanism. The seismic performance of old structures, designed without appropriate provisions, may be further aggravated by corrosion. It is noted that more than 120 000 bridges in the USA (20 % of the total stock) should be repaired or replaced in order to ensure their functionality and seismic resistance (Li et al., 2016). In addition, it is estimated that 45 % of bridges in the USA are deficient because of structural deterioration and/or increased traffic loads (Val et al., 1998).

5.2 Impact on seismic performance of RC buildings

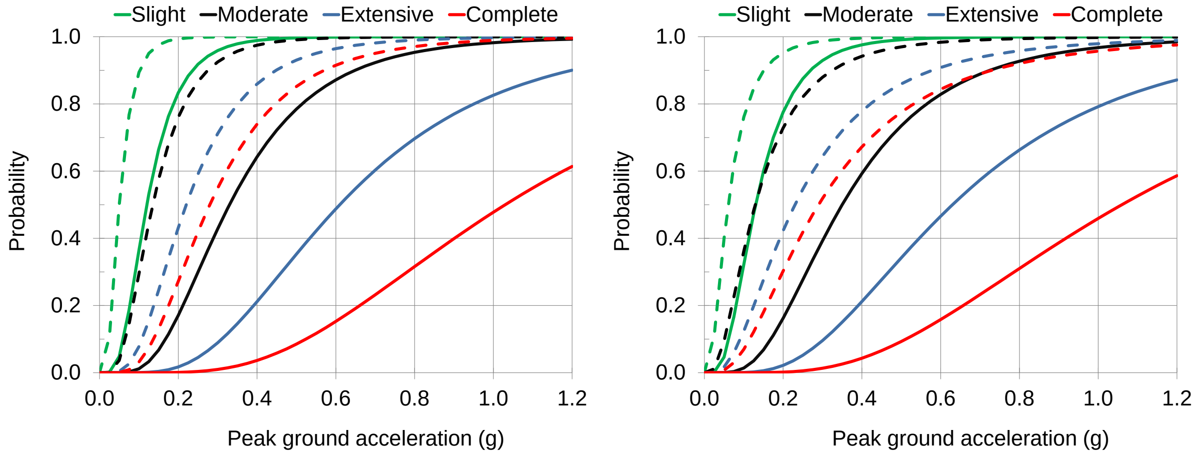
Focusing on the level of structural elements, Afsar Dizaj et al. (2018) performed pushover analysis of RC columns subjected to corrosion. The results showed that corrosion reduces significantly the lateral force capacity and ultimate drift. For the case of a lightly confined column, corrosion resulted also in a change of the failure mode from a ductile one, due to failure of steel rebars, to a brittle one, due to crushing of the concrete core.

Several studies have analysed the effect of corrosion on the seismic response of RC buildings. Examples found in the literature include a two-storey two-bay frame (Berto et al., 2012), a three-storey irregular frame building (Celarec et al., 2011), low- and mid-rise plane frame structures (Fotopoulou et al., 2012), an eight-storey hospital built in 1971 (Karapetrou et al., 2016), prototype frames with different heights and levels of seismic design (Pitilakis et al., 2014), and a seven-storey frame building designed with a high-level code (Roohbakhsh and Kalantari, 2018). Most of these studies presented the results in terms of fragility curves of the buildings and demonstrated that corrosion leads to an increase of the probability of damage of buildings with time. The increase was more evident in the higher damage grades than in the lower ones, as may be observed in the fragility curves shown in Figure 29.

Similar conclusions were drawn from a study of corroded precast concrete structures (Biondini et al., 2011, Titi and Biondini 2014). Pushover analysis of a single-storey industrial building subjected to corrosion showed a significant reduction of base shear and ultimate deformation capacity over time. For the case of a three-storey building with moment-resisting beam-column connections and where only the external faces of columns were subject to corrosion, further to the reduction of strength and stiffness, an undesirable soft storey mechanism was observed.

