THE FRENCH MONUMENTAL HERITAGE FACING GLOBAL CLIMATE CHANGE

an outline for curators, restorers, decision-makers, researchers and teachers

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Chambord Castle in the Loire Valley, inscribed on the UNESCO List, before and during the exceptional flooding of the River Cosson in June 2016

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ABSTRACT

The French Cultural Heritage has so far been the subject of little research concerning its future behaviour towards the current climate change on our planet. The evolution of phenomena resulting from the increase in greenhouse gases emissions in the Earth atmosphere and which can have consequences for the tangible cultural heritage is first described: *temperature, humidity, precipitation, ocean level.*

Their foreseeable impacts on the cultural heritage are summarized in two main tables, distinguishing between events with *slow onset* and those with *rapid and violent onset* in extreme situations.

The results obtained by French researchers who have invested in this issue, as well as other extrapolated research on a European scale, are presented, in particular those concerning *the facades of monuments in stone, the old stained glass windows, the predictable behaviour of metals, the crystallization of salts in porous walls, the river floods and low water, the coastal archaeological sites, the studies of dendroclimatology.* On the other hand, important subjects have not been discussed on French heritage: *the effects of freeze-thaw on porous materials, the stability of buildings on clay soils, the indoor climate of museums, libraries and the collections they house, the carbon footprint of French cultural heritage.*

A French strategy for adapting to the impacts of climate change on tangible cultural heritage concerning basic and applied research, education and training, the funding and the economy is suggested in conclusion.

RESUME

Le patrimoine monumental français n'a fait à ce jour l'objet que de peu de recherches concernant son comportement face au dérèglement climatique en cours sur notre planète. L'évolution des phénomènes consécutifs à l'augmentation des émissions de gaz à effet de serre dans l'atmosphère terrestre et pouvant avoir des conséquences pour le patrimoine culturel matériel est d'abord décrite : *température, humidité, précipitations, niveau des océans.*

Leurs impacts prévisibles sur le patrimoine monumental sont résumés dans deux grands tableaux, en distinguant les évènements à survenue *lente* de ceux qui ont une survenue *rapide* et violente en situation extrême.

Les résultats obtenus par les chercheurs français qui se sont investis dans cette problématique, ainsi que d'autres extrapolés de recherches à l'échelle européenne, sont présentés, en particulier ceux qui concernent *les façades en pierre des monuments, les vitraux anciens, le comportement prévisible des métaux, la cristallisation des sels dans les murs poreux, les crues fluviales et les étiages, les sites archéologiques côtiers, les études dendroclimatologiques*. En revanche, des sujets importants n'ont pas été abordés sur le patrimoine français : *les effets du gel-dégel sur les matériaux poreux, la stabilité des édifices sur sols argileux, le climat intérieur des musées, des bibliothèques et des collections qu'ils abritent, l'empreinte* carbone du patrimoine *monumental français.*

Une stratégie française d'adaptation aux impacts du changement climatique sur le patrimoine culturel matériel concernant la recherche fondamentale et appliquée, l'enseignement et la formation, les financements et l'économie, est suggérée en conclusion.

INTRODUCTION

There is little dispute in 2020 that the change in the Earth's climate or, to put it better, its imbalance, is real and that certain extreme weather events (heat waves, intense rains or droughts depending on the region, coastal marine erosion and submersion...) have been more numerous and more intense at global level in recent decades. It is thus accepted that the warming of the Earth's atmosphere is due to the emission by human activity of greenhouse gases (GHG) and particles, partly masked by the parasol effect of a few other particles: no other credible explanation exists to coordinate all observations and understand the processes involved.

If a general consensus is thus reached on the reality and causes of global warming - to the point that a new geological epoch, the "Anthropocene" [1] - has been proposed to mark the importance of the phenomenon, it cannot be said that the same is true for its foreseeable effects, which are not yet all identified, catalogued and evaluated. Thus, its impacts on Cultural Heritage and the adaptation measures had not been taken into account as such in the first four Reports of Working Group II "Impacts, Adaptation, Vulnerability" of the Intergovernmental Panel on Climate Change (IPCC). The same is not true in the 5th of these Reports, which was published more recently (2013-2014) [2].

The role of Monumental Heritage in the local climate is not insignificant: for example, the clean and clear surfaces of monuments reflect solar radiation, heat less and thus contribute to the reduction of the effect of Urban Heat Island (UHI), while the same surfaces blackened by air pollution had a significant reverse action until recently. Its role in the global climate is no less negligible because the built Cultural Heritage is considerable: its heating in winter and air conditioning in summer lead to significant GHG emissions. The mass tourism it generates also has a significant influence on the energy balance of the planet.

France has an important tangible Cultural Heritage, movable and immovable, as evidenced by its 44,000 historical monuments and archaeological sites, as well as its numerous and rich museums and collections. In addition, 42 French monuments and sites are inscribed on the UNESCO World Heritage List.

The built Cultural Heritage includes the monuments and hearts of historic cities, museums, libraries, collections, reserves, decorated caves and archaeological sites... and what they house: murals or easels, frescoes, stained glass, mosaics, art objects in wood, metal, glass, ceramics, paper, tapestries, polymers, films... Add to this the unbuilt tangible heritage such as cultural landscapes, gardens and outstanding agricultural heritage, the fruits of centuries of human practices and particularly sensitive to the effects of climate change. This includes ancient, modern and contemporary heritage.

All this heritage is exposed to the direct effects of the climate (temperature, rain, wind...) and its indirect effects (development of parasites: insect pests, fungi, superior plants... invasion of foreign species). As cultural assets are often unique, valuable and irreplaceable, the impacts of climate change on their materials, stability and conservation mode should be assessed for transmission to future generations.

In France, the future of Cultural Heritage in the new situation created by climate change is little or no addressed. In 2011, the Department of Studies, Foresight and Statistics of the Ministry of Culture and Communication conducted a cultural foresight exercise called “*Culture - Media 2030*“ containing a thematic sheet N°1 entitled "*Climate Change*" [3]. Only some of the effects of climate change are addressed and only on a global scale. The only French monument mentioned is the Eiffel

Tower "*exposed to accelerated corrosion of the metals that make it up*" without further details. This document is important for its awareness of phenomena, but it has unfortunately remained at the descriptive, subjective and qualitative level (except for the numerical data on climate change itself, on a global and French scale).

The 2nd French National Plan for Adaptation to Climate Change (2018-2022) [4] gives only vague recommendations in the field of heritage, without any specific comprehensive climate action plan yet in place in 2021: "*The Ministry of Culture, museum curators and public cultural cooperation institutions will work to integrate the impacts of climate change into Cultural Heritage management plans and Cultural Heritage preservation efforts, and will ensure that plans to safeguard cultural property are adapted to the foreseeable climatic hazards in the medium and long term."* For example, the Ministry of Culture has stated in its Research Strategy for 2017-2020 [5] "*The study of the impact of the environment (natural hazards, pollution and climate change) on cultural property... as well as research aimed at strengthening the energy performance of old buildings and at developing the modes of rehabilitation that respect their heritage value."*

The way to quickly decrease the CO_2 emissions and to obtain the Net zero CO_2 emissions (Carbon neutrality) is not or little approached in France in the cultural sector, by considering, for example, the manner of heating and insulating the ancient cultural buildings by taking advantage of past frugal practices. A recent study [6] analyses the theoretical targets and practical measures able *to reduce the carbon footprint of cultural buildings* representing a wide percentage of the European buildings and among them 35% being older than 50 years and 75% having an inefficient use of energy. Therefore, the potential contribution of the cultural sector to the reduction of GHG is significant and requires actions, for example, by avoiding to travel by air for attending international conferences or for works on distant monuments, or by the reduction of computer calculations.

Cultural heritage can contribute to the *past and recent history of climate* in relation to that of its environment (for example, through dendroclimatology from timbers of built heritage) or make a contribution to *future climate change* through mitigation and adaptation measures concerning it (for example, by reducing its carbon footprint).

It can be estimated that *136 of the 1,121 World Heritage properties* listed by UNESCO in 2019 would be affected by major floods: not just Venice, London, Pisa, Pompeii... but also Arles, Mont Saint Michel, Le Havre and the Port de la Lune in Bordeaux [7]. Similarly, of the *49 Mediterranean coastal sites* on the UNESCO List, 47 (including Arles) would be affected by submersion (37 sites) and/or coastal erosion (42 sites) by 2100 [8]. This means that the French heritage is indeed threatened by the sea level rise that will affect the entire Atlantic and Mediterranean coast.

It is also a pity that, in his manifesto book "*Save Our Heritage*" [9], the talented and very active Stéphane Bern does not mention what will become, in the coming decades, the heritage he helped to save when the climate, which has changed, will no longer be the one that existed when the monuments had been built or restored. Similarly, to mention only "*for years the irreparable outrage that threatens our monuments*" (p. 11) to explain the state in which many find themselves is rather reductive when we know that the passing of time is the only variable over which man has no control, while he has one on pollution and climate. Similarly, to write: "*We cannot treat the passing of time with indifference, for it is not indifferent to our buildings. Its effects are real, sometimes irreversible, but the good news is that we can do something about it: by looking after our heritage, by deciding on sufficient maintenance work...early enough, we can slow down or even cancel the degradation processes" (*p. 95) is to address the effects rather than the real causes of the degradations caused by pollution and climate that urgently need to be monitored and acted upon because maintenance and restoration works don’t eliminate the causes of degradation.

Restoring Notre-Dame de Paris after the fire of 15 April 2019 without worrying about its future in the Parisian climate would be an impasse when designing its new roof and insulation, the new mode of heating in winter and air conditioning in summer, while the average temperature in Paris is expected to have increased in 2070 by 3°C in winter and 4°C in summer [10], an increase exacerbated by the UHI effect, especially in the event of a heatwave. This concern responds to the recommendation made on 23 May 2019 at the Parliamentary Office for the Evaluation of Scientific and Technological Choices by the President of ICOMOS-France, Jean-François Lagneau: "*Restore Notre Dame... without missing the notions of sustainable development and climate change."* It is this same concern that led ICOMOS-France to create within it a Working Group "Heritage and Climate". Similarly, the French High Council for Climate recommends in its Report "Renovate Better: Lessons from Europe" (2020) (www.hautconseilclimat.fr @hc_climat) of: "*Taking into account the comfort of any season and ventilation during the overall renovation of buildings: identifying the adaptation needs of French buildings according to regions and climatic zones” defining a repository of the building's performance in terms of comfort in all seasons."*

French climatologists are not insensitive to the problems posed by Cultural Heritage. In 2015, in the journal "*La Météorologie* “[11] an article stated: "*The impact of climate change and air pollution on high-value buildings such as historic monuments is also a concern. Warmer temperatures, frost, rain, crystallization of salts present on porous materials such as stone, or the acidity of certain particles associated with air pollution affect most buildings. These factors will evolve in line with the expected changes in climate and air quality, and the preservation of built heritage will have to result in targeted adaptation measures based on regions and materials...”*. The situation cannot be summarized up better.

The aim of this brochure is to present, in a form accessible to a wide public, the climate models and scenarios projected for France, then the various predictable impacts of the future climate on the French tangible Cultural Heritage, as well as suggestions for adaptation of the latter. The results of the research carried out in France in this context will be specially developed although they are quite few: *erosion and blackening of limestone facades, alteration of medieval stained glass windows and metals, capillary raising in porous walls and crystallization of salts, floods and river low waters, erosion/submersion of coastal archaeological sites...* It is not surprising that Paris takes an important place in the developed examples, not that climate and heritage are exclusive to Paris, but it turns out that many of the French studies on this subject have concerned the capital, its climate and its heritage.

Other potential impacts of climate change will be described. These are either extrapolations for France of the results of studies concerning Cultural Heritage at European level (*metals, effects of freeze-thaw, interior environments*), or studies not specifically concerning Cultural Heritage but whose results can be reasonably transposed to it (*the stability of buildings on clay soils*).

We will not deal here with certain areas of Cultural Heritage that are very important: *intangible heritage, cultural landscapes and archaeology* (except coastal sites threatened by marine erosion and submersion), reserving these themes for experts who are knowledgeable about these issues. Similarly, the purpose will be restricted to the French metropolis area, the *ultra-marine heritage* being located in the Atlantic, Indian and Pacific oceans in tropical climate (except Saint Pierre and Miquelon), undergoes majority marine influences that take it far from the climate of metropolitan France; the impacts of climate change are therefore different and therefore deserve special studies.

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1^rst^ Part:

Overview on climate change

in relationship with

Cultural Heritage

This 1^st^ Part outlines generalities concerning the relationship between climate change and the World, European and French Cultural Heritage.

The first step is to take stock of the international texts, scientific projects and results, which are very recent and still largely to be accomplished, especially in France.

Climate change models and scenarios on a global, European and French scales are then presented in a way that is simple enough to be accessible to a wide audience.

Finally, three useful concepts are developed: the speed of events involving heritage, slow or extreme; the possible contribution of Cultural Heritage to the resilience of cities; Dose-Response Functions, which are the key to a quantitative approach to material damage.

Finally, a very limited summary of the vocabulary used in this area is provided.

France's Cultural Heritage facing global climate change:

a recent story still largely to be written ...

The founding texts and scientific works

The problems posed to Cultural Heritage by climate change have always been and remain a major concern of UNESCO, especially with regard to the 1,121 cultural, natural and mixed properties (including 45 in France) that it has listed since 1972 [1, 2]. For example, in 2007 the UNESCO World Heritage Centre published its first major "*Report on climate change and World Heritage*" [3] using a *climate factors* approach that may interact with Cultural Heritage in the future and adopting a *uniquely qualitative* but highly imaginative vision.

Although not focused on but encompassing France, most of the scientific research on Cultural Heritage in its relations with climate change has been conducted primarily in three projects funded by the European Commission: "*Noah's Ark*" [4, 5], "*Climate for Culture*" [6.7] and "*3encult*" [8] . Unlike UNESCO's 2007 Report, these projects have a mixed approach, by *climatic factors and materials*, further making recommendations to the various actors in charge of Cultural Heritage for its protection against current and announced climate change. These are *quantitative assessment* of projections into the future using predictive climate models under several scenarios, damage functions and the representation of geographical distribution at European level of impacts on the movable and immovable, interior and exterior Cultural Heritage

The 5th Report of the Intergovernmental Panel on Climate Change (IPCC) [9] published in 2013-2014, cites for the first time built heritage, cultural or not; this is an important sign for the scientific community involved in this issue: "*Increased climate variability, warmer temperatures, changes in precipitation and greater humidity will accelerate the deterioration and meteoric degradation of stone and metal structures in many cities... The increased risks that climate change brings to the built environment... are also valid for built heritage...* ».

Considering that "*the role of cities in combating climate change is particularly important given the increase in urban populations, where 68% of the world's population is expected to live in cities by 2050"*, the IPCC decided to include a Special Report on climate change and cities in its AR7 cycle after 2023 and organized an international scientific conference ("Cities IPCC")[10] on this topic in Edmonton, Canada, in March 2018.

The Frameworks for Disaster Risk Reduction of Hyago (2005-2015) [11] and Sendai (2015-2030) [12], which have been adopted at UN World Conferences, call on Member States to "*ensure or promote the protection of cultural institutions, collections and sites of historical, cultural or religious interest."* Disasters resulting from climate change fall within these frameworks.

In his book "*Microclimate for Cultural Heritage*" [13]. Dario Camuffo, of the Italian National Research Council in Padua, Italy, gives a well-documented presentation on the Cultural Heritage-climate change relationships; it is a synthetic vision that is currently making reference. In addition, three books cover the contents of a series of doctoral courses given from 2007 to 2017 at the European University Centre for Cultural Heritage in Ravello (Italy) on the same subject [14, 15, 16]. Another book, "*Preservation of Cultural Heritage and Resources Threatened by Climate Change*," includes 10 contributions published in the journal *Geosciences* in 2018, including a French one on degradation by salts [17]. A Report to the Council of Europe [18] and three articles in French journals [19, 20, 21] further illustrate the French contribution to the problem and its modesty.

A *Climate Vulnerability Index* (CVI) [22] has been created and applied to some World Heritage sites, but none in France.

One brochure was published by the US National Park Service in 2016 [23], followed by two others, published in 2019, one by ICOMOS-International [24] and the other by Historic Environment Scotland [25]: they are intended for the public interested in protecting Cultural Heritage in the context of climate change. In 2020, the ICOMOS General Assembly [26] adopted a resolution on *Cultural Heritage and Climate Emergency* that "*Calls on all the ICOMOS community to implement heritage responses to climate change that seek to safeguard all types of heritages from the current and projected adverse impacts of climate change, both rapid and slow onset, by undertaking vulnerability and risk assessments, monitoring, and by implementing appropriate, climate change adaptation strategies and risk informed, disaster mitigation, preparedness, response and recovery strategies".*

A detailed and exhaustive review of the *literature* existing at global scale on this topic appeared recently on line [27] .

All of these approaches are very general, with no geographical focus (except one on Scotland). France is therefore not directly mentioned, although the subjects dealt with implicitly concern it. This brochure was designed in the same spirit to address this shortfall.

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Global climate change models and scenarios

The *main cause of global climate warming* of the Earth is the accumulation in its atmosphere of *gases and greenhouse particles* produced, among others but above all, by human activity: O_3, CO_2, CH_4, N_2O, CFC... inorganic carbon soot... that prevent the radiative energy emitted by the Earth from evacuating to space. Water vapour (H_2O) has a very important greenhouse effect; but a vapour is not a gas, therefore its concentration in the atmosphere is regulated by the climate, regardless of human activity (except the effect of man on the climate). Conversely, sulphates, nitrates and organic carbon particles, mainly from human and/or volcanic activities, *decrease the temperature* of the Earth's atmosphere by shielding the penetration of solar radiation.

To project possible change in climate and its impacts, researchers use both climate system models and economic and demographic studies. The climate simulations are based on General Circulation Models. To best simulate climate change, many "forcings" are taken into account, whether natural (volcanic eruptions, solar activity, ...) or anthropogenic (greenhouse gas and aerosols emissions). If, for the recent past climate, all forcings can be determined from observations, for future climate simulations only anthropogenic forcings are determined through emission scenarios [1].

The IPCC publishes an Assessment Report (AR) every six years. The next one (AR6) will be published in 2021. Three, more specific, special reports will have been published during this 6th assessment cycle: *Global Warming at 1.5°C* (SR15) [2], *Climate Change and Land Use* (SRCCL) [3] and *Ocean and Cryosphere in a Changing Climate* (SROCC) [4].

In the first four IPCC Assessment Reports, climate projections were based on the SRES (Special Report on Emission Scenarios: A1, A2, B1, B2, A1B...) [5] proposing several socio-economic developments (population, economics, industrial and agricultural development) as well as atmospheric chemistry and climate change (*Fig. 1*).