Reduction of strength and deformation capacity due to corrosion was also observed by Kagermanov et al. (2017) for a case study on a non-engineered flat slab structure. The same authors report that extensive corrosion contributed to the damage suffered by RC buildings during the Muisne (Ecuador) earthquake of April 16th, 2016.

Figure 29. Seismic fragility curves for low-rise (left) and mid-rise (right) reinforced concrete frame buildings at t = 0 (solid lines) and t = 50 years (dashed lines), data from Fotopoulou et al. (2012).



5.3 Impact on seismic performance of RC bridges

Damage scenarios due to environmental effects are, in general, more critical for reinforced concrete bridges compared to buildings as, usually, the entire bridge structure is directly exposed to the aggressive environment. The influence of corrosion on the performance of bridges has been widely studied (e.g. Alipour et al., 2013, Estes and Frangopol 2001, Val et al., 1998), showing that the deterioration of performance resulting from reinforcement corrosion could have a significant effect on both serviceability and ultimate limit states.

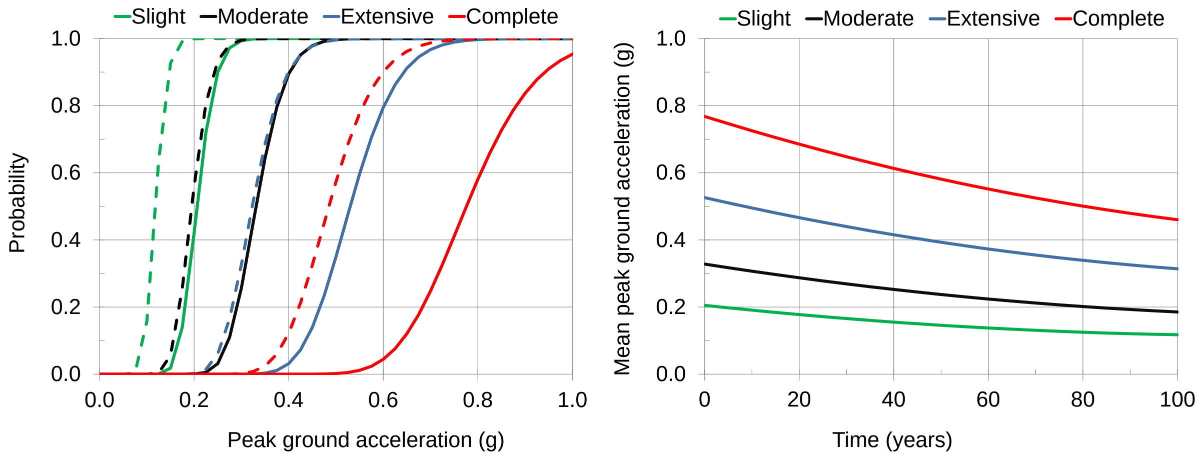
Recent studies show that the effect of corrosion becomes even more relevant if the bridges are subjected to seismic loading, since the transversal load-carrying and deformation capacity can be significantly affected by corrosion of both longitudinal and transverse reinforcement. The majority of past studies refer to two-span (Alipour et al., 2011, Choe et al., 2009, Dong et al., 2013) and three-span (Ghosh and Padgett, 2010, Li et al., 2016) reinforced concrete bridges with continuous deck, with characteristics typical of highway bridges in the USA. The results of pushover analyses indicated that corrosion affects mostly the base shear capacity and only slightly the ultimate deformation capacity of bridges. The fragility analyses showed an increase of the probability of damage for the corroded bridges. Such increase was more significant for the higher damage states, as observed for buildings, and become higher near the end of the bridge lifetime.

Figure 30 (left) presents the fragility curves for a three-span continuous RC bridge at the time of construction and after 90 years, where it is evident that the probability of damage increases with time. As shown in Figure 30 (right), the mean values of peak ground acceleration (PGA) of the fragility curves are reduced by around 40 % in 100 years for all the damage grades. Similar results were obtained by Ghosh and Padgett (2010), who also report a much smaller change of the standard deviation of the fragility curves due to corrosion.

It is interesting to note that, while in most cases corrosion will increase the probability of damage of the complete bridge, it may decrease the fragility of certain elements, for instance the steel expansion bearings over the abutments, due to increased friction (Ghosh and Padgett 2010). Similarly, Zhong et al. (2012) highlighted that the effect of corrosion on flexural and shear failure modes of bridge piers varies in time.

Fewer studies exist in the technical literature for European highway bridges. Zanini et al. (2013) examined a real three-span simply-supported highway bridge located in north-east Italy and concluded that the time-variant probability of damage increased due to corrosion, particularly for the higher damage levels. A four-span bridge with a deck-pier connection through bearings was studied by Biondini et al. (2014) with particular focus on uncertainties. Regarding the reduction of steel rebar diameter and of the strength of concrete and steel, the scatter around the mean values increased with time, as the uncertainty related to corrosion was added to the variability of mechanical and geometric properties. At the level of cross-section, corrosion increased the scatter of the values of ultimate curvature, while the scatter of the yield moment, ultimate moment and yield curvature remained almost constant in time.

Figure 30. Seismic fragility curves for a three-span continuous RC bridge (left) at t = 0 (solid lines) and t = 90 years (dashed lines) and time-variant mean peak ground acceleration for different damage states (right), data from Li et al. (2016).



Akiyama et al. (2011) studied the seismic response of corroded RC bridge piers considering the reduction of rebar diameter and concrete cover. An analysis of a cantilever pier located in three Japanese cities with different seismic hazard and climatic conditions, showed that the probability of failure after 50 years from construction was highest for the bridge pier located in the city with the lowest seismicity and the shortest distance to the coast.

Bridges with different layouts, geometric and material parameters, and located on sites with varying climatic conditions were also examined by Ou et al. (2013). Depending on these parameters, the capacity of some of the bridges was found to be exceeded by the design value of PGA during their lifetime. The authors proposed an increase in the order of 6 % of the design PGA to account for this.

A coastal bridge considering the different impact of corrosion on the atmospheric, splash and submerged zone of the piers was studied by Guo et al. (2015). As expected, there was higher reduction of steel rebar area in the splash and tidal zones. The moment capacity of the pier was reduced to almost half of the initial value after 100 years. Furthermore, a relocation of the plastic hinge from the bottom to the top of the submerged zone was observed as a result of corrosion. An interesting conclusion was that, in a probabilistic framework for loss analysis, the decrease of seismic risk in the remaining life of an existing bridge may compensate for the reduction in strength and deformation capacity.

Kumar et al. (2009) examined the combined effects of corrosion and cumulative damage during the life cycle of bridges through Monte-Carlo simulations that considered as random variables the parameters that define the seismic action, i.e. magnitude, distance from source, depth of bed rock, etc. For an example bridge located in California, cumulative damage due to low-cycle fatigue was found to have a stronger influence on the probability of damage than corrosion.

5.4 Impact of climate change on corrosion damage

The impact of climate change on corrosion and on the performance of RC structures has been scarcely studied to date. Peng and Stewart (2014) carried out a detailed study of the impact of the expected change in CO_2 concentration, temperature and relative humidity, on the initiation of corrosion and consequent damage (see Table 3). They examined buildings and bridges located in one coastal city and two inland ones in China, corresponding to cold and temperate climatic conditions, and with different durability requirements for reinforced concrete structures. To account for uncertainties, climate projections from six climate models were considered for the period 2010 - 2100. The results in terms of corrosion initiation and damage showed a small variability with the climate models. As the requirements for concrete cover are stricter for bridges than for buildings, carbonation depths and corrosion damage were higher for the latter. It was estimated that corrosion-induced damage to RC building would increase up to 20 % due to the effect of climate change. Lastly, a sensitivity analysis showed that the change in relative humidity had the highest impact on damage due to corrosion, followed by temperature and then CO_2 concentration.