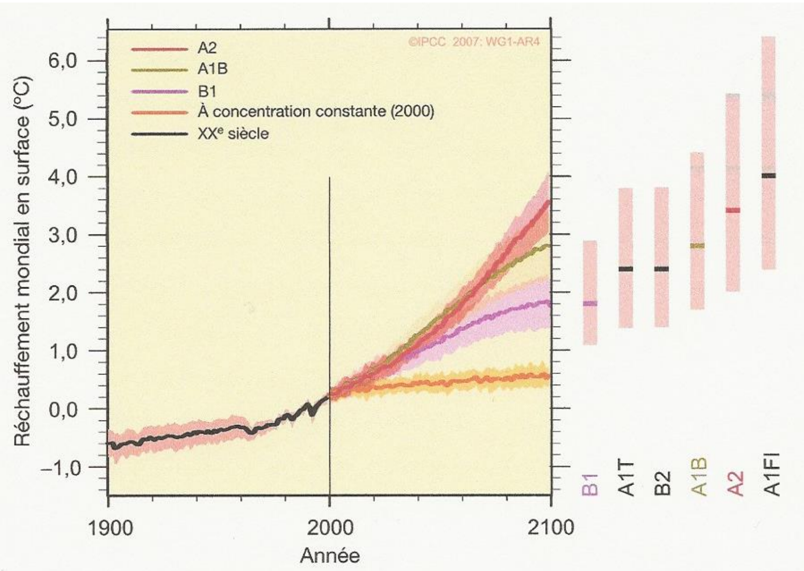

Fig. 1 - Evolution of average global surface temperature between 2006 and 2100 compared to 1986-2005 under the SRES scenarios of the 4 IPCC Report [5].

For its 5th Assessment Report [6], based on the scientific literature, the IPCC introduced four new scenarios called Representative Concentration Pathways (RCP) (*Fig. 2*).

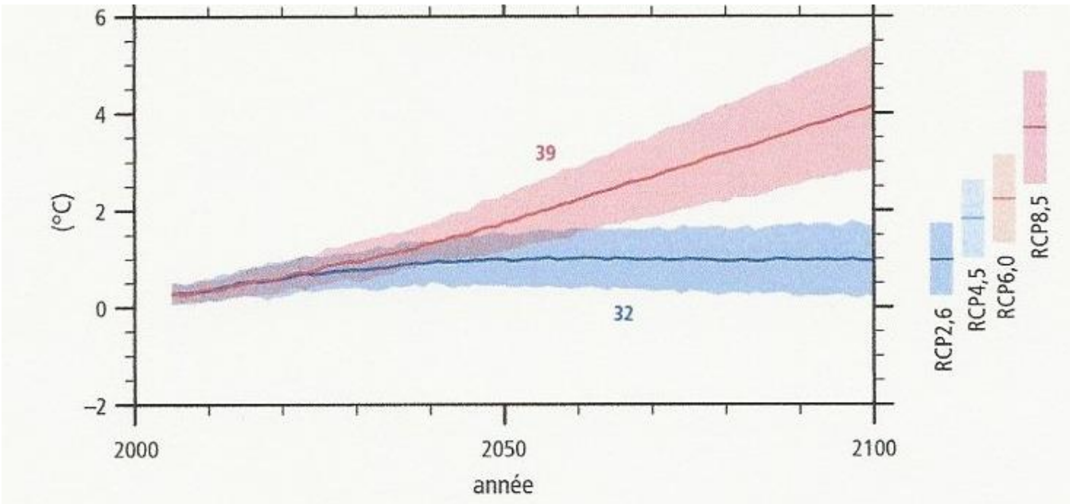

Fig.2 - Evolution of average global surface temperature between 2006 and 2100 compared to 1986-2005 under the RCP scenarios of the 5th IPCC Report [6].

This 5th IPCC Report reaffirms, following previous Reports, that *the increasing concentrations of greenhouse gases (GHG) could lead to major changes in temperature*, and thus melting ice and rising sea level. Whatever the nuances, the general conclusion is very clear: human activities, including the use of fossil fuels, are leading to an exceptional increase in the concentration of GHG that is transforming the climate at a rate never seen before. The link between human activities and rising temperatures is extremely likely (over 95%).

In this 5th Report, the four RCP scenarios allow us to model the future climate based on four different assumptions about the amount of GHG that will be emitted in the coming years (period 2000-2100). Each gives a variant deemed likely to the climate. The four scenarios are named after the anthropogenic radiative forcing range obtained for the year 2100: the RCP2.6 scenario corresponds to a forcing of +2.6 W/m^2, the RCP4.5 scenario of +4.5 W/m^2, and the same for the RCP6.0 and RCP8.5 scenarios. Radiative forcing is the difference between the radiative energy received and the radiative energy emitted by the Earth. If it is positive, it leads to an absorption of energy by the climate system and thus to a warming.

In 2021, the IPCC will introduce in its 6th Assessment Report (AR6) *Shared Socio-economic Pathways* (SSP) [7], or plausible alternative profiles of economic development in society and ecosystems which, in combination with RCP, enable research into impacts, adaptation and mitigation of climate change, particularly in cities.

By signing the Paris Agreement at COP21 in 2015, 195 countries pledged to limit global warming well below 2° C. The *IPCC Special Report SR15* [2] explores options to contain this warming to a very low level (RCP1.9 type), i.e. 1.5°C above pre-industrial level. While this goal is not impossible to achieve, it requires strong and immediate action. In this idea, CO_2 emissions should be reduced to almost zero over the next ten years (2030).

While in 2011 the average concentration of the atmosphere in CO_2 was 391 ppm, in 2100 it would be 421 ppm according to RCP2.6, 538 ppm according to RCP4.5, 670 ppm according to RCP6.0 and 936 ppm according to RCP8.5. However, if we take into account not only CO_2, but all greenhouse gases and particles, we arrive at 475 ppm of CO_2 equivalent for RCP2.6, 630 ppm for RCP4.5, 800 ppm for RCP 6.0 and 1313 ppm for RCP8.5. These concentrations depend directly on emissions.

Greenhouse gas emission scenarios are shown *Fig. 3.* The RCP2.6 scenario involves significant reductions in GHG emissions by the international community: this is the most optimistic. The RCP8.5 is the most pessimistic, but extreme because it is very using coal, but it remains likely because it corresponds to the extension of current emissions.

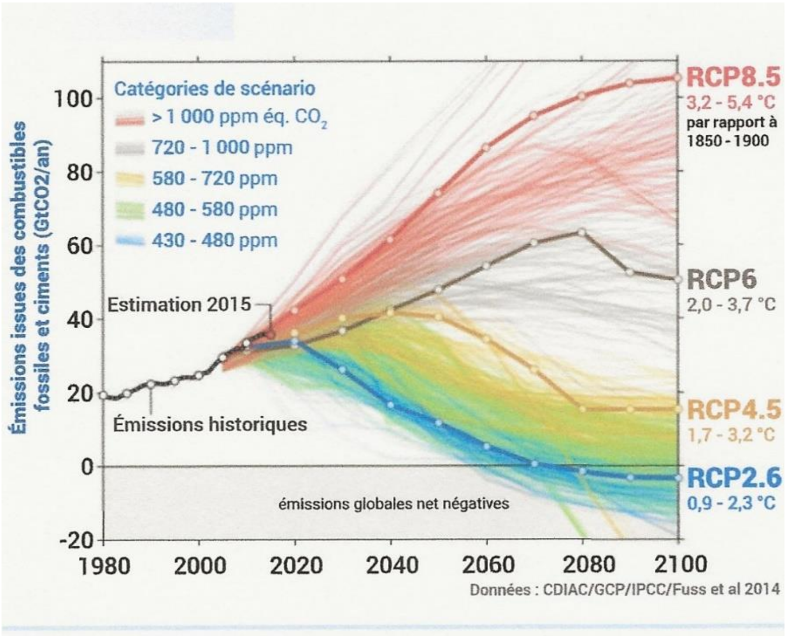

Figure 3 - Evolution of greenhouse gas emissions (CO_2 equivalents) from 1980 to 2100, according to RCP scenarios 2.6, 6 and 8.5 of the 5th IPCC Report [13]

The 5th Report forecasts an increase in temperatures of 1.5 to 4.5°C (*Fig. 2*) and sea level rise between 29 and 82 cm by the end of the 21st century (2081-2100) due to melting ice in Greenland and Antarctica, and the thermal expansion of the mass of ocean waters. This estimate was revised upwards in 2019 [4]: between 43 cm according to RCP2.6 and 84 cm according to RCP8.5 in 2100. But the occurrence of very high sea levels increases sharply with the gradual rise in ocean levels: for example, some records of the past century, which occurred once a century, could occur each year, with the risks of submersion and coastal erosion that they imply.

On average, *precipitations will increase* globally by the end of the 21st century. Wetlands today will become wetter overall and dry areas will become drier. It is "almost certain" that there will be a trend towards an increase in the intensity of rain events. According to *the IPCC Special Report SR15* [2], the risks from droughts and rainfall deficits, particularly in the Mediterranean, will be greater for an overall temperature increase of 2°C than for 1.5°C. This has implications for the stability of buildings, especially cultural ones, built on soils containing clay minerals that are inflated by moisture and then retracted by drought.

Air quality (Pollution by ozone and PM2.5 -Particulate Matter ≤ 2.5 µm - in the lower air layers) is essentially determined by emissions rather than physical climate change, except for the leaching of the atmosphere by rain, especially if it becomes more frequent.

An assessment of the effects of climate change and pollutant emissions on air quality in Europe in the 2030s and 2050s, compared to climate and emissions from the recent past, was made by applying the outputs of the Arpège-Climat model from Météo France in the RCP8.5 scenario[8]. The pollutants in question are of interest to Cultural Heritage: O_3, NO_x, SO_2, PM2.5, PM10, CH_4, NH_3. This assessment shows that an increase in surface ozone in Northwest Europe and a decrease in the South are foreseeable. Sulphate aerosols are expected to increase in 2030 in Northern Europe, but decline in the continental part in the summer. In winter, there will be a decline across the territory in 2030 and even more so in 2050.

The climate models used by French researchers interested in impacts of climate change on Cultural Heritage are: Arpège-Climat and Aladin-Climat from Météo France and Hadley from the British Met-Office. Projections for air pollution are based on the European GAINS emissions model[9]. The two European projects, “Noah's Ark” [10] and “Climate for Culture “[11] , whose mapping included France, used respectively the Hadley model and the REMO [12] model of the Max Plank Institute in Hamburg.

Finally, we should note the existence in France of the very practical portals DRIAS [13] and ClimatHD[14] of Météo France, which make available to the general public regionalised climate projections in various forms, in corrected data, indices or even map representations.

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What future climate for Cultural Heritage in Europe?

P. Brimblecombe, of the University of East Anglia in Norwich (United Kingdom), introduced the concept of "*Heritage Climatology*" [1] and proposed a simple mapping based on those of Kottek-Grieser *et al.* [2]. Rather than being based on weather variables such as temperature and precipitation, this new approach considers potential damage to built structures. Seven climatic heritage regions divide Europe, the Middle East and North Africa, from a very hot and arid area to a polar and mountain zone (*Fig. 1*):

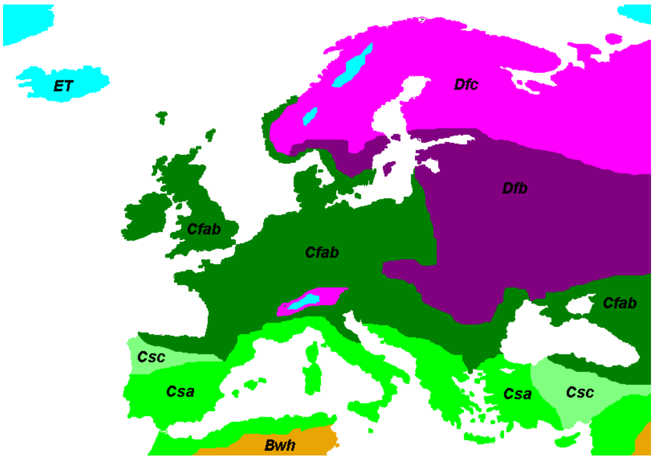

Fig. 1 - Map of Koppen-Gieger, modified by Kottek et al. [2], and adapted by P. Brimblecombe [1] to Cultural Heritage:

Bwh – hot arid climate – Dry ground, little vegetation so there is a chance of wind blown sand, extreme thermal stress. Earthen buildings are frequent in this climate and the materials are friable and additionally sensitive to the rare but heavy falls of rain.

Csa – warm climate with hot summer - Thermal stress on materials exposed to strong insulation. Dry conditions in the summer may minimise fungal attack.

Csb- warm fully humid climate with dry warm summers - Drier conditions and lower variation in humidity lead to less salt damage, and some potential for frost weathering. Some potential for thermal stress on materials exposed to strong insulation.

Cfab – warm fully humid climate with warm to hot summers - Damp conditions and variation in humidity that cause salt damage, occasional freezing events present the potential for frost weathering. Warm and damp conditions lead to the potential for fungal attack.

Dfb – fully humid snow climate with warm summers - Lower variation in humidity leads to less salt damage, but a potential for frost weathering.

Dfc- fully humid snow climate with cool summers - Lower variation in humidity leads to less salt damage, but cold winter conditions mean a high potential for frost weathering in the spring and autumn

E – polar or mountain climate - Conditions so cold that ground may remain frozen. This is a potential problem if temperatures increase as there can be frost heave, disrupt soils and archaeological sites.

The French heritage is therefore currently concerned with *Csa*-type climate in its Mediterranean region and *Cfab* in the rest of the territory, except for a *Dfc* climate restricted to a small part of the Alps. This distribution is fairly consistent with that of the "*Salt Climatology*" of B. Menèndez [3] but differs significantly in coastal areas where wind carries and deposits salts.

P. Brimblecombe concludes its *Heritage Climatology*[1] by confirming that there are special factors linking climate to damage to heritage materials. But the conventional parameters of meteorology are not always the most suitable for estimating the potential damage: the cumulative parameters of Koppen-Geiger are useful but do not take into account neither the wind which is an important parameter for the heritage both by its slow (transport and orientation of rains, sand and salts ...) and extreme (storms, tornadoes...) actions, nor the vulnerability of coastal areas highly exposed to rising sea waters and salted marine aerosols. They also do not take into account the humidity of the air because it is included in precipitation alone, whereas the air is generally humid between rains.

Thus, this approach to climate may seem somewhat obsolete, whereas modern climatology has made considerable progress in recent decades, especially for map representations. We must realize that the intersection of climatology with heritage sciences is still in its infancy.

The *future* mapping evolution of heritage climatology across Europe was drawn up in the two European projects "Noah's Ark" [4] and "Climate for Culture" [5]. We reproduce in the chapter devoted to salts and in comparison with those of B. Menéndez for France [3], the maps at the scale of Europe realizing the projected changes between the current period and the end of the 21st century for the crystallization of salts as they were produced in each of these projects. Similarly, in the corresponding chapters, we reproduced the map projections of the "Noah's Ark" project for the erosion of facades and the impact of the freeze-thaw, and those of the "Climate for Culture" project for the interior climate of the buildings.

Porous materials are particularly sensitive to changes in the phase of water that produce tension during frost, crystallization of salts or mineral transitions with changes in volume (anhydrite-gypsum or thenardite-mirabilite). Extreme events such as storms and floods are also an important part of heritage climatology because their effects can be devastating.

It remains to quantify the damage caused by climate action on materials using Dose-Response Functions and to integrate them into climate models and scenarios.

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What future climate for French Cultural Heritage at the end of the 21st century?

The projections contained in the 5th IPCC Assessment Report [1] at global scale are fortunately supplemented, for our purpose, by those contained in the *4th Climate Report of France in the 21st century* [2] and in the one presented to the French Senate in 2019 by R. Dantec and J.-Y. Roux, entitled: "*Adapting France to climate change by 2050: Emergency Declared*" [3]. They were updated in 2020 by *The new climate projections of reference for the metropolis*, published by Météo-France on the portal DRIAS [4] and which we report below for phenomena that directly interest Cultural Heritage: *temperatures and therefore frost; rainfall, extreme rainfall and droughts.*

1 - *Average annual temperatures* in France, under three scenarios of the 5th IPCC Report 1 (*Fig. 1*), will increase similarly until 2040. But by the end of the century, there will be divergence and warming is expected to be in the order of 1°C for RCP 2.6, 2.2 °C for RCP 4.5 and 4.5 °C for RCP 8.5.

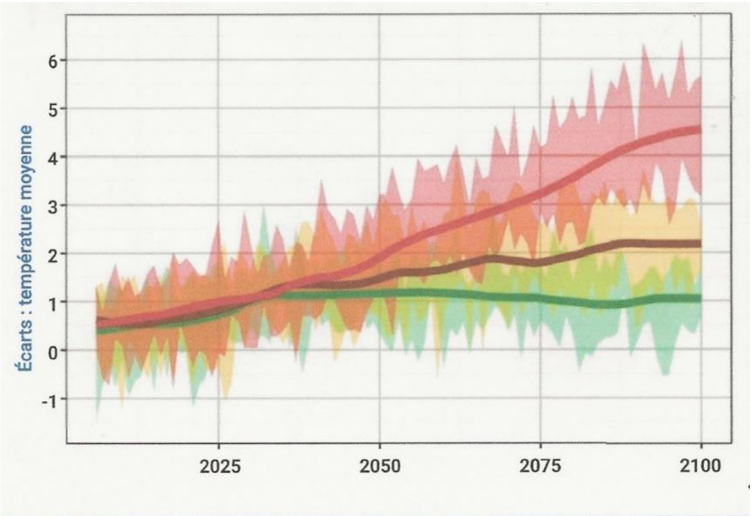
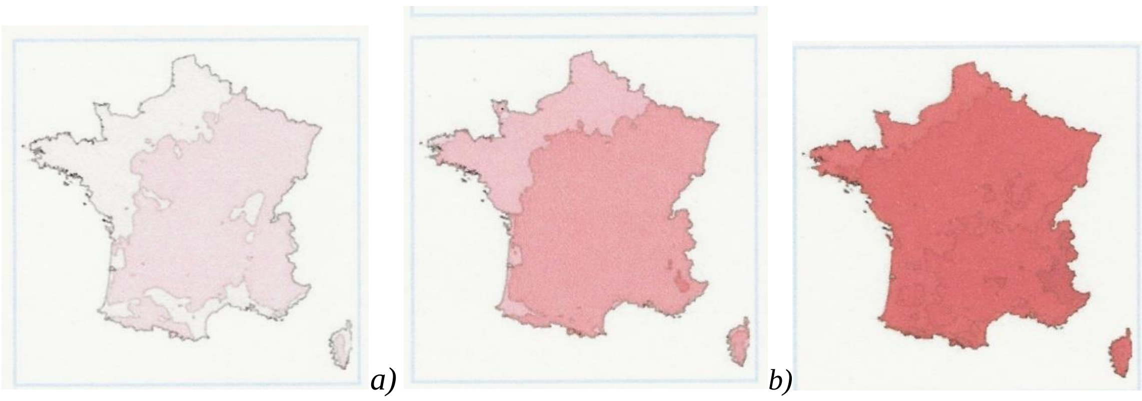


Fig. 1 - Evolution of the annual average temperature gap in France during the 21st century (compared to the 1976-2005 reference) for 3 scenarios of the 5th IPCC Report [1]: RCP 2.6 in green, RCP 4.5 in orange and RCP 8.5 in red [4] .