A similar study was undertaken by Saha and Eckelman (2014) for the city of Boston in the USA, employing two scenarios for CO_2 concentration (IPCC A1 and B1) and four models for temperature (CCSM, HADCM2, GFDI and PCM, see Figure 21). As previously mentioned in Section 4.1.4, penetration depths are expected to exceed the specified concrete cover thickness until 2050 for almost 60 % of the existing reinforced concrete buildings in Boston and the entire stock will face degradation issues by 2080. Besides, climate change is estimated to cause corrosion damage to new buildings in around 60 – 80 years after their construction. As a countermeasure and considering the worst climate change scenario, the authors (Saha and Eckelman, 2014) propose an increase by approximately 10 mm in the concrete cover prescribed in the building codes and the use of technologies to protect the existing structures against corrosion.

5.5 Concluding remarks

The studies presented in the previous sections confirm that corrosion has a detrimental effect on the seismic performance and functionality (strength, ductility, dynamic properties and failure mode) of reinforced concrete structures. Overall, the impact of corrosion appears to be higher on strength than on deformation capacity. In addition, bridges are more vulnerable to corrosion than buildings, as all of their structural elements are exposed to the environmental conditions.

The extent of the impact of corrosion depends on a number of parameters that include the material properties, geometry (dimensions and exposure of each element to corroding agents), level of seismic design, environmental conditions and climate change scenarios. Therefore, the examples discussed in this chapter are to be read as a qualitative indication of the effects of corrosion. Comprehensive parametric analyses are necessary to propose specific measures or guidelines for the protection of structures from corrosion.

Few studies exist on the influence of climate change on corrosion damage. It may be assumed that climate change will also increase the probability of damage of reinforced concrete buildings and bridges due to earthquakes. Further research is needed to address both these issues.

Lastly, in durability assessment of structures, increase of corrosion and seismic damage due to climate change should be examined together with other issues that may affect the structure during its life, such as cumulative damage and the reduction of seismic risk in the remaining life of existing structures.

6 Main findings and way forward

6.1 Rationale

The European Green Deal shows EU determination to tackle climate change and its commitment to becoming the world's first carbon-neutral continent by 2050.

In line with the Green Deal objectives, the construction sector is encouraged to adopt more sustainable and circular economy practices, extend the lifetime of buildings, improve material efficiency, promote waste reduction, and strive for a better life cycle performance of buildings and infrastructure.

Climate change requires building standards to adapt to new frequency and intensity of climate-related impacts in order to safeguard existing and new infrastructure and ensure their resilience to a changing climate. The adaptation of the design of buildings and infrastructure to climate change can also provide environmental benefits over their lifetime by bringing them closer to the principles of circular economy.

The current report evaluated the expected variations in climatic factors causing corrosion and carried out a literature review on the implications of climate-induced corrosion on the deterioration of concrete and steel structures, and on their seismic resistance as well.

Further research needs on the quantitative impact of climate change on the corrosion of buildings at European level and on adaptation strategies to climate change induced corrosion will be identified thereafter.

6.2 Key findings of the study

Increase in CO_2, as in different weather variables associated to global warming, could accelerate reinforcement corrosion, affecting the safety and serviceability of the European built infrastructure. Specifically, globally averaged concentration of CO_2 in the atmosphere rose from 280 ppm in 1750 to 390 ppm in 2011 (IPCC, 2014b), while remarkable growths for the different scenarios were estimated up to 2100 with peaks of about 1000ppm of CO_2 equivalent under the RCP8.5 scenario.

At the same time, further worsening is induced by temperature increase potentially exceeding 6°C in southern Europe in summer season, while increase in humidity (accelerating corrosion processes) is limited to northern Europe and hardly exceeds 4%. It is worth noting that the severity of the concentration scenarios forcing the climate models plays an important role on the magnitude of temperature increase. In addition, scenarios of future anthropogenic emissions and natural forcing are uncertain (IPCC, 2018). Moreover, the projections consider the midterm scenario for year 2070 (the central point of the interval 2056-2085) compared to the reference period 1971-2000, while the trends could be exacerbated considering the end of XXI century. Note that temperature estimates are related to ensemble projections assessments while single simulations could greatly differ, and the temperature increase is expected to not be regionally uniform. The number of days on which the mean temperature exceeds 25°C is more pronounced in southern Europe with larger variations, up to 50 more days per year, under the RCP8.5 scenario. At the same time, a large part of the Scandinavian Peninsula, Great Britain and Ireland are not affected by such increases.

Regarding the incidence of days with relative humidity higher than 80 %, reduction up to 40 days in southern Europe and increase of comparable magnitude in northern Europe (especially in Scandinavian Peninsula) were assessed.

Assessing the effects of climate change is difficult as the relationship between the degradation of structures and climate is complex (Cole and Paterson, 2010). Nevertheless, as suggested by all studies reviewed in this report, the changes in temperature, concentration of pollutants, rainfall patterns, etc. induced by climate change could have a significant impact on the service life of infrastructures and cannot be ignored.

This report focused on two of the most popular construction materials, concrete and steel, carrying out a state-of-the-art review on the corrosion of those structures under different climatic scenarios and exposure conditions.

In relation to reinforced concrete structures, the reviewed authors suggest that the two main processes that lead to corrosion, the carbonation ingress and the chloride ingress, tend to accelerate with an increased temperature and CO_2 concentrations. These conclusions were observed in different locations around the world, but on a limited number of research works.

On the other hand, the effects of climate change on steel structures are more difficult to be estimated since the number of available studies is very limited and results are very sensitive to local exposure conditions. In fact, in most cases, it was found that the corrosion rate will substantially increase in coastal locations and in locations where the projected rainfall is expected to decrease, thus reducing the cleaning of pollutants in metallic surfaces. In inland locations, corrosion rate is influenced by the variation of relative humidity, which is expected to be slightly reduced by an increase of temperature, so it may decrease moderately. These studies have been performed on specific locations and environmental conditions, showing that pollutants greatly affect the corrosion rate of steel structures.

Corrosion has been confirmed to have a detrimental effect on the seismic performance of reinforced concrete structures, being, in general, more critical for exposed concrete bridges than for buildings. However, few studies exist on the influence of climate change on seismic damage and more research is needed to address this topic.

Furthermore, it is noteworthy that the uncertainties inherent to climate projections and estimation of corrosion trends are limiting the conclusions of the studies presented in this report, although some authors (Nguyen et al., 2013) state that for engineering design purposes, the uncertainties associated with climate change models are of lower importance.

Corrosion is currently an important concern for the built infrastructure across the world. Peng and Stewart (2016) reported that 36% of concrete buildings in the UK have to be rebuilt or replaced because of corrosion and that annual losses due to corrosion in the USA amount to about €300 billion, with 40% of this being due to carbonation-induced corrosion. Moreover, Schmitt (2009) estimated the annual cost of corrosion worldwide to exceed $1.8 trillion, or between 3% to 4% of the Gross Domestic Product of industrialised countries. Therefore, any potential increase of the corrosion induced by climate change effects may lead to substantial maintenance and repair costs.

6.3 Needs for adaptation of standards to climate change induced corrosion

As mentioned earlier in this report, changes to structural design and/or to prescribed maintenance practices can eventually accommodate the uncertain effects of a changing climate, by preventing or mitigating the corrosion of structures and improving their performance and durability.

For instance, Stewart et al., 2011 suggested that improved concrete compressive strength and other enhanced durability design specifications will result in a reduced rate of carbonation.