The *geographic distribution map of annual average temperature differences* at the end of the 21st century under the 3 RCP scenarios (*Fig. 2*) thus shows a general warming of increasing intensity from RCP 2.6 to RCP 8.5, with identical distributions according to a growing north-west/south-east gradient.



a) *b)* *c)*

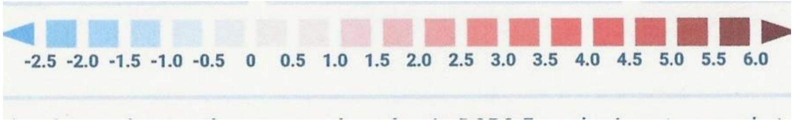


Fig. 2 - Map of the annual average temperature differences for France at the end of the 21st century (compared to the 1976-2005 reference), according to the scenarios of the 5th IPCC Report [1]: RCP 2.6 (a), RCP 4.5 (b) and RCP 8.5 (c) [4]

2 - At the end of the century, the *decrease in the number of days of frosts* (minimum temperature below 0°C) is 10 to 15 for RCP 2.6 and 20 to 35 for RCP 4.5 and 8.5. *Fig.3* shows the geographical distribution of this projected decrease. Freezing days may become rare in all scenarios.

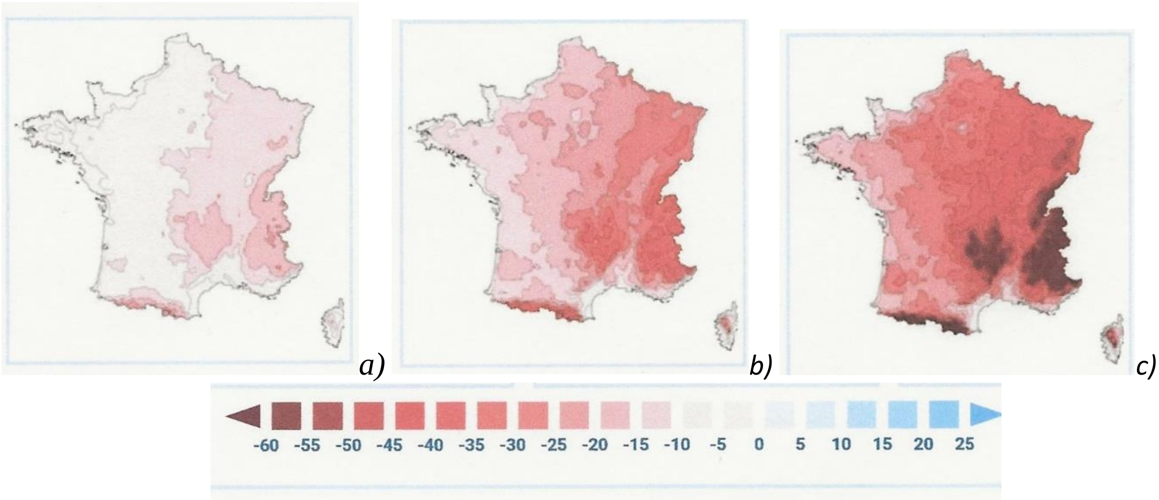


Fig. 3 - Map of annual differences in the number of frozen days at the end of the 21st century in France (compared to the 1976-2005 reference), according to the scenarios of the 5th IPCC Report [1]: RCP 2.6 (a), RCP 4.5 (b) and RCP 8.5 (c) [4]

3 - The *annual rainfall accumulation* for the three RCP scenarios during the 21st century is marked by little variation over the course of the century (*Fig. 4*).

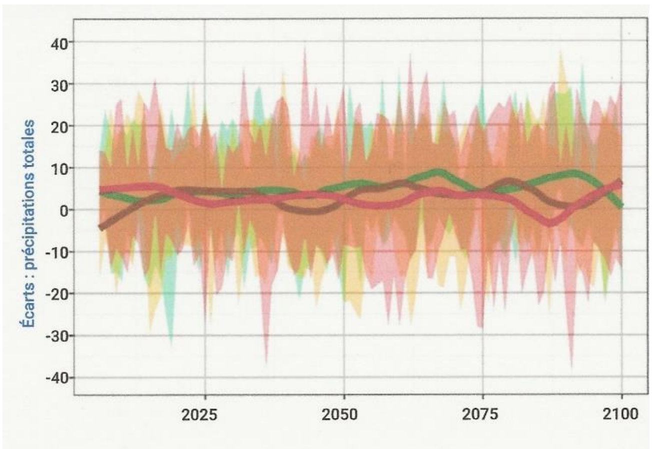


Figure 4 - Evolution of the relative difference in annual precipitation accumulation over the 21st century (compared to the 1976-2005 reference) for the three scenarios RCP 2.6 in green, RCP 4.5 in orange and RCP 8.5 in red [4].

The *geographic distribution map of annual precipitation* cumulative differences at the end of the 21st century (*Fig. 5*), according to the three scenarios, shows small trends but with different regional characteristics from one scenario to another: small and relatively uniform increase in RCP 2.6, slightly more pronounced in the South-East; low increase in RCP 4.5, with the exception of the Pyrenees, and a sharper increase in the east of the country; north-south signal more contrasted with RCP 8.5 with a decline in the southern half and an increase in the northern half, especially near the north-eastern borders.

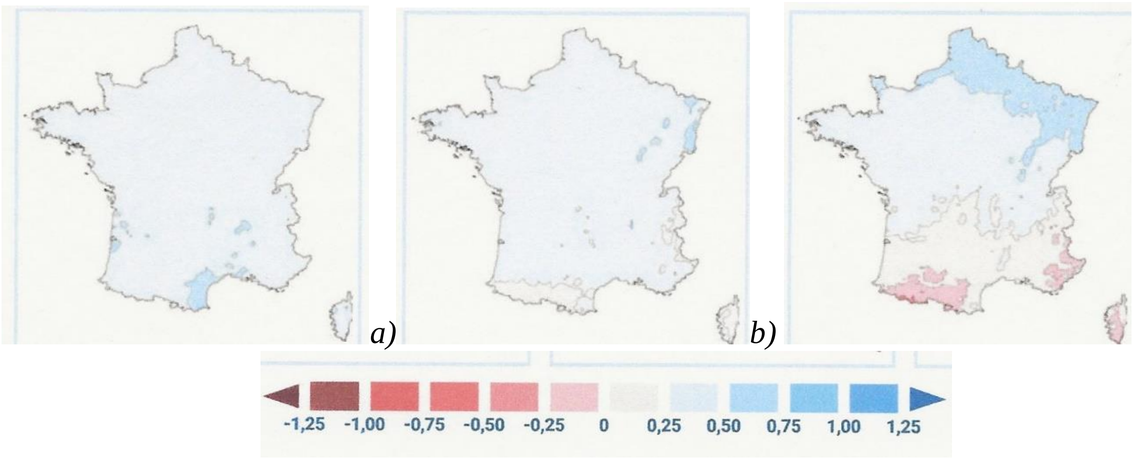


Fig. 5 - Map of annual precipitation accumulation differences (mm/day) for France at the end of the 21st century (compared to the 1976-2005 reference) according to the scenarios of the 5th IPCC Report [1] RCP 2.6 (a), RCP 4.5 (b) and RCP 8.5 (c) [4]

This trend is undergoing a strong seasonal modulation with a systematic increase in winter, often above 10% and conversely, a near-systematic decline in summer, up to -10 to -20% at the end of the century with the RCP 4.5 and RCP8.5 scenarios.

4 - *Extreme rains* (30 to 60 mm/day) occur on average 3 days a year. However, Mediterranean episodes can often exceed 150 mm/day. The intensity of these extreme rains increases slightly throughout the century across virtually the entire territory and with the three RCP scenarios considered (*Fig. 6*). The most exposed regions are those in the northern half, including the northern and north-eastern borders and the Channel coast.

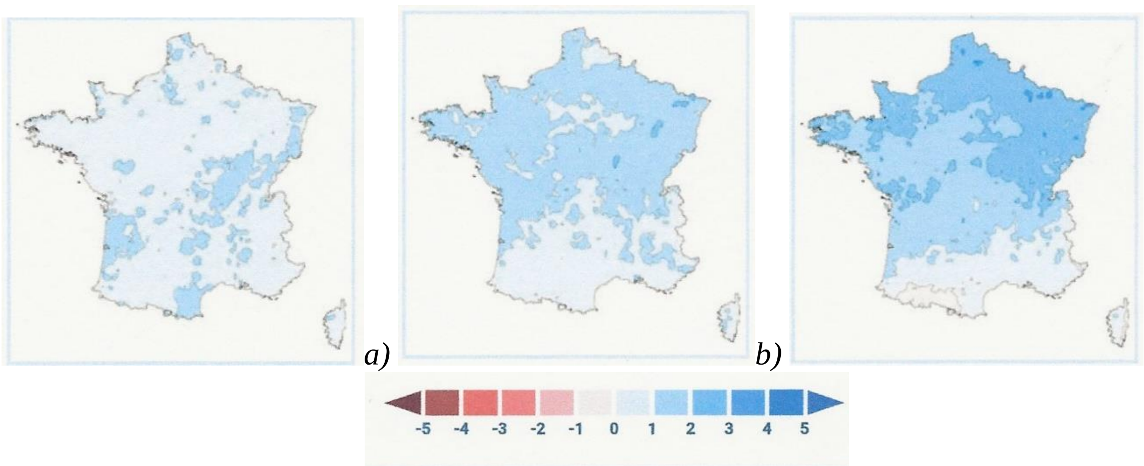


Fig. 6 - Map of deviations in mm of extreme rainfall intensity at the end of the century (compared to the 1976-2005 reference) according to the scenarios of the 5th IPCC Report [1]: RCP 2.6 (a), RCP 4.5 (b) and RCP 8.5 (c) [4]

5 - *Weather drought* is characterized by the maximum number of consecutive dry days in summer (where precipitation has not exceeded 1 mm). There is also a soil and a hydrological drought (river flow). The effects of climate change, due to the increase in evaporation due to rising temperatures, are more intense over the latter two. Simulations at the end of the century, do not record any evolution of weather droughts in RCP 2.6 or even a slight decrease. The same is not true for the RCP4.5 and RCP8.5 scenarios, for which there is an increase of 5 days and 10 days respectively. The regions most affected by these developments are those of the south-western half of the country, including the Mediterranean, Aquitaine basin and western France (Brittany and Loire countries) (*Fig. 7*).

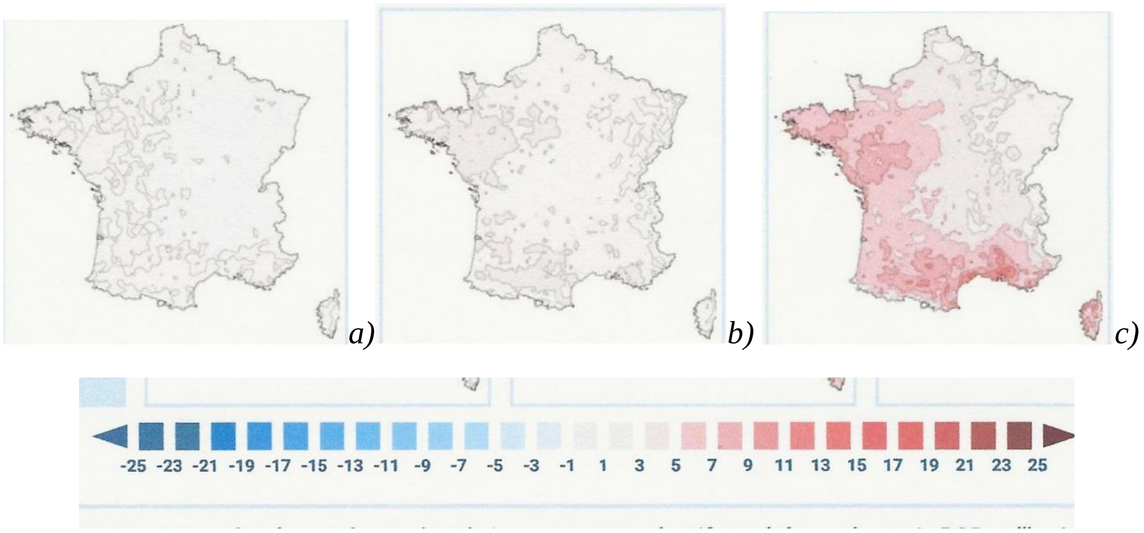


Figure 7 - Map of differences in consecutive dry days in summer (compared to reference 1976-2005) according to the 5th IPCC Report [1] scenarios: CPR 2.6 (a), RCP 4.5 (b) and RCP 8.5 (c) [4]

5The *climate analogue method* [4] was used to define for Paris, among the current local climates, an analogue most resembling the climate expected for the French capital at the end of the century, in terms of temperatures and total monthly precipitation. Thus, Paris could have in 2070-2100 the climate of Bordeaux according to the French model Aladin-Climat or that of Cordoba according to the English model Hadley, both in scenario A2 of the 4th IPCC Report. In both cases, therefore, the changes would be very significant.

Finally, an *Urban Heat Island* (UHI) affects urban areas. It is explained by the combination of multiple factors: urban forms that limit the circulation of air and the evacuation of heat by radiation; high proportion of mineralized surfaces and low vegetation cover; high concentration of heat-generating activities that add to natural heat; use of heat-retaining materials, etc… [3] . The UHI leads to an over-use of air conditioning which, although increasing interior comfort, increases energy consumption and also the temperature of the streets and thus the demand for refreshment.

The phenomenon of UHI has been studied for example in Paris, Dijon, Lyon, Toulouse... This phenomenon could be added to the impacts associated with an increase in the intensity and duration of heat waves: for example, in 2003, during the heat wave that affected Europe, the temperature difference between central Paris and the surrounding rural areas reached 8°C [6, 7, 8] (*Fig. 6*). However, one study showed that, for the period 2046-2055 and in scenario A1B of the 4th IPCC Report, although the average temperature in Paris may rise by 1.8°C, climate change is expected to have a neutral impact on the average annual urban heat island [9].

The vegetation of cities, especially the facades and roofs or terraces of cultural buildings, in order to fight against the UHI, should be a major concern for the Architects of the Buildings of France, because "*it is necessary to avoid that the preservation of the authenticity of the building merges with the mineralization of spaces"* [3] . This doctrine, however, deserves a great deal of caution in its practical application, especially to emblematic historical monuments.

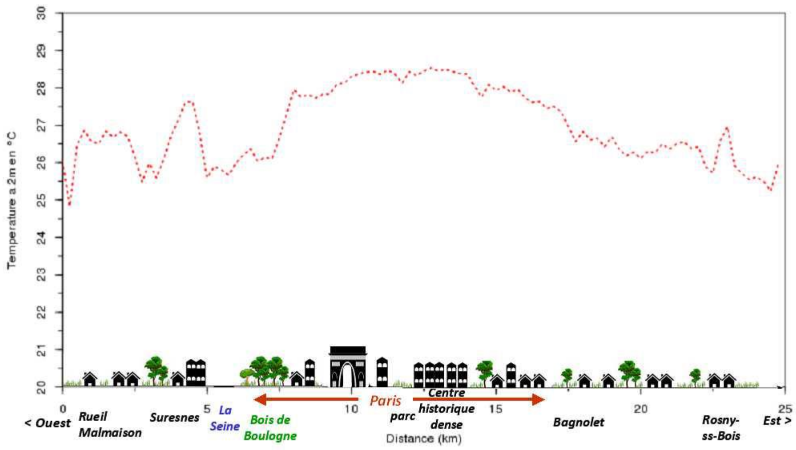


Fig. 7: Cross-section of the Urban Heat Island crossing Paris from West to East during the summer heatwave of 2003 [6, 7, 8]

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Extreme events and slow events

To describe the impacts of climate and its effects on Cultural Heritage, it is essential to distinguish between *rapid events* and *slow-occurring events* [1, 2]:

- *Rapid or extreme events* are short-lived, acute, intense, recurrent, highly damaging and uncontrollable. They include extreme winds, hurricanes, typhoons, storm surges, extreme precipitation, extreme droughts, hailstorms, flash floods, landslides, heat waves, cold waves and spontaneous fires. Climate change is expected to increase the frequency and intensity of some of these types of events around the world;

- *Slow-occurring events* are long-lasting, gradual and potentially slow transitions that are not harmful in the short term, but can have profound consequences in the longer term. They are the result of slow global warming that causes glaciers to melt, sea level rise, aridification, desertification and changes in seasonality and species distribution. For built heritage, the interactions of climate change with air pollution are concerned (e.g. the recession/erosion of limestone and marble facades, the blackening of stone surfaces, the chemical leaching of ancient stained glass windows and the corrosion of metals...) as well as the crystallization of salts in porous walls (e.g. stone, brick, plaster, mosaics, murals, etc.), the growth of pests, fungi and superior plants.

It is mainly *extreme events*, especially high winds, extreme rainfall, flash floods, heat waves and droughts, that pose a major threat to Cultural Heritage.

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The contribution of Cultural Heritage to the resilience of cities

Resilience is a new concept in the area of the city and of Cultural Heritage. The United Nations International Risk Reduction Strategy [1] defines it as "*the ability of a system, community or society to be exposed to risks, to resist, absorb, welcome and correct the effects of a hazard, in a timely and effective manner, including the preservation and restoration of essential structures and basic functions.*" How is Cultural Heritage a potential player in the resilience of cities in a post-crisis climate change situation?

Climate-related stresses affect cities, whether they are chronic (changes in temperature and rainfall, the effect of Urban Heat Island, air pollution, etc.) and especially acute ones (floods, storms, heat waves, etc.). Cultural Heritage, located at the heart of these, should be taken into account in their resilience strategies, although, for example, Paris has forgotten this in 2017 in its own Resilence Strategy [2] . It can indeed be a powerful lever in post-crisis social and economic reconstruction, as it is about the framework and quality of life of urban dwellers, and it is an important tourism motivation with the resulting economic benefits.

M. Reguezza, in his book "*Paris coule-t-il? (Is Paris sinking?)*" [3] recently addressed this notion about the floods of the Seine: "*Resilience is a vague but very fashionable concept in risk management. It is an imported concept of the physical sciences. The etymology of the word (from the Latin resilire) refers to the idea of "rebound" ... A society facing a crisis... is resilient if it is able to absorb a shock, to cope with it, to maintain its organization and operation, to return to "normal", to recover, to rebuild itself. At best, society is learning from the disaster. This ability to learn allows it to better anticipate future disasters... In this context, the return to normality is reduced to the reconstruction and repair of physical damage. In particular, there is a strong tendency to rebuild in the same way. It's easier and faster, because you know how to do it; it is also less expensive in most cases; it's finally the best way to pretend that nothing has happened."*

F. Macalister addressed the issue of resilience in the specific area of Cultural Heritage [4]. This is, to our knowledge and to date, the most focused study on this sector: *" Conservators and others working in the Cultural Heritage sector are in a unique position to aid a community's recovery in the event of a large scale disaster… Effective response and recovery require collaboration and regional, national and international networks, including the use of social media*".

The Charter of Rome on the "*Resilience of the Cities of Art to natural catastrophes*" [5] contains fundamental points for our purpose: "*The distinctive feature of cultural assets is that they have aesthetic, historic, educational, social, symbolic and spiritual value that along with their economic value determine the willingness of people to fund their preservation…Cultural Heritage resources are genuinely unique and not replaceable by any means once lost or damaged… Cities of Art must also be able to absorb external shocks without losing their characteristic functions: they must become resilient cities…The success of the recovery phase depends crucially on the preservation of major schools of conservation/restoration…Risk mitigation of museum collections deserves special attention."*

An application of the notion of resilience, without a relationship established by its authors with climate change, was made to an emblematic art city, *Florence* (Italy), following its flood by the Arno in 1966 [6, 7]. In this study a mathematical model of resilience has combined a hydrological model simulating flooding and a model of vulnerability and recovery estimating physical damage to Cultural Heritage and temporal persistence of direct and indirect consequences. The variables selected on the state of the system are the number of monuments open to the public and the number of visitors after the flood which represent a measure of the indirect social and economic impact on the city. The results show that the resilience model helps in indirectly quantifying impacts due to the loss of accessibility of Cultural Heritage and allows for an assessment of the effectiveness of preventive measures.

In May 2017, the *Academies of Sciences of the G7 countries*, including the French Academy of Sciences [8], issued a joint statement at the Taormina Summit in Sicily, stressing major scientific challenges. The resilience of Cultural Heritage to natural disasters has been identified as a scientific priority. The Academies of Sciences stress the importance of strengthening public awareness of the specifics of the vulnerability of Cultural Heritage. They propose several actions and recommendations: further research to assess risks and predict the various categories of natural disasters; establish procedures that allow optimal preparedness at the time of these disasters; properly fund heritage conservation/restoration schools and have them interact with research centres; facilitate crowdfunding strengthening international cooperation.

Unfortunately, all of these recommendations find immediate application in the context of the Corona virus pandemic in the spring of 2020. For example, the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM, Rome) issued a statement on 10 April 2020, the terms of which could also apply to a post-disaster situation related to climate change: *"ICCROM draws the world's attention to the significant role of culture and Cultural Heritage in social and post-traumatic support in the event of a crisis enabling social cohesion and building community resilience... The protection and conservation of our Cultural Heritage must be included in all recovery plans and in post-crisis development projects."* Similarly, the City of Paris has reactivated its Resilience Strategy [2] in which it would be desirable to include a symbolically important point for the reconstruction of the image and living environment of Parisians, as well as for the resumption of economic activity related to tourism: the reopening and acceleration of the restoration work of Notre-Dame Cathedral whose structure burned down on 15 April 2019.

It is understandably that our approach to the resilience of Cultural Heritage is cautious and modest, as it is an almost unexplored area, especially in France. Research on the relationship between climate change and French Cultural Heritage has focused on impacts, but very little on adaptation, let alone resilience, methods of assessing vulnerability, exposure and risk analysis.

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Predicting and quantifying the evolution of material damage: the Dose-Response Functions

Dose-Response Functions (DRF) are equations that quantitatively express, based on current behaviour, the behaviour of a material placed in a new environment and in new climatic conditions, current or future, or even allowing to reconstruct its past behaviour. These DRF have been widely developed and discussed recently [1] .

The *doses* are the parameters influencing the response; they correspond to climatic factors (meteorological) and environmental doses (pollution). Their influence is different depending on the conditions of exposure to rain: dry (sheltered from rain) or wet (under rain). The *response* is a measurable modification of the material: corrosion, recession, blackening, chemical leaching, bio colonization... The general expression of an DRF is:

$$\textit{Response (damage)} = \textit{Doses}_{dry}\,(T, RH, [SO_2], [HNO_3], [O_3], [PM], t\ldots)$$

$$+\ \textit{Doses}_{wet}\,(Rain, [H^+], t\ldots)$$

with : T : Temperature ; RH : Relative Humidity ; PM : Particulate Matter ; t : time.

DRF are obtained empirically, either *in the laboratory* by exposure in atmospheric simulation chambers where different doses are introduced, or more frequently during *exposure campaigns* at real sites with diverse environmental and climatic parameters that are measured throughout the experiment. The duration t of the experiment is considered a dose. Only the measured doses are taken into account, excluding all others, although they could be possible causes of damage, but unknown or unmeasurable at the time of the experiment. These DRF also have the crucial property that their results can be mapped, as are climatic and environmental factors. A DRF, like any empirical function, is only valid under conditions that are identical or close to those of its development: the consistency of the validity areas of DRF with climate and pollution data must therefore be verified.

A first damage function, similar to an DRF, was established by F. W. Lipfert [2] in 1989, during *laboratory experiments* on the dissolution of calcite ($CaCO_3$), the main mineral of *limestone and marble.*

Several other DRF, relating to *metals* (steel, zinc, copper, bronze) and *Portland limestone*, were obtained from environmental material exposure campaigns during the United Nations International Cooperative Materials Programme (1997-2001) and the European MULTI-ASSESS project (2002-2005).

For the glassy material, a DRF expresses the *haze of modern silico-calco-sodic glass* due to the deposition of atmospheric particles [5] , two other DRF express the chemical leaching (lixiviation) of K and Ca of the *silico-calco-potassic ancient stained glass* [6,7].

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A summary of the vocabulary of Cultural Heritage facing of climate change

Below are only a minimum of definitions of the terms used in the study of the relationship between climate change and Cultural Heritage. Others are given through the pages of this brochure. Finally, more numerous and more supplied, exist in glossaries complementing recent publications referring to the field [1 to 6] . The reader will be able to refer easily to them.

Adaptation: an approach to reduce vulnerability to the effects of current or future climate change by moderating damage or exploiting potential beneficial opportunities**.**

Mitigation: human intervention to reduce sources or increase greenhouse gas sinks.

Downscalling: a method of transforming model information and results analysis from a global scale to a regional or local scale.

Exposition: the presence of cultural property in places where they may be affected adversely.

Maladaptation: actions to increase the risk of climate-related adverse effects such as increased greenhouse gas emissions or increased vulnerability.

Carbon neutrality or Zero net emissions: the principle of offsetting greenhouse gas emissions into the atmosphere: if a certain amount is emitted in one place, it can be compensated by removing the same amount of these gases elsewhere, e.g. by improving the energy efficiency of cultural buildings.

Representative Concentration Pathways (RCP): a temporal evolution of greenhouse gas emissions or other climate forcings into a future state.

Resilience: the ability to absorb climate disturbances by keeping the same basic structures.

Risk: potential adverse consequences of the impacts of climate change on cultural property or of human responses to climate change.

Vulnerability: propensity or predisposition to be affected by adverse effects**.**

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2nd Part :

The potential impacts of climate change on France's Monumental Heritage and adaptive opportunities

This 2nd Part is a *qualitative and descriptive approach* to the impacts that could potentially affect the French Metropolitan Cultural Heritage, as well as possible adaptations that could limit the damage resulting from these impacts. It is an inventory of possibilities, drawn up from general considerations and general phenomena that are not specifically French. These are not, therefore, scientific results consolidated by expert publications. They have the advantage of being general and fairly comprehensive, thus giving clues for future research.

The potential impacts of climate change on French Cultural Heritage are summarized in *Table 1* for the *exterior* envelopes of monuments and buildings, and in *Table 2* for the *interior* of cultural buildings (museums, libraries, reserves...), unheated and un-air-conditioned, housing art objects and collections.

Each table has horizontal blocks of different colour corresponding to each of the *key factors of climate origin*: increased global temperature, precipitation and atmospheric humidity, rising sea level and a combination of climate change and air pollution.

One vertical column concerns the *speed of action* of these factors: slow or extreme. The next two columns deal with the *general modalities,* the other the *specific modalities* of impact on heritage. Finally, the last column suggests *actions of adaptation, remediation and resilience*.

These two tables, which are *qualitative, descriptive, subjective, non-exhaustive and non-hierarchical,* should be considered only as an indication. However, references to *quantitative* studies are given when they exist in the scientific literature.

Table 1: Predictable impacts of climate change on the exterior envelopes of monuments and cultural buildings in France

Key factor of climate origin	Speed of action	General modalities of impact	Specific modalities of impact on Cultural Heritage	General actions of adaptation, remediation and resilience.
Increase in global temperature	**Slow**	1-Influence on local summer and winter average temperature - Urban Heat Island (UHI) Effect	1- Increase in the outside temperature of buildings -Increased exposure of facades to sunlight with thermoclastism - Increased growth of lichens, algae, fungi, superior plants on facades -Increased damage to wooden structures due to pests	1-Achieving thermal insulation of cultural buildings while respecting their aesthetics -Mitigate the UHI Effect by vegetation and watering -Lighten vertical facades and horizontal parts to increase their albedo, by reducing pollution and cleaning
		2-Influence on atmospheric and oceanic circulation	2-Wind effects: burial by migration of continental and coastal dunes	2-Fighting burial of buildings by sand (plant screens)
		3-Influence on freeze-thaw cycles	3- Breaking wet porous materials -Destabilization of buildings by thawing permafrost in high mountains	3- Shelter porous materials from rain (drying) - Consolidating destabilized structures
	Extreme	1 - Heat waves - Extreme droughts	1-Significant thermoclastism - Increased fire risk of wood infrastructures and frames	1-Increased fire protection
		2-Influence on the regime of high winds	2-Damage due to high winds, tornadoes and storms	2-Secure roofs, shutters, exterior doors - Protection against burial

Precipitation and atmospheric humidity	**Slow**	1-Increased intensity and duration of precipitation	1- River flooding - Overflow of gutters and pipes	1- Rising cultural buildings (stilts) - Resizing gutters and pipes -Rising electrical installations (counters, power sockets) -Installing anti-reflux valves on water disposal devices
		2-Saturation of ground in water	2-Landslides with destruction and burial of buildings	2-Inventory and map areas at risk of landslides and prohibit new constructions, especially cultural ones
		3-Wind-driven rain	3- Increased erosion of stone facades, plaster, brick, concrete	3-Use of more water-resistant stones, concretes and coatings -Regular maintenance and refit
		4-Capillary raising of salt-laden waters in porous walls	4-Salty efflorescences and moisture stains outside porous walls	4-Installing drains at the base of the walls
		5-Freeze-thaw effect on porous materials	5-Breaking and cracking of materials of façades	5-Protection of porous materials against frost: water shelter
		6- Swelling-shrinkage of clay soils	6-Destabilization of foundations and cracking of the walls of buildings on clay soils	6-Inventory the clay areas -Inventory and consolidate the weakened structures -Chaining of buildings, sidewalks anti-evaporation
		7-Action on wood	7-Dilatation and decay of wood	7-Protection of wood from moisture
		8-Action on metal	8- Rust and corrosion of metals	8-Metal protection (paintings)
	Extreme	1 – Inundation by recurrent river flooding and flash-flows	1 - Damage by water force, debris, sediment, pollutant inputs - Impact on electrical installations	1 - Inventory heritage areas and buildings threatened by river and flash floods -Isulation and elevation of electrical installations - Installation of anti-reflux valves (water evacuation) -Developing emergency response plans in case of recurrent and sudden floods -Identifying refuge sites to accommodate cultural properties and to dry and restore them - Consolidation of historic bridges
		2 - Floods by urban rain runoff in artificialized environments (concrete, asphalt, stone pavers...)	2 - Overflow of stormwater collection and transport systems	2 - Making artificialized soils permeable - Optimizing stormwater collection and flow -Extension of urban parks and gardens

Sea level rise	**Slow**	1-Coastal erosion 2-Invasion of continental areas by marine waters	1-Destruction of monuments, cultural buildings and archaeological sites on the coast 2-Significant intake of salt-laden waters in buildings in the continental zone and corrosion by these salts	1-Inventory monuments, cultural buildings, archaeological sites and cultural landscapes threatened by coastal erosion -Strategic withdrawal 2-Inventory low-lying areas susceptible to marine invasion -Strengthening protection and sealing structures -Proscribe new unsuitable buildings in flood-prone or unstable coastal areas -Elevation of cultural buildings (stilts)
	Extreme	- Crossing and breaking of protective structures	- Submersion of coastal and island cultural sites	- Strengthening protection structures
Combination of climate change and <u>outdoor</u> air pollution	**Slow**	1-Deposition of anthropogenic particles: fly-ash and soot 2-Alteration of glass 3-Alteration of metal 4-Degradation of concrete 5-Biodegradation of façades	1-Development of black gypsum crusts -Blackening of façades by soot deposit 2-Lixiviation and corrosion of stained glass windows 3-Rust and corrosion of metals 4-Carbonation of cement and corrosion of steel rebars 5-Change in colour of façades	1-Reduction of air pollution (traffic) -Pedestrianisation of historic city centres -Monitoring the atmospheric environment of monuments by automatic stations 2-Installing double protective glazing in self-cleaning glass on stained glass windows 3-Protection of metals (paintings) 4-Formulation of new concretes and metal rebars 5-Air pollution reduction

Table 2: Predictable impacts of climate change on the interiors of monuments, cultural buildings, museums, collections, libraries, archives, reserves... unheated and un-air-conditioned in France

Key factor of climate origin	Speed of action	General modalities of impact	Specific modalities of impact on Cultural Heritage	General actions of adaptation, remediation and resilience.
Increase in global temperature	**Slow**	1 - Influence on the indoor temperature of buildings - Urban Heat Island (UHI) effect	1-Increased temperature in museums, collections, libraries, reserves, archives, decorated caves.... -Increased pressure on air-ventilation-humidification systems -Increased growth in the number and activity of pests -Increased chemical degradation	1-Achieving the interior thermal insulation of cultural buildings while respecting their aesthetics - Develop models of the effect of external climate variations on the indoor microenvironment -Adapt air conditioning-ventilation and humidification systems to climatic variations -Amplify the use of LEDs for lighting - Respect the indoor historical climate during the construction period of buildings or production of works (historical climate)
		2-Influence on freeze-thaw cycles	2-Fissuration-scaling of damp porous materials (brick interior walls...)	2- Protect porous frost-sensitive materials (drying)
	Extreme	-Heat waves and dog days	-Extreme temperature and droughts in museums, collections, libraries, reserves, archives...	-Strengthen air conditioning, humidification and natural ventilation of the premises

Precipitation and atmospheric humidity	**Slow**	1-Recurrent river flooding 2-Capillary raising of salt-laden waters in porous walls 3 - Freeze-thaw effects on porous water-soaked materials 4-Action on wood 5-Action on organic materials (except wood) 6 - Action on metals	1 - Wetting interior floors and walls and objects 2 - Fissuration and flaking of porous materials (brick interior walls...) 3 - Cracking and flaking of damp porous materials (brick interior walls...) 4 - Deformation and cracking of structures (frames) and wooden objects (furniture, statues, handicrafts...) 5 - Increased risk of mould for paper, books, photos, polymers, textiles, contemporary works of art... 6 - Rust/corrosion of unprotected metals	1 - Waterproof exits and elevation of objects - Raising electrical installations 2 - Shelter in refuge sites for drying and restoration 3 Action on the outside of porous walls (drains at the base of walls) 4 - Special adaptation of indoor temperature and humidity 5 - Increased protection of organic materials 6 – Protection of metals
	Extreme	-Inundation by recurrent river flooding and flash floods	-Salt efflorescences and moisture stains inside porous walls -Fissuration/removal of frescoes, murals, mosaics.	-Inventory sites at risk -Installing drying-restoration workshops for flooded objects

Sea level rise	**Slow**	1-Coastal erosion 2-Invasion of continental and coastal areas by marine waters	1-Destruction of objects and collections inside buildings 2-Wetting and crystallizing salts on interior walls in flooded areas	1- Provide refuge sites to evacuate cultural property -Relocating collections inland (Strategic withdrawal) 2 - Strengthen the waterproofing of structures -Provide refuge sites for cultural property -Creation of drying-desalination workshops of objects
Combination of climate change and <u>indoor</u> air pollution	**Slow**	1-Change in the indoor climate of museums, libraries, collections, archives, reserves... 2-Greenhouse gases emission 3-Deposition of natural and anthropic particles	1-Increased diffusion of volatile organic pollutants emitted by premises and objects' cleaning products 2-Heating and air-conditioning poorly controlled - Transport of art works to a long distance -Travel of staff -Massive use of computing 3-Dusting of objects	1-Restricting the use of volatile organic pollutants -Choose neutral cleaning products 2-Strengthening air-conditioning and heating controls -Reducing distances between museums, laboratories and reserves - Reducing air travel (congress, terrain...) -Reduce computer calculations 3-Adapting indoor air filtration systems

3^{rd} Part:

Studies of phenomena

affecting

the French Cultural Heritage

in the context of climate change

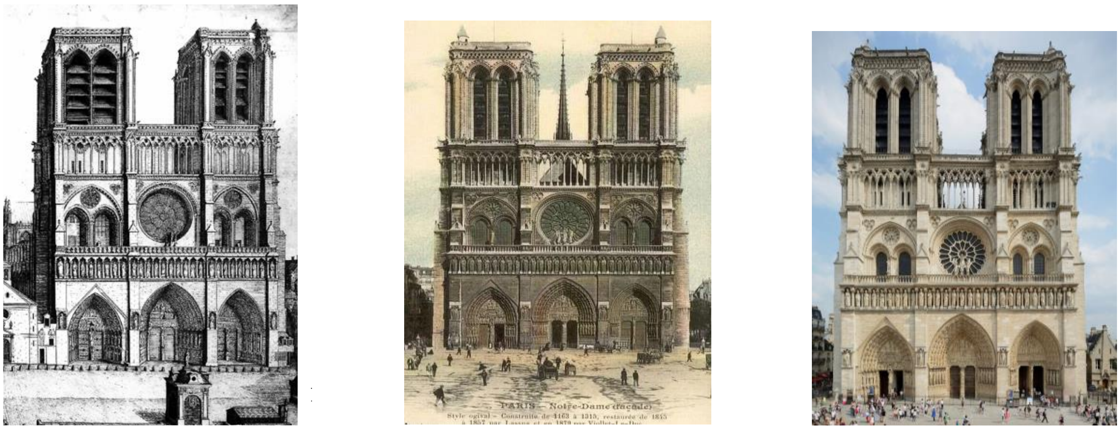
This 3^{rd} Part presents the results of the few studies of the impacts of climate change carried out on French Monumental Heritage. These studies are to date (2020) very limited and have been performed by French-involved teams only in 6 cases: *the blackening and erosion of monumental facades in stone, the chemical leaching of medieval stained glass windows, the alteration of metals, the crystallization of salts in porous walls, the floods and river low waters, the vulnerability of coastal archaeological sites, the dendroclimatology on woods of heritage.* The facades, stained glass windows, metals and flooding were studied in Paris, the problem of salts having been the only one to be addressed at the scale of the metropolitan territory in its entirety. The coastal archaeological sites studied are located in Lower Normandy, Brittany and the Loire Region. Dendroclimatology studies on trees or beams of monuments were carried out in Fontainebleau and Angoulême, and applied in Paris.