Bastidas-Arteaga and Stewart (2016) proposed some recommendations to be added to European standards (EN 1991 Actions on structures; EN 1992 Design of concrete structures; EN-206-1:2000 Concrete - Part 1: Specification, performance, production and conformity) concerning cement content, use of admixtures, use of stainless steel, and increase the minimum cover required to reduce the risk of chloride ingress.

Stewart and Bastidas-Arteaga (2019) provided relevant suggestions for standards that need to deal with a non-stationary climate, including strategies to improve material quality and protection systems, and the consideration of the spatial variability of environmental factors affecting corrosion.

Authors of this report (Section 4.2) highlighted the urgent need to understand the impact of climate change on protection systems of steel structures, in particular coatings.

The study of the costs and benefits of adaptation measures, as proposed in Section 6.4, would provide further insight on the adaptation of standards to climate change.

6.4 Further research needs to access the impact of climate change on corrosion in Europe

It is observed that most of the studies reviewed in this report, addressing the effects of climate change on the corrosion of reinforced concrete and steel structures, were carried out outside Europe or targeted European specific locations and materials. Moreover, studies focussing on the impact of climate change on the European built infrastructure are very limited and do not allow to extract global conclusions.

A quantitative assessment of the impact of climate change on the corrosion of structures is essential to assess the cost-effectiveness of adaptation measures and assist the formulation of adaptation strategies to potential effects of climate change. Peng and Stewart (2014) advised to conduct a life-cycle cost analysis to assess the cost-effectiveness of adaptation measures. For instance, proposals to increase the design concrete cover should be analysed in detail to reduce the rise of environmental burden caused by such measures.

Further research is proposed to support the development of adaptation strategies, at a pan-European scale, accounting for the effects of a changing climate on the corrosion of buildings.

A first step would involve the overall assessment of the impact of potential climate scenarios on selected corrosion metrics (*e.g.* Saha and Eckelman, 2014), compared to a reference situation. For this purpose, it will be necessary to consider the variations in environmental factors such as temperature, atmospheric humidity and carbon dioxide concentration that are provided by climate projections and socioeconomic scenarios, incorporating adaptation and mitigation measures. A geo-referenced database of the building stock across Europe containing relevant building characteristics, such as age, will be used.

In a second phase, the study would focus on the regions where the corrosion impact is expected to be higher. In those regions, climate scenarios will provide high-spatial resolution weather variables influencing corrosion. In addition, more detailed data need to be collected, namely site-specific carbon dioxide levels, and other characteristics of the exposed building stock (*e.g.* incidence of RC buildings, or the state of buildings conservation). The goal is to estimate the potential for corrosion damage and the magnitude of economic costs of corrosion in the regions identified as critical, taking into account regional climate change scenarios (*e.g.* Bastidas-Arteaga and Stewart, 2016). Adaptations measures should not be considered in this second phase, *i.e.* the current standards' prescriptions are adopted for the baseline and simulated scenarios, *e.g.*, current maintenance measures are assumed in both situations.

A final challenging task would be to evaluate the costs and benefits of adaptation measures to optimise structures' performance when subjected to a changing climate. A broad range of adaptation measures to be investigated were identified by Stewart and Bastidas-Arteaga (2019), namely improved solutions for the design of new structures, retrofitting of existing structures, utilization of new materials, or changes to inspection and maintenance regimes. Implementation of regulations to improve air quality and reduce carbon dioxide concentration levels in urban regions is another possible solution. Stewart and Bastidas-Arteaga (2019) advise risk-based approaches to assess the optimal level of adaptation measures, in case they are indeed needed. However, the authors also emphasise the great complexity and resources required to implement such approaches, which are subject to considerable uncertainty.

To conclude, estimates on the impact of corrosion at a global level indicate that the cost of corrosion to economies and society is significant. The eventual acceleration of the corrosion process due to climate change can further increase its direct and indirect costs, implying that this subject deserves further attention from the research community, with the purpose of assessing the best adaptation measures for the existing building stock and improving the design of new structures.

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