Monumental facades in stone facing air and rain pollution, and climate change

The facades of monuments and Haussmannian buildings in Paris have recently been the subject of studies related to climate change; we will take them as examples. These facades have suffered greatly from air pollution in the past, but are suffering much less now. We will see how climate change will likely affect them by the end of the 21st century.

The *slow impacts of pollution* are not randomly distributed on the facades because their location is governed by rain [1, 2] (*Fig. 1*):

- In *rain-sheltered areas*, atmospheric particles - derived mainly from the combustion of coal or wood (in the past) and of fuel oil or gasoline (currently) - settle and can be cemented, if the atmosphere contains a large amount of SO_2, within a centimetre *black crust* of gypsum ($CaSO_4$, $2H_2O$). If atmospheric concentrations of SO_2 are reduced, as now, the particles form only a thin *grey or blackish carbonaceous film*. In both cases, there is blackening (or soiling).
- In *areas exposed to rain*, on the contrary, the particles deposited between two rains are evacuated by the next and the substrate remains clean, clear and no crust or film can develop. It is then eroded.



a) ***b)*** ***c)***

Fig. 1 - a) Notre-Dame de Paris designed in 1669 by Antier (Département des Estampes, French National Library); b) View at the beginning of the 20th century, blackened by pollution, especially in its low-lying parts sheltered from the rain, while the high parts are more leached by rain; c) View in 2013 after a clean-up and restoration campaign.

Air pollution is not a new phenomenon in Paris because, since reliable data have been available, i.e. since at least 1500 (use of wood), this pollution has only increased, especially in the 17th century (introduction of coal) and in the first half of the 20th century (use of petroleum derivatives), before decreasing drastically in the second half of the same century. The GAINS [3] model indicates that this decline is expected to continue until the end of the 21st century [4] (*Fig. 2*).

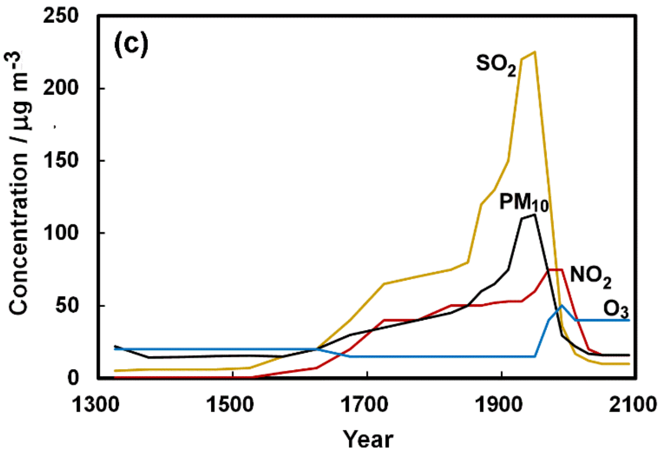


Fig. 2 - Concentrations in SO_2, PM10, NO_2 and O_3 in the Paris air from 1500 to 2100 [4].

The *blackening of the stone* at *t* time can be expressed by the measurement of its opposite, the *reflectance* R_t (relationship between the reflected light flow and the incident light flow). An equation connects R_t to the initial *reflectance* (clean stone) and the concentration of air in fine *PM10* particles (<10 m), with a rate of blackening k_s [5]:

$$R_{t\%} = R_{0\%} \cdot exp\left(-k_s \cdot [PM_{10}]_{\mu g.m^{-3}} \cdot t_a\right)$$

This equation clearly expresses that the blackening of rain-sheltered facades depends solely on particulate pollution and not on climatic parameters such as temperature or relative humidity of the air. Its improvement in the 21st century therefore logically follows that of air pollution (*Fig. 3*) and not that of climate, and therefore depends solely on the scenarios of emissions of pollutants. However, between the sources and the deposition of pollutants, many phenomena related to meteorology, and therefore to climate, are involved: leaching of gases and particles from the atmosphere by rain, dispersion by wind...

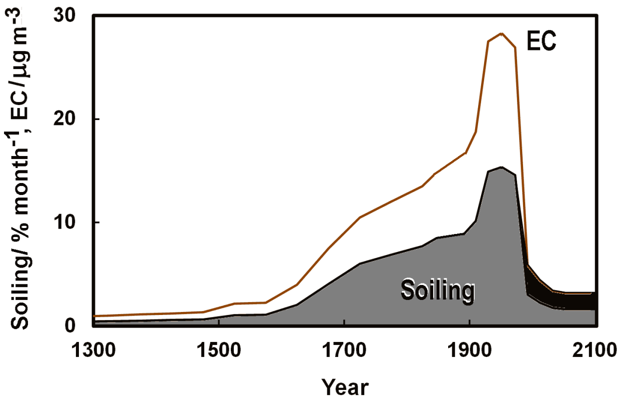


Fig. 3 - Evolution of monthly blackening (Soiling % per month) of rain-sheltered limestone facades from 1300 to 2100 in Paris according to the equation above, based on historical data, current records and

GAINS model emissions of pollutants[3]*. EC* m^{-3}*: elemental carbon concentration. The shaded zone shows the increase in PM10 on high-traffic streets* [4]*.*

Two Dose-Response Functions express the *recession-erosion of limestone*. The first is that of F.W Lipfert [6] obtained during *laboratory experiments* on the dissolution of calcite ($CaCO_3$), the main component of *limestone and marble*:

$$\text{Recession}_{\mu m\ a^{-1}} = 18{,}8\ \text{Rain}_{m\ a^{-1}} + 0{,}016\ [H^+]_{\mu mol\ l^{-1}} \text{Rain}_{m\ a^{-1}} + 0{,}18\ (V_{dS\ cm\ s^{-1}}\ [SO_2]_{\mu g\ m^{-3}} + V_{dN\ cm\ s^{-1}}\ [HNO_3]_{\mu g\ m^{-3}})$$

The first factor in the Lipfert equation represents the action of "clean" rains (karst effect), the second the action of acid rain and the third and fourth the action of dry acid deposition (VdS and VdN being respectively the deposition speed of SO_2 and HNO_3). This equation shows that the erosion-recession of limestone or marble facades depends on both climatic factors (clean rains) and pollution (acid rains, dry deposits of SO_2 and HNO_3).

The *recession-erosion of limestone* is also expressed by a second Dose-Response Function, that of the United Nations International Cooperative Materials Programme (ICP-Materials) [7] obtained during *exposure campaigns at actual sites*:

$$\text{Recession}_{\mu m} = 2{,}7\ [SO_2]^{0,48}_{\mu g.m-3} \exp(-0{,}018T)\ t^{0,96}{}_a + 0{,}019\ \text{Rain}_{mm}\ [H^+]_{mg.l-1}\ t^{0,96}{}_a$$

The recession-erosion of limestone facades *in Paris* (*Fig. 4*) follows, like blackening, an evolution similar to that of pollution (*Fig. 2*), but it is also influenced by that of climate. It was highest in the 20th century, followed by a dramatic decline in relation to the decrease in pollution and acidity of the rain. At the end of the 21st century, it is expected to grow again, but slowly, according to the Lipfert equation and the RCP8.5 scenario, because of the increase in temperature and atmospheric CO_2 concentrations that will increase the acidity of the rain, which itself increases when it is intense, especially in the North of France.

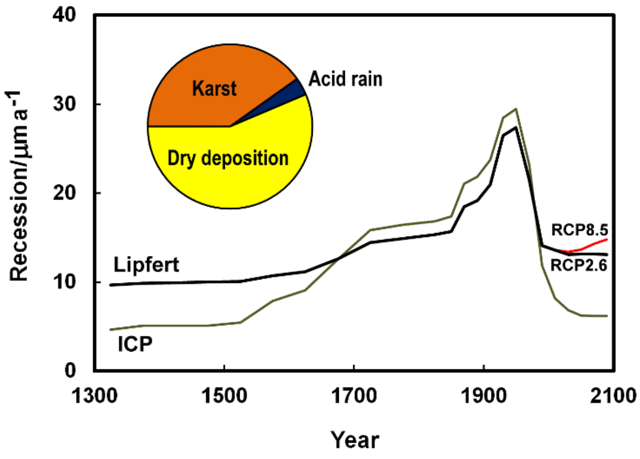


Fig. 4 - Evolution of the annual recession (in µm) of limestone facades exposed to rain from 1300 to 2100 in Paris [4] *according to the FDR of Lipfert* [6] *(in black) and ICP-Materials* [7] *(in red), using historical data, current records and values calculated for the 21st century with the Aladin-Climat and GAINS models, in the RCP2.6 and 8.5 scenarios of the 5th IPCC Report.*

The *change in the colour of the stone of the facades* of monuments in the context of climate change has already been addressed [9, 10]. This change in colour and brightness in urban environments, although traditionally seen as governed by air pollution, may also be affected by climate and its change. In the past, buildings were blackened by soot of wood and coal, then oil and gasoline, but now new pollutants rich in organic compounds are causing buildings to take on warmer tones. In addition, the increased frequency of intense, wind-oriented rain events, changes the distribution of damage to facades and warmer climate can promote biological colonization on stone buildings. The colour, distribution of deposits and biological growths on the facades have important aesthetic implications and may require the cleaning of the surfaces.

The *Paris Climate-Energy Plan (2018)* [11] and the *Paris Resilience Strategy (2017)* [12] did not take into account the Cultural Heritage of the French capital, which is considerable and is largely on the UNESCO World Heritage List. Only the first plan mentioned in its original version (2007) the problem of the rehabilitation of existing heritage: "*In old buildings, there is the difficulty of achieving insulation from the outside, the facades of Paris being not deeply modified both for aesthetic reasons and because of their complexity*." Similarly, it was suggested to "reprocess" zinc roofs, essential elements of the Parisian heritage. The white painting of the facades was a rejected idea, because it would alter too much the traditional image of the capital. Finally, it is worth noting the effort of the Parisian municipality to introduce "*nature in the city*", although a vegetation of the facades and roofs of cultural buildings must be done with the utmost restraint so as not to alter their history and aesthetics.

In conclusion, although the facades of monuments and buildings in limestone in the historic heart of Paris have suffered from air pollution in the past, their situation has undoubtedly improved in recent decades. Climate change will only likely affect their erosion by rain at the end of the century. This is consistent with the extrapolated conclusions of the Noah's Ark project maps [8]: the recession of limestone and marble facades is expected to be stable or slightly decreasing (-1µm/year) in the near future (2010-2039) throughout France, and be in greater decline (-2 to - 4 µm/year) in its southern part in the distant future (2070-2099) (*Fig. 5*).

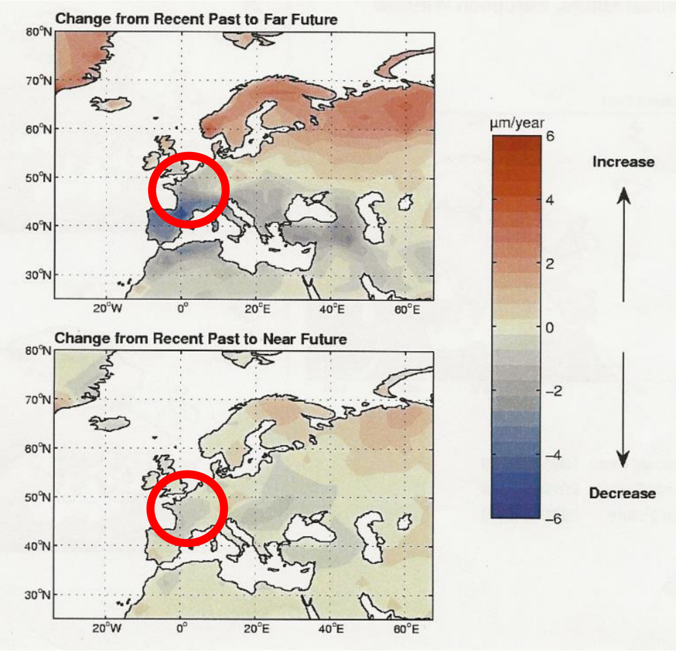


Fig. 5 - Evolution of the recession of limestone facades in Europe and France between the recent past (1961-1990) and the near future (2010-2039) (at the bottom) and the recent past and the far future (2070-2099) (at the top), according to the English model HadRM3 in the A2 scenario of the 4th IPCC Report, mapped in the Noah's Ark project. [8].

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This presentation on the behaviour of monumental **facades facing air and rain pollution, and climate change** will be concluded with ***recommendations*** for ***specific adaptation and remediation measures:***

- *Reduce air pollution* due mainly to car traffic and create or expand *pedestrian zones* around monuments and in the historic centre of cities;
- *Reduce the Urban Heat Island effect* by regular watering during heatwaves. The increase in albedo of facades (through regular cleaning) and pavements (by clear coatings) as well as vegetation are more sustainable solutions;
- Continuously monitor the air quality around the monuments by installing *automatic environmental monitoring stations* to measure and record the meteorological parameters (temperature, precipitation, relative humidity of the air, wind...) and pollution (SO_2, NO_2, O_3, fine and ultra-fine particles...).

Other specific measures concerning the impacts that will be developed later in this brochure and which also concern the monumental facades are grouped here:

- Protect the lower parts of the facades from the unsightly and destructive *capillary raisings of salt-laden water,* by systematically installing drains at the foot of porous walls;
- Protect porous materials from *freeze-thaw cycles*: stone, mortars, coatings, brick... avoiding watering during freezing periods;
- Selectively protect *glass* of facades from dirt, using *self-cleaning glass* during construction or repairs and replacements;
- Install *double protective glass windows* in self-cleaning glass on stained glass windows;
- Protect *metals* with regular maintenance (painting, anti-oxidant coatings, etc.);
- Strengthen *roofs and chimneys* from high winds and storms;
- Resize *gutters and drains* to cope with heavy rainfall.;
- Cover the *interior courtyards* of buildings with glass roofs that would reduce the surface area of buildings exposed to outdoor air by 40%.

Ancient stained glass windows facing of air and rain pollution, and climate change

To our knowledge, in France, only the stained glass windows of the Sainte-Chapelle of Paris have been the subject of research concerning their degradation in the context of climate change.

The Sainte-Chapelle of Paris, built in the 12th century in the heart of the capital, in the Ile de la Cité, has retained all its original glassworks, despite the restorations of the 19th century [1] (*Fig. 1 a*). It has recently been the subject of important restoration works: the old stained glass windows have been pushed back into the building and a new stainless steel structure has been installed outside to accommodate protective glass windows made of self-cleaning glass (*Fig. 1 b*). This chapel was one of the experimental sites of the European VIDRIO project on the protection of stained glass by double protective glazing windows [2].

a)

b)

Fig. 1 - a) The glass windows of the Sainte-Chapelle of Paris; b) Stainless steel structure for the installation of double-glass windows to protect stained glass windows.

Its stained glass windows, of silico-calco-potassium composition, are very alterable because of their high potassium content. In their rain-sheltered parts, they were covered with black gypseous crusts when sulphur pollution was high in Paris (*Fig. 2*). In their parts exposed to rain or between rains their alteration by liquid water or by atmospheric humidity can be measured by the depth of chemical leaching (lixiviation) of the ions K and Ca [3]. The superficial leaching of K and Ca results in the formation of a layer of hydrated silica gel on the surface of the stained glass, which plays a protective role. This leaching occurs in acid pH; in basic pH, the silica network is destroyed and the glass is corroded locally and craters form (*Fig. 3*).

Fig. 2 - The stained glass window of Saint John the Baptist, in the Sainte-Chapelle of Paris, before its restoration, had lost much of its initial transparency (a) due to the development on its outer face (b) of a gypseous crust containing atmospheric particles.

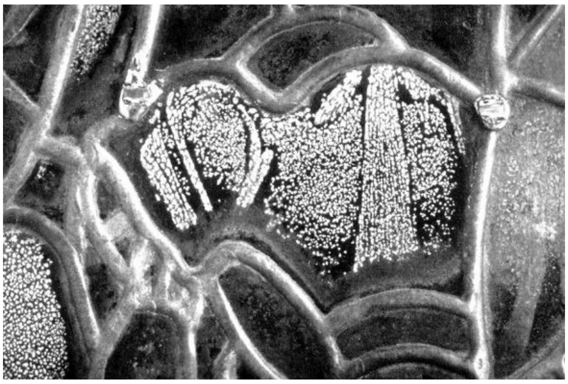

Fig. 3 - Local corrosion in micro-craters on a stained glass window.

The evolution, depending on the time t_a , of the depth of leaching of medieval stained glass windows in Paris from 1500 until 2100 has been reconstructed for the past and projected for the future on the basis of the evolution of climatic parameters ($HR_{\%}$: Relative humidity of the air; $T_{\circ C}$: Temperature) and air pollution (SO_2, NO_2) [4, 5] by applying the following Dose-Response Functions [3]:

$$d(K)_{\mu m} = -0{,}64 + \left(0{,}03 \cdot HR_{\%} + 0{,}04 \cdot [SO_2]_{\mu g.m^{-3}}\right) \cdot \sqrt{t_a} - \left(0{,}05 \cdot T_{\circ C} + 2{,}03 \cdot [NO_2]^{-1}_{\mu g.m^{-3}}\right) \cdot t_a$$

$$d(Ca)_{\mu m} = -0{,}79 + \left(0{,}03 \cdot HR_{\%} + 0{,}03 \cdot [SO_2]_{\mu g.m^{-3}}\right) \cdot \sqrt{t_a} - \left(0{,}04 \cdot T_{\circ C} + 1{,}91 \cdot [NO_2]^{-1}_{\mu g.m^{-3}}\right) \cdot t_a$$

This evolution was projected into the 21st century using either the Hadley HadRM3 model in scenario A2 of the 4th IPCC Report [4] , or the Aladin-Climat model in the RCP2.6 and 8.5 scenarios of the 5th IPCC Report [5] . The leaching of K and Ca will be virtually the same under each of the RCP2.6 and 8.5 scenarios (*Fig. 4*). The decline observed at the end of the 20th century reached very low values, mainly due to the reduction of air pollution. But climatic factors (RH, T) will maintain a non-zero leaching in the 21st century, showing that stained glass windows will continue to be vulnerable in Paris and that their protection by double glazing will remain a necessity.

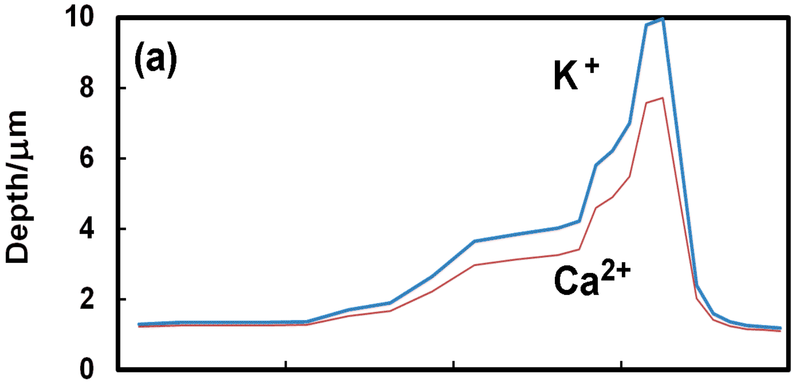

Fig. 4 - K and Ca leaching depths (in µm) under the surface of a new stained glass, of Si-Ca-K composition, the first year of exposure in Paris sheltered from the rain from 1300 to 2100, using historical data, current surveys and, for the 21st century, the Aladin-Climat and GAINS models in the RCP2.6 and 8.5 scenarios of the 5th IPCC Report [5] .

These projections made for stained glass windows in Paris coincide well with those that can be extrapolated for the whole of France from maps drawn on a European scale in the Noah's Ark project [6] (*Fig. 5*). Thus, in the near future (2010-2039) the annual thickness of leached glass would be 0 to 0.1 µm lower than in the recent past (1961-1990) and, in the far future (2070-2090), 0.3 to 0.5 µm lower. This is indeed a general decrease in the vulnerability of glass from medieval stained glass in the future, but not a total cancellation.

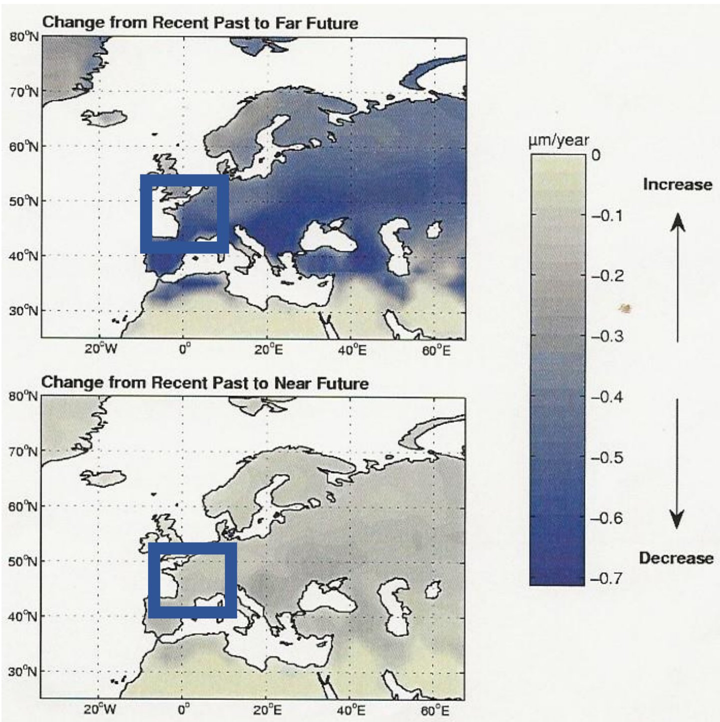

Fig. 5 - Evolution of the leaching thickness of medieval Si-Ca-K glass in Europe and France between the recent past (1961-1990) and the near future (2010-2039) (at the bottom) and the recent past and

the far future (2070-2099) (at the top) according to the English model HadRM3 in the A2 scenario of the 4th IPCC Report, mapped in the Noah's Ark project[6]

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The metals of French Cultural Heritage in climate change

Metals are omnipresent in French Cultural Heritage, either in statuary and art objects, or in buildings. Two Parisian examples illustrate this well (*Fig. 1*), not to mention the Eiffel Tower, which is however painted, and lead roofs like those of Notre-Dame and Sainte-Chapelle.

a) *b)*

Fig. 1 - a) Bronze statue "The Triumph of the Republic ", Place de la Nation, in Paris , b) The zinc roofs of Paris are part of the capital's landscape.

The bronze statue "The Triumph of the Republic" in Place de la Nation, Paris (*Fig. 1a*), work of Dalou, was erected in 1889. It was restored on the occasion of the bicentenary of the French Revolution in 1989. Exposed to the capital's air pollution, it shows on the surface green (by altering copper from bronze to rain) and black (by depositing particles cemented by gypsum in the sheltered parts of the rain) millimetric crusts[1] .

Zinc roofs (and fewer slates) are an integral part of the Parisian landscape to the point that some would like to see them listed as such on the UNESCO List. They cover a considerable area and require regular maintenance (one restoration every 40 years). The adoption of this metal as a cover dates from the Haussmann period because of its lightness and the relative ease of its work which allow the economy of important frames and thus make housing the last or even the last two floors of the buildings (*Fig. 1b*).

Dose-Response Functions exist for most metals [2, 3, 4]. They relate *mass* loss with different *climatic factors* (Temperature (T), Relative Humidity (RH), amount of rain) and *environmental factors (*concentration in SO_2 , HNO_3, PM10 particle deposit, acidity of the rain H+).

Most metals have maximum corrosion around 10°C in the atmosphere: at lower temperatures corrosion increases with temperature due to increased wetting time by rain, while at higher temperatures corrosion decreases due to faster evaporation

The *mass loss* for each of the metals are expressed in this way according to time:

$$\text{-for } \textit{zinc} : \text{mass loss}_{g.m\text{-}2} = 1{,}82 + \{1{,}71 + 0{,}471[SO_2]^{0{,}22}{}_{\mu g\ m\text{-}3}\ e^{0{,}018HR+f(T)} + 0{,}041\ \text{Rain}_{\ mm.an\text{-}1}[H^+]_{mg.l\text{-}1} + 1{,}37[HNO_3]_{\ \mu g\ m\text{-}3}\}t^{\ 0{,}6}{}_{a}$$

with f(T) = 0,062(T-10) when T<10°C, otherwise : -0,021 (T-10)

$$\text{-for } \textit{copper} : \text{mass loss}_{\ g.m\text{-}2} = 3{,}12 + \{1{,}09 + 0{,}00201[SO_2]^{0{,}4}{}_{\mu g\ m\text{-}3}\ [O_3]_{\ \mu g\ m\text{-}3}\ RH_{60}e^{f(T)} + 0{,}0878\ \text{Rain}_{\ mm.an\text{-}1}[H^+]_{mg.l\text{-}1}\}t_{\ a}$$

with f(T) = 0,083(T-10) when T<10°C, otherwise: -0,032(T-10)

$$\text{-for } \textit{steel}: \text{mass loss}_{g.m\text{-}2} = 29{,}1 + \{21{,}7 + 1{,}39[SO_2]^{0{,}6}\ RH_{60}e^{f(T)} + 1{,}29\ \text{Rain}_{\ mm.an\text{-}1}[H^+]_{mg.l\text{-}1} + 0{,}593\ PM10_{\ g\ m\text{-}2a\text{-}1}\ \}t^{\ 0{,}6}{}_{a}$$

with f(T) = 0,15 (T-10) when T<10°C, otherwise : -0,054 (T-10)

$$\text{-for } \textit{bronze} : \text{mass loss}_{\ g.m\text{-}2} = 1{,}33 + \{0{,}00876[SO_2]\ RH_{60}e^{f(T)} + 0{,}0409\ \text{Rain}_{mm.an\text{-}1}[H^+]_{mg.l\text{-}1} + 0{,}0380\ PM10_{\ g\ m\text{-}2a\text{-}1}\ \}t_{a}$$

with f(T) = 0,06(T-11) when T<11°C, otherwise: -0,067(T-11)

The evolution of the alteration of metals in the Parisian atmosphere, from 1300 to 2100, was established, as part of a study on Notre-Dame after the fire of April 19, 2019 [5]. The mass loss of *steel* is expected to return to its pre-industrial values at the end of the 21st century (*Fig. 2a*), *Bronze* (*Fig. 2b*) follows a similar evolution but with lower corrosion rates. *Copper* corrosion (*Fig. 2b*) is more sensitive to ozone, so it increases with sunlight and volatile organic compounds. *Zinc* follows a similar trend to other metals (*Fig. 2c*) but peak is less pronounced in the 20th century because it is less sensitive to SO_2.

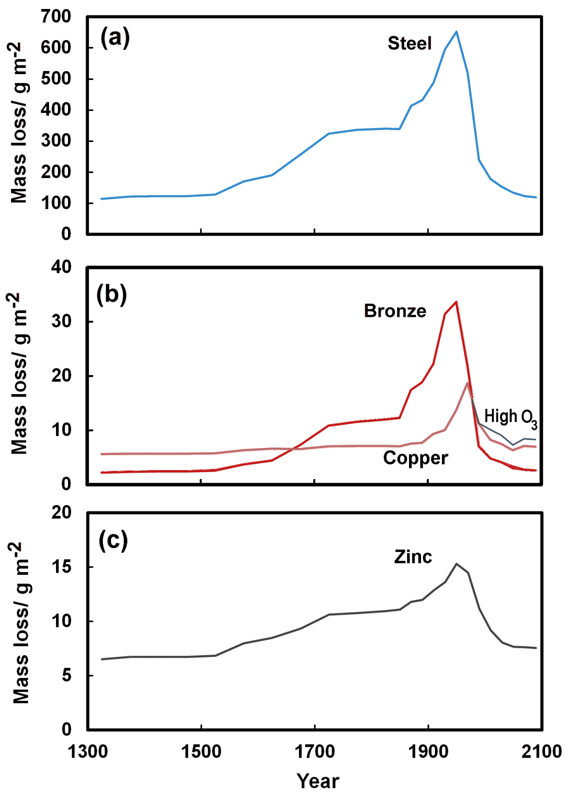


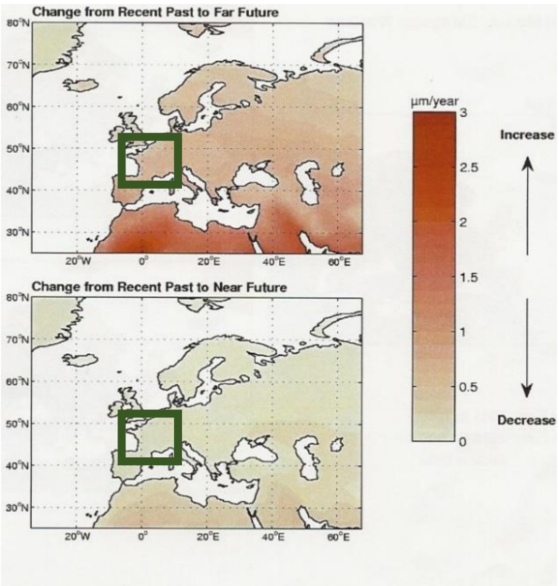
Figure 2 - Evolution of metals in the Paris atmosphere from 1300 to 2100, using historical data, current surveys, dose-response functions and, for the 21st century, the Aladdin-Climate and GAINS models in the RCP2.6 and 8.5 scenarios of the IPCC [5].

No DRF exists for *lead*, which is omnipresent in the built cultural heritage: roofs, spires and domes (Notre-Dame de Paris, Sainte-Chapelle, Pantheon, Invalides...), in the seals of iron stones and staples, fountains and sculptures, piping and ancient paintings... Its contemporary atmospheric corrosion has recently been studied in the Paris region on non-heritage experimental sites [6].

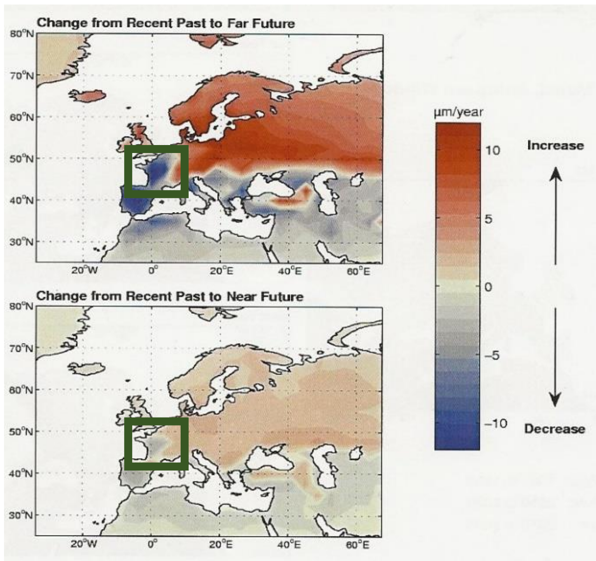
The Noah's Ark Project [7] drew European-wide maps of the distribution of annual metal corrosion with the HadRM3 model in scenario A2 of the 4th IPCC Report (*Fig. 3*), using the Dose-Response Functions developed above. We can extrapolate data for France.

For *zinc* (*Fig. 3a*), contrary to what was established in Paris [5] (*Fig. 2c*), there is a small increase in corrosion (0 to 0.5 m/year) in the near future and a slightly stronger one (0.5 to 1 m/year) in the distant future. *Copper* and *lead* follow the same trends but less pronounced.

For *steel* (*Fig. 3b*), there is a decrease in corrosion (0 to -5 m/year) in the near future and a greater decline in the distant future (-5 to -10 m/year) in line with what is projected in Paris [5] (*Fig. 2a*). *Iron* and *bronze* follow the same trends.



a) Zinc



b) Acier

Fig. 3 - Evolution of metal corrosion in Europe and France between, at the bottom, the recent past (1961-1990) and the near future (2010-2039), and, at the top, the recent past and the far future (2070-2099), according to the English model HadRM3 in the A2 scenario of the 4th IPCC Report, mapped in the Noah's Ark project [7]

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The degradation of walls by salt-laden water rises and climate change

The water in the soils, laden with dissolved salts, rises from the base of the porous walls thanks to the capillarity forces that pull them upwards. The ascent stops when the weight of the water compensates for the capillary forces of ascent. Throughout the ascent route, dissolved salts crystallize successively according to their solubility and the evaporation of water, itself governed by the temperature and relative humidity of the ambient air [1, 2].

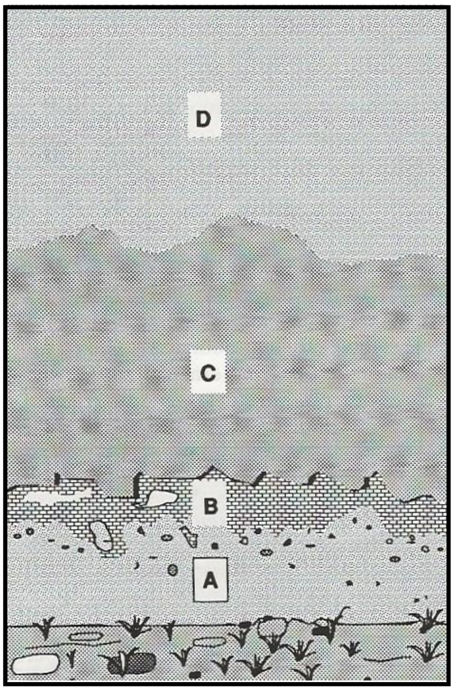

Fig. 1- Zones of capillary rise in a porous wall [1]

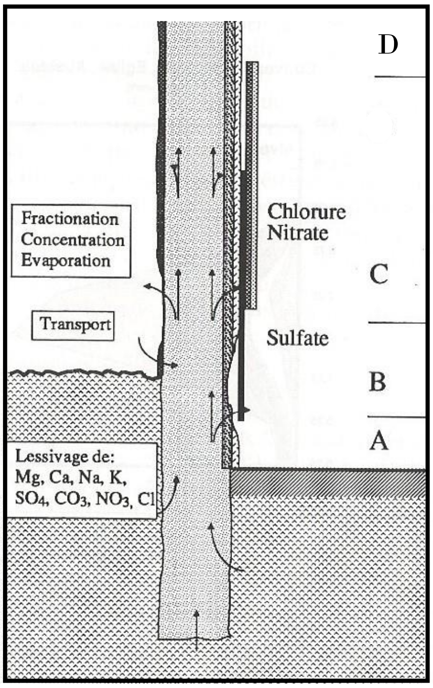

Fig. 2 - Summary of phenomena in the area of capillary rises [1]

The different areas of distribution of these salts and the degradations they produce by crystallizing are distributed as follows (*Fig. 1 and 2*) [1]:

- Zone A: little degradation; calcium (*Calcite*) and magnesium (*Magnesite*) carbonates precipitate;

-Zone B: significant efflorescences of magnesium (*Epsomite, Kieserite, Hexahydrite*), sodium (*Thenardite*, *Mirabilite)* and calcium (*Gypsum*, *Anhydrite*) sulphates, potassium nitrate (*Nitrokalite*), and sodium carbonate (*Natrite*), causing the most significant degradations: sandy disintegrations, alveolizations, crumblings, plaque peelings;

- Zone C: crystallization of nitrates and chlorides of calcium (*Nitrocalcite and Antarticite*), magnesium (*Nitromagnesite and Bischofite*) and sodium (*Nitronatrite and Halite*), which are hygroscopic, hence the dark and moist appearance with little or no deterioration or efflorescence;

-Zone D : preserved.

The likely behaviour of these salts and their potential damage in the past and in the 21st century in the context of climate change can be quantified by calculating the likely number of dissolution-crystallization events (phase transitions) per unit of time, which depends on temperature and relative humidity. The salts that have been studied are: *Halite, Thenardite-Mirabilite, Gypsum-Anhydrite* and *a mixture* of many more salts, which better reflects the reality on monuments than isolated salts.

A "*climatology of salts on the Europe* [3,4,5] *and French* [6,7] *scales* " linking the salt crystallizations, the climate and the degradations caused by these phenomena has been developed at sites in Western Europe (including in France Rouen, Caen and Paris) and for the entire French metropolitan area. Salt phase transitions were calculated using daily relative temperatures and humidity obtained from weather observations and climate model outputs in two scenarios in the 4th and 5th IPCC Reports (A2 and RCP4.5). The results show that it is possible to associate the climate types of Koppen-Geiger [8] (see chapter "*What future climate for heritage in Europe?"* p. 18*)* with potential salt damage and they also suggest future changes in these types of climates; for example, Western Europe, with its very humid climate, could change to a more Mediterranean or drier climate with, as a result, a different seasonality for the salt transitions.

The "*climatology of salts on the scale of France*" [7] can be represented cartographically for 41 Météo-France stations evenly distributed throughout the territory (*Fig. 3*). It is based on past climate data collected by these stations or projected by the Aladin-Climat model, in the RCP4.5 scenario. For each location, the average, minimum, maximum and standard deviation of daily temperature and relative humidity were calculated over 30 years. The daily number of phase transitions evolves from the recent past (1971-2000) to the far future (2071-2100):

- For *Halite (*Fig. 3a*)* the number of transitions will remain stable in 22 Météo-France stations, will increase in 17 and decrease in 2;

- For *Thenardite-Mirabilite* (*Fig. 3b*) the number of transitions will remain stable in 26 stations, decrease slightly in 12 and increase in 3.

- In the case of *Gypsum* (*Fig. 3c*), it is the number of days of high relative humidity that is considered because it allows water to penetrate the porous system and the Gypsum to precipitate. The variations will be greater than for the Halite and the Thenardite-Mirabilite. There will be a decrease in the NW half of France and a decrease in the SE half. A total of 18 stations will remain stable, 23 will decline and only 1 will increase.

- For the *mixture* of previous salts (*Fig.3d*), the risk will decrease (in 4 stations) or be constant (19 stations) on the coasts of NW, SW and the Mediterranean, but will increase in the central part of the country (19 stations).

- The *increase in volume of salts* that will precipitate is represented *Fig. 3e*. It concerns the sulphates of Na, Mg and Ca, the nitrates of Mg, Na, K, the chloride of Na, a double salt of sulphate and Na nitrate, and another of Na and Mg sulphate. Generally speaking, the risk will increase over time: in 14 stations it remained constant and in 24 it will increase. France's SE will remain the most vulnerable area.

In conclusion, we see that the risk of degradation due to the crystallization of salts in porous walls in France at the end of the 21st century will be constant or upward compared to the reference of the end of the 20th century and that it will be higher for salt mixtures than for isolated salts, a situation more in line with the reality of the walls. This study was conducted under the RCP4.5 scenario, which is rather optimistic. There is no doubt that with the RCP8.5 scenario, the forecast would have been much more pessimistic.

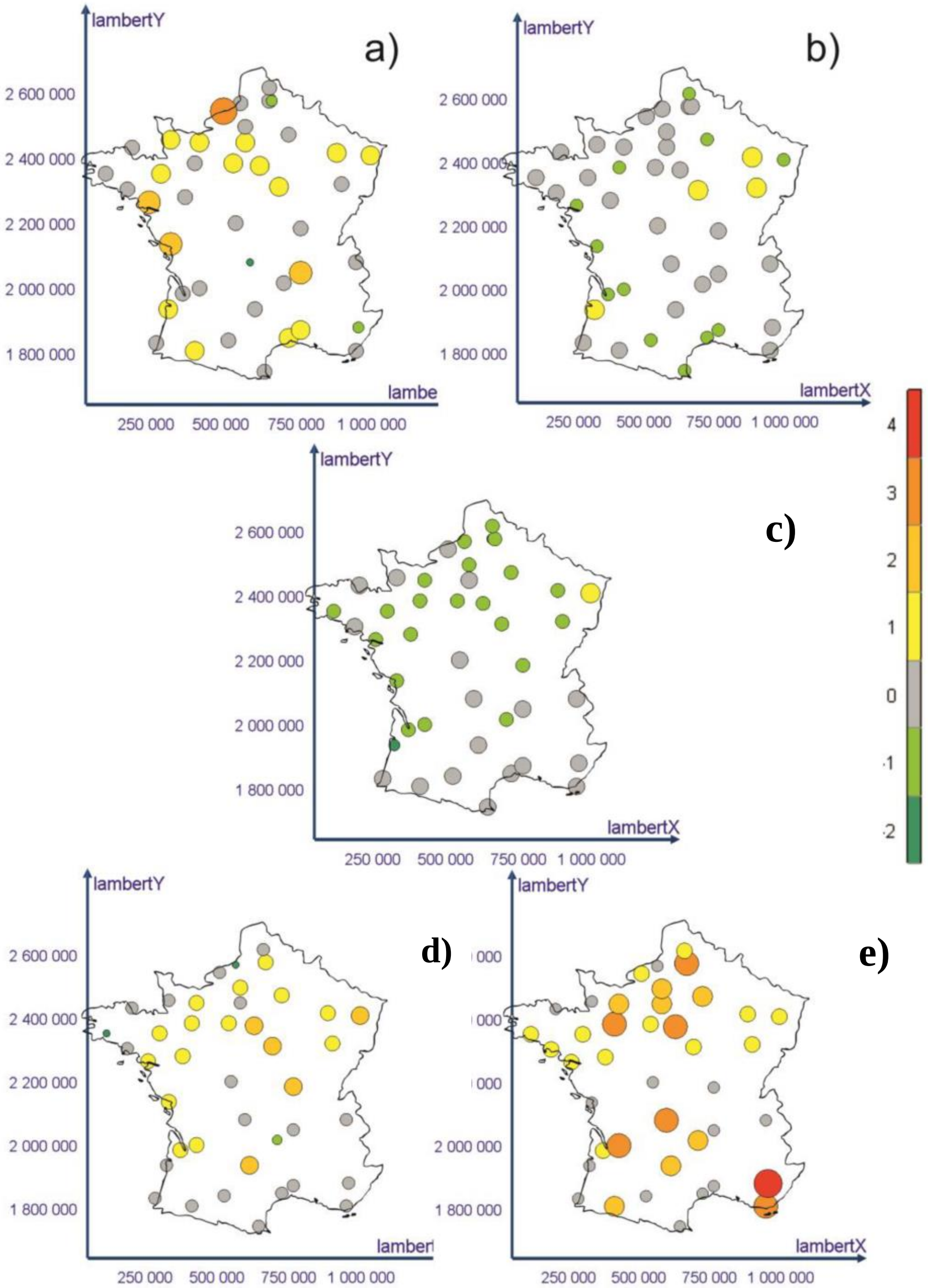

Fig. 3 - Change in the number per year of phase transitions of salts between the recent past (1971-2000) and the far future (2071-2100) taking into account: (a): NaCl; (b): Na_2SO_4; (c): $CaSO_4$; (d): the previous 3 salts at the same time, and (e): the overall change in volume, according to the Aladin-Climat model of Météo-France, in the RCP4.5 scenario of the 5^{th} IPCC Report[7].

The evolution of heritage climatology across Europe has been mapped in the two projects "Noah's Ark" [9] and "Climate for Culture" [10] . Below are the maps showing the projected changes between the current period and the end of the 21st century for the crystallization of salts as they were produced in each of these two projects (*Fig. 4 and 5*).

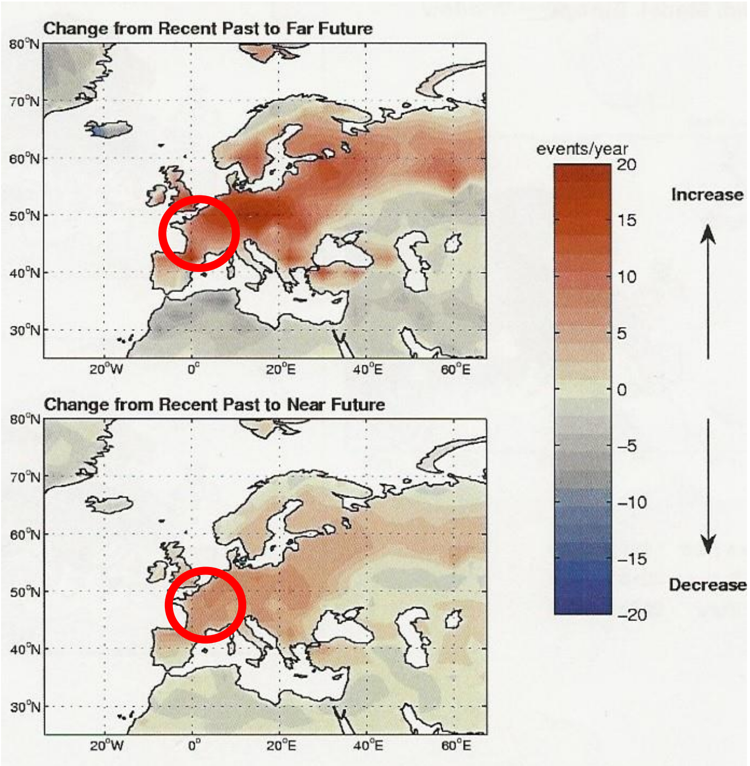

Fig. 4 - Changes in Europe and France in the crystallization of salts (number of events/year) between, at the bottom, the recent past (1961-1990) and the near future (2010-2039), and, at the top, the recent past and the far future (2070-2099), according to the English model HadRM3 in the A2 scenario of the 4th IPCC Report, mapped in the Noah's Ark project [9]

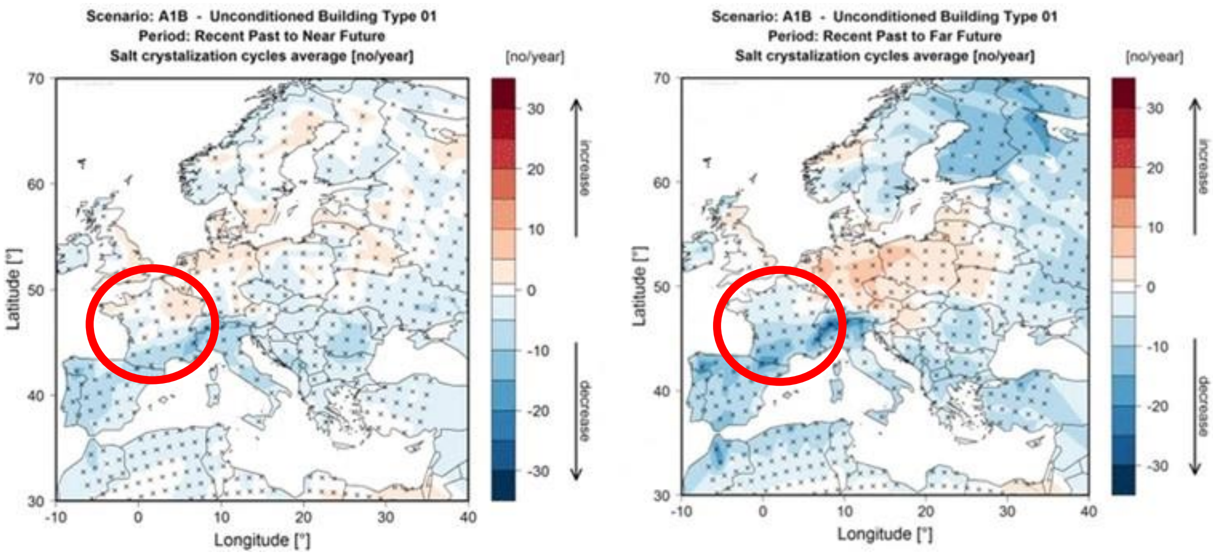

Fig. 5 - Changes in Europe and France in the crystallization of salts (number of events/year) in an unheated and un-air-conditioned building between the recent past (1961-1990) and the near future (2010-2039)(on the left), and the far future (2070-2099) (on the right), according to the REMO model in scenario A1B of the 4th IPCC Report, mapped in the Climate for Culture project [10]

From the maps of the Noah's Ark project (*Fig. 4*) we can extrapolate that in the near future there would be 0 to 5 events/year of crystallization in France compared to the recent past and from 5 to 10 events per year in the far future, with the A2 scenario in the HadRM3 model.

On the other hand, according to the maps of the Climate for Culture project (*Fig. 5*), the situation would be stable in the *North of France* in the near (0 to 5 cycles/year) and far (0 to -5 cycles /year) future, but would see the number of events decrease in the *South of France* for the near (-5 to -10 cycles/year) and far (-10 to -15 cycles / year) future according to the A1B scenario in the REMO model.

These differences between models and scenarios can be explained at first sight by the fact that A2 scenario projects a higher temperature increase than A1B. These differences are also related to what the Noah's Ark project considers the exterior of cultural buildings and the Climate for Culture projects the interior of unheated and un-air-conditioned buildings.

However, these studies focused either on France or on the whole of Europe bring more precise results than those that concern the whole of the globe [11].

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French monuments and cultural sites threatened by floods and river low waters

Apart from the invasion of continental areas by marine waters, flooding of cultural buildings can be caused by overflowing rivers, rising water table or storm water runoff in artificialized urban areas (concrete, asphalt, stone pavers with joints, etc.) that do not allow water to seep in, especially during extreme rains that overflow storm water collection and transport facilities.

With regard to *urban runoff flooding*, the European Environment Agency has published a "*Map of Urban Floods in Europe*" [1] (*Fig. 1*) linking the percentage of waterproof soils with the average number of days per year with extreme rainfall (> 20 mm/day). The percentage of soils waterproofed by urbanization is 50-74% in major French cities, especially in Paris (75-100%): they are conducive to flooding, especially during extreme rains, the number of which is expected to increase in the North of the country but decrease in the South, on annual average.

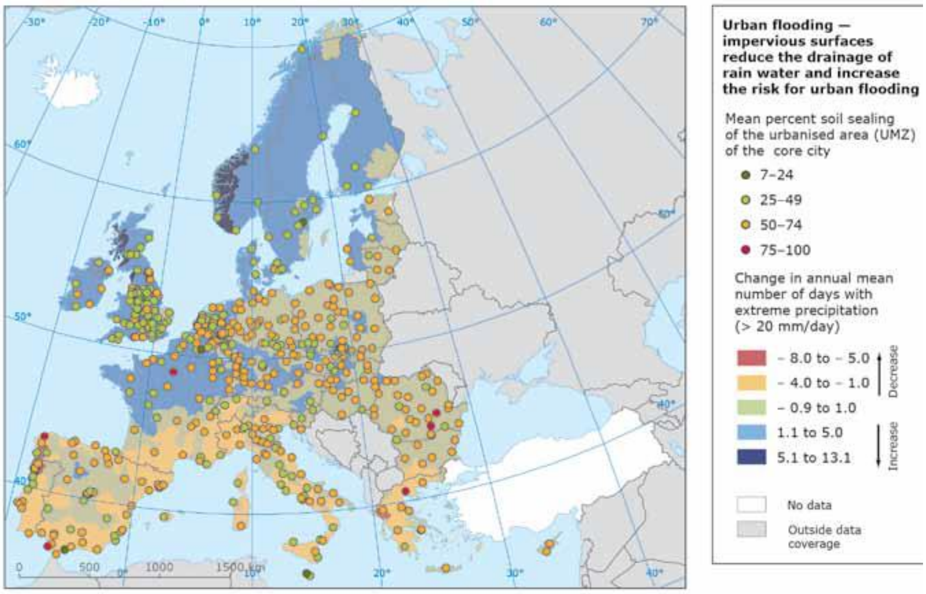

Fig. 1 - Urban floods in Europe. Percentage of waterproof surfaces and changes in the number of days per year with extreme rainfall [1].

According to the same European Environment Agency [2] climate change will bring about significant changes in river flows in Europe with a decline in summer, even where annual flows are expected to increase.

The projected changes in the hydrological cycle of French rivers in the 21st century has been studied in the context of climate change [3, 4]. A decrease in flows is projected in the three major basins of the Seine, Loire and Garonne, especially in summer and autumn, but a relative stability of the Rhône's flows (*Fig. 2*).

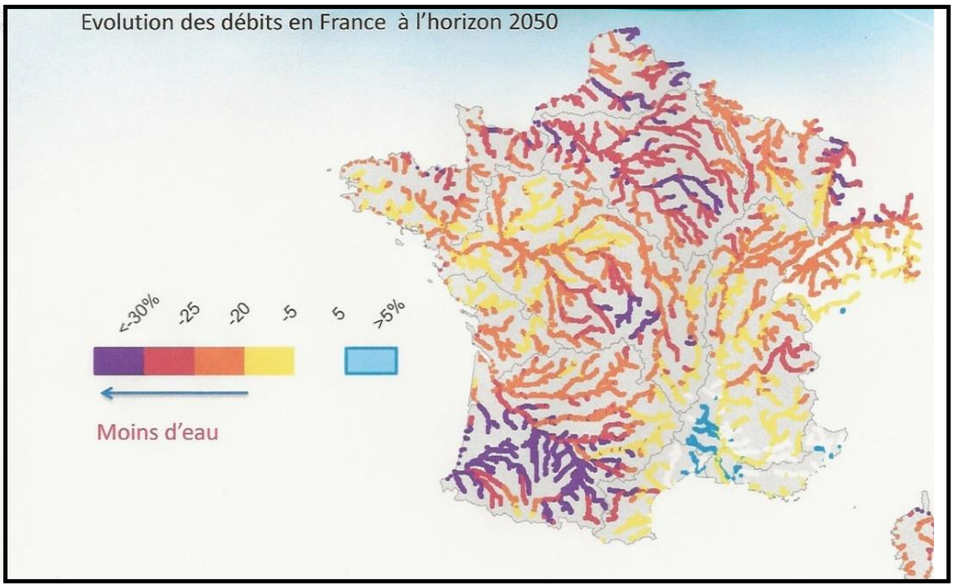

Fig. 2 - Projected evolution of river flows in France by 2050 (F. Habets [4])

We will take the example of the French capital where the banks of the Seine, a veritable "Valley of Museums", are particularly exposed to the risk of flooding.

The part of Paris inscribed on the UNESCO List (the banks of the Seine between the Sully Bridge in the East and the Eiffel Tower in the West) is fully included in the map of the overflows of the Seine during the flood of 1910 (*Fig. 3 and 4*). The threat is therefore real and the impact on heritage materials is expected to be considerable.

a) ***b)*** ***c)***

Fig. 3 - Some examples of the Cultural Heritage of Paris threatened by the flood of the Seine in 1996: a) The Louvre and the Royal Bridge; b) The left bank docks, the Pont de la Tournelle, Notre-Dame and Ile Saint-Louis; c) The famous statue of the "Zouave du Pont de l'Alma", a symbolic scale of the floods in Paris, is part of the capital's emotional image.

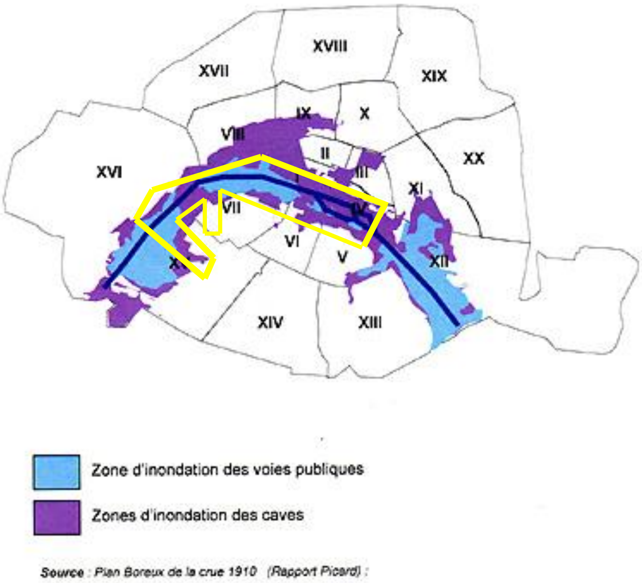

Fig. 4 - Map of the 1910 Paris flood (Flood Risk Prevention Plan, 2006). In yellow: approximate extension of the UNESCO List in Paris.

The floods of the Seine and their occurrence in the future are closely linked, among other things, to the regime of precipitation on its drainage basin. This regime itself will depend on future climate change in Northern France.

A decrease in water tables and flows by the end of the century is projected in the Seine basin resulting in a pronounced drying [5]: the decrease in flows would have more effect on low water than on high water; extreme floods would not change significantly; finally, the 100-year flood would remain of the same order of magnitude as it is now.

M. Reghezza-Zit makes some references to Cultural Heritage in his book "*Is Paris sinking?*" [6].

« ... Water circulations in basements are extremely dangerous... because they remove the foundations of the buildings....

... Multiple examples give an idea of the extent of flooding in basements. Cultural buildings are particularly numerous in this case. The National Museum of Natural History... contains an extraordinary collection of several hundred thousand specimens of animals and insects. This zootheque occupies three underground levels a few hundred meters from the river Seine...

... For its part, the Louvre houses in the basement - in addition to reception areas, an auditorium and all the technical equipment (electricity, heating, air conditioning, Research and Restoration Centre of the Museums of France...) - its collections of Islamic and Egyptian art, ancient sculptures and the medieval Louvre.... ...

The School of Fine Arts also has big concerns in perspective. In 1910, the water reached about 1.20 meters in the courtyard Bonaparte and the chapel of the Little Augustine ... In these buildings, classified as historical monuments, the School retains many priceless collections...

... Intangible losses are varied in nature. For example, if the capital suffers a flood, its image

will be tarnished for several months. Tourists are likely to turn away from it. The loss of image is an intangible cost that will lead to tangible costs for hoteliers, restaurateurs, tour operators, etc. ».

We will add, to give a concrete example of the risks, that the Louvre Museum relocates its reserves at risk of flooding to Liévin (250 km far from Paris) and that the Quai Branly museum was recently built on stilts on the banks of the Seine (*Fig. 5*). On the other hand, in the Report of the mission "*Ile de la Cité, the Heart of the Heart*" [7], which presents a complete urban reconfiguration project of this island located in the heart of Paris, the risk of flooding the important infrastructures it foresees in sub-surface, in particular the archaeological crypt of the forecourt of Notre-Dame, is not mentioned. Nor are there any mention of the consequences of the Seine's low waters for tourist landings and floating platforms with swimming pools that are planned to be installed on the small arm of the river on the Southern flank of the island. This forgetfulness of the potential climatic impacts associated with the river is all the more surprising because the authors are sensitive to the climatic impact that heating and cooling of old buildings would have in the face of the near impossibility of effectively isolating them from the outside or the interior. They foresee the development of a "smart energy network" to replace the current highly dilapidated and energy-consuming installations, and the coverage of the many interior courtyards of buildings with glass roofs that would reduce by 40% the surfaces of buildings exposed to outdoor air.

Thus, in the case of the floods of the Seine, some specific aspects of the Cultural Heritage of Paris are mentioned: the foundations of the buildings, the collections, the museums, the art schools, the archaeological sites and the economic benefits of tourism. A flood of Paris by the Seine would have considerable consequences for its Cultural Heritage, especially in the basement: wetting and soiling works, collections, archives and museum reserves, forcing important drying and restoration work. On the surface, the banks, quays, bridges and old foundations would be weakened causing structural instability. Floating debris could damage buildings and destroy small heritage objects. When the waters recede, dark haloes would betray the residual moisture of the walls and unsightly haloes of capillary risings of salt-laden waters would appear.

The *historic bridges* of Paris, with their numerous and constricted arches and piles, which are also listed on the UNESCO World Heritage List, could become dangerous because they would slow the flow of floodwaters of the Seine, as was the case with the Ponte Vecchio on the Arno during the catastrophic floods in Florence in November 1966 [8].

Can the *Seine low waters*, as in 2017, have an impact on Paris' Cultural Heritage? The answer is delicate: it is certain that the foundations of the buildings established on the alluvial water table of the Seine could suffer from a restriction of water in the basements that would cause the dry land to contract. The absence of clay soils in the shallow Parisian subsoil, on the other hand, would limit the risks associated with the retraction of the inflating clays. However, future water restrictions, as suggested by climate models [5], could have adverse consequences on the vegetation of the capital's parks, gardens and tree-lined outlook, on green facades and roofs, jeopardizing the municipality's entire "nature in the city" policy, and on the possibility of watering to cool the urban atmosphere during a heat wave. Thus, and paradoxically at first glance, the construction of a fifth lake of reservoir of the Seine becomes urgent, not so much to regulate the floods as to serve as a reservoir to compensate for future low waters.

In 2016, the *Cosson flood*, which was diverted to form a canal and feed the moat of Chambord Castle, reached this one, as shown in the images on the cover of this brochure. The director of the castle estimates that he is "*losing between 150,000 and 200,000 euros due to the five days of forced closure due to the floods... Many damage is to be regretted, including the collapse of 125 meters of walls, the metal doors of the estate have been torn off, a pond dam has been carried over a width of ten meters, the electrical system of the shop is out of use, the fire-fighting device partially attained, the condition of the roads and forest alleys near the castle is alarming... and the cost of repairs is estimated at between 500,000 and 1 million euros* [9]*.''*

As elsewhere in the world, most historic French cities have been built on rivers, making them vulnerable to flooding and low waters. The examples of Paris and Chambord, which we have developed, show that the risks associated with climate change must be taken into account quickly as was the case with the design of the *Musée du Quai Branly*, built on stilts on the banks of the Seine and inaugurated in 2006 (*Fig. 5*).

a)

b)

Fig. 5 - The Museum of Early Arts of Quai Branly, on the banks of the Seine, was built by Jean Nouvel on stilts to avoid damage due to flooding of the river (a). In addition, its façade has been vegetated, contributing to the mitigation of the Urban Heat Island effect (b).

The risk of *flooding by urban storm runoff or floods and low waters* in areas where Cultural Heritage is exposed, needs:

- *Inventory and mapping* cultural buildings threatened by floods;
- Produce *emergency plans* in the event of a flood;
- Identify *shelter sites* that can house cultural property in the event of a flood
- Specially monitor *historic bridges* that become a flood hazard by slowing the flow of water and blocking floating objects;
- Prevent some of the flooding by the *permeabilization of roadways* and the extension of urban parks and gardens;
- Install *anti-return valves* on water pipes in basements;
- Provide *drying and restoration sites* for works and objects submerged during a flood;
- Prohibit *new unsuitable cultural constructions* in areas at risk of flooding;
- Mapping areas at risk of *rising groundwater*;
- Predict the consequences of *low waters periods* (water storage in upstream reservoirs).

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French monuments and archaeological sites threatened by rising sea waters

The impacts of rising seawater on the coast in relation to climate change have been the subject of many recent studies [1].

As we have written in the Introduction, it is estimated that 136 of the 1,121 World Heritage properties identified in 2019 would be affected by significant flooding due to sea level rise, of which Arles (altitude: 0 to 57m, *Fig. 1*), Mont Saint Michel (erosion of the base of the ramparts, *Fig. 2*), Le Havre (0 to 105 m, *Fig. 3*) and the Port de la Lune in Bordeaux (1m, Fig. 4) [2].

Fig. 1 - Arles, on the banks of the Rhône, facing the wet plain of the Camargue that separates it from the Mediterranean. Listed by Unesco in 1981, the city retains Roman monuments and a major monument of Romanesque art: The Cathedral of St. Trophime and its cloister.

Fig. 2 - The Port de la Lune in Bordeaux along the water of the Gironde. Inscribed in 2007 on the UNESCO List, it is an exceptional architectural ensemble created during the Lumières period.

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Fig. 3 - Mont Saint-Michel, threatened by the erosion of the base of its ramparts. The Gothic-style Benedictine abbey and the village, listed by UNESCO in 1979, are built on a rocky islet amid huge shore subjected to the comings and goings of powerful tides.

Fig. 4 - Le Havre, on the banks of the Seine and the English Channel, rebuilt by Auguste Perret after the Second World War. Listed by UNESCO in 2005, it is a remarkable example of post-war architecture and urbanism with the use of prefabricated concrete. © Erik Levilly / City of Le Havre.

Across the Mediterranean, 49 UNESCO List sites, including Arles (*Fig. 1*), are located in low-lying coastal areas: 37 are at risk of submersion and 42 are threatened by 2100, according to a recent study[3] of the risks from 2000 to 2100, in 4 scenarios of sea level rise (RCP 2.6, 4.5, 8.5 and a "very high" representing the 95th percentile of RCP 8.5). A *submersion risk index*, combining the height and frequency of storm surges with the submerged surface and the depth of the flood, ranges from 0 (no risk) to 10 (very high risk, when at least 50% of the site is submerged with a depth of at least 1m). An *erosion risk index*, combining sea level rise with coastal distance and site sensitivity to erosion (but not internal site characteristics), still ranges from 0 to 10. According to the highest scenario, for the Arles submersion index, the only French site affected by the study, will go from 0 in 2000 to 4 in 2100, and for the erosion index from 0 to 4-7. By comparison, Venice and its lagoon, which in 2000 already had a >9 submersion index and an erosion index of 7-9, will go in 2100 to 9-10 for both indices under the same very high scenario.

The European Commission's "*Eurosion*" study [4] - which made a special mention of the Alabaster Coast in Upper Normandy (*"The White Cliffs of Upper Normandy... are famous all over the world by the striking beauty of Etretat, south of the coast... The region derives a substantial part of its revenue from tourism")* - recommends research on the impacts of climate change on the coastline and on the phenomenon of saline water intrusion.

In addition to coastal erosion, *coastal submersion* can be achieved by simply rising waters, crossing protective structures by storm surges and breaking these structures. The frequency of very high sea levels increases sharply with the gradual rise in ocean levels: centennial phenomena of the past could become annual by 2050 in many regions, with the risks of coastal submersion and erosion that they imply. The result, in addition to the destruction of cultural buildings or archaeological sites, is an invasion of continental areas by waters laden with salts harmful to heritage materials.

Erosion of sandy beaches has become a major problem with rising sea level. Beaches cover 40% of the world's coastline, but half of them could disappear by the end of this century. However, actions could prevent 40% of this erosion because they are resilient to climatic variations and can be accommodated by reprocessing and adapting their morphology [5]. They often contain archaeological sites and are adjacent to buildings that could be threatened by erosion.

A quarter of France's metropolitan coastline is receding due to marine erosion, namely 1,720 km of coastline. The decline of the coastline, however, is not a widespread phenomenon for the entire French coastline [6, 7]. Marine submersion affects a significant part of this coastline: no less than one million inhabitants could be flooded each year in 2050, mainly in the Loire-Atlantique, Vendée, Charente-Maritime, Gironde, Seine-Maritime and Pas-de-Calais [8]. The French Bureau of Geological and Mineral Research (BRGM) has conducted several studies on the erosion and submersion of the French metropolitan coastline, in particular the Languedoc-Roussillon coastal zone (Miseeva Project) [9] and the Breton coastline (Atlas of coastal hazards) [10]. All these regions are rich in *built Cultural Heritage and archaeological sites*.

Assessing the vulnerability of *coastal archaeological heritage* is difficult because the sites are of various types and are subject to various constraints: sediment inputs, wave action, wind direction, nature of the remains, local impact of past and present human behaviour [11].

Since 2006, the ALeRT (Archaeology, Coastal and Earth Warming) project [11, 12, 13], coordinated by the CReAAH (Centre for Research in Archaeology, Archaeosciences, History) of the University of Rennes, has developed a methodology to numerically assess the vulnerability, resilience and management of coastal archaeological sites (Vulnerability Evaluation Form: VEF). Ten impacts, at least two of which are related to coastal erosion, and therefore to climate change, are included in this assessment: the distance to the edge of the nearest cliff and the site's exposure to waves and wind. Resistance (or "resilience") refers to that of archaeological objects and that of bedrock. Vulnerability is estimated between -2.8 (lowest vulnerability) and 5.2 (highest vulnerability) by crossing impacts and resistance.

This methodology has been applied to Lower Normandy, Brittany (Fig. 5) and the Loire countries, as well as in Galicia. A mobile app has been created for data collection. The system was tested following the severe storms of the 2013-2014 winter on Roc'h Santec Island where changes and damage were assessed, in part by 3D reconstructions.

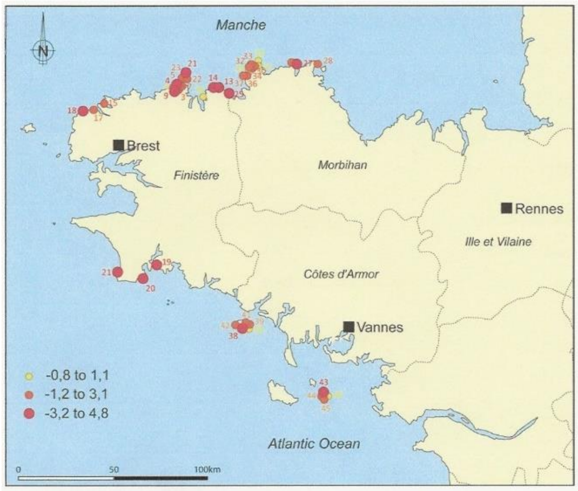

Fig. 5 - Simplified map of the vulnerability of archaeological sites in Brittany in 2014 [13].

Measures to adapt Cultural Heritage facing rising sea levels:

- *Inventory* buildings, archaeological sites and cultural landscapes threatened by coastal erosion and marine invasion;
- Introducing Cultural Heritage into *coastal protection and sustainable development plans;*
- Adapt territories and architectural projects to *coastal areas at risk of flooding or unstable;*
- Create *warning systems* and crisis action plans;
- Prohibit *new unsuitable cultural constructions* in flood-covered or unstable coastal areas;
- Strengthen *protective and waterproof structures*;
- Plan the *strategic retreat* of the most vulnerable or remarkable built heritage

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The contribution of Cultural Heritage to the past and recent history of climate in France: written documents, ancient weather records and dendroclimatology

Tangible Cultural Heritage can make an original contribution to the reconstruction of past France's climate by exploiting three documentary sources belonging to this Heritage: written documents, ancient weather records and recordings contained in rings of trees engaged in historical constructions.

In the absence of direct instrumental readings of past climate parameters (temperature, precipitation, relative humidity...), an indirect reconstruction can be made by means of *proxies*.

"*Literally, a proxy is an authority to represent or act for another. In climatology, proxy data are observations based on certain physical phenomena that may represent some atmospheric variables, e.g. tree ring width may be representative of the temperature in the preinstrumental period, and a tree is used as a proxy sensor, instead of a thermometer.*" [1]

The past and recent climate of France has been the subject of numerous historical researches carried out in recent decades using *written documents*, themselves belonging to Cultural Heritage, preserved in archives and libraries. The most well-known studies are those of Emmanuel Le Roy Ladurie [1] and his school [2]. However, the results of this research are most often *descriptive and qualitative* (at least until the appearance of weather records in the 17th century), and concern above all only *extreme events* (high heat and cold, intense rainfall, floods, droughts, storms…) the quantitative data being limited to dates and durations of slow geographical events (retreat of glaciers...) or socio-economic ones (grape and cereal harvests, scarcity of food...) [3, 4].

On the other hand, there are *ancient quantitative data:* these are either *temperature and humidity* readings, or combined measurements of age and temperatures obtained on the rings of trees used for the construction of cultural buildings: these are *dendrochronology and dendroclimatology* established on the woods of the frames. These woods have the advantage of being engaged in cultural constructions of generally fairly well-known age, which allows to compare this historical data with the results of dendrochronology.

These two types of results for the past (weather records and dendroclimatology) are extremely useful, if not essential, in verifying the robustness of current predictive quantitative models in the context of climate imbalance.

In *Paris*, for example, the first *temperature readings* were carried out, from 1658 to 1660, by Ishmael Boulliau [5]. Monthly temperatures in the capital are known since 1658 [6]; for the *Paris region*, they are available since 1676 [7].

The principles of *dendroclimatology* were summarized recently by Valérie Daux [8]: "*Trees have certain advantages in paleoclimatology: 1) they are widespread over a large part of continental surfaces; 2) in regions with a Mediterranean, temperate, subarctic, or mountainous climate, trees make annual rings made of organic matter containing mainly carbon, oxygen and hydrogen; 3) by combining the woods of living trees,* ***beams of historic buildings,*** *or even subfossil trees, it is possible to achieve chronologies of several hundred years, dated with precision; 4) isotopic analysis of a few individuals is sufficient to obtain a signal of regional* *value, 5) and, finally, variations in the isotopic composition of oxygen ($\delta^{18}O$) and carbon ($\delta^{13}C$) of the cellulose of the rings are generally strongly correlated with those of climatic parameters... However, trees are not perfect climatic archives... ».*

Below, we will report, as French examples, the results of studies carried out on the **beams of historic buildings** in *Fontainebleau* and *Angoulême*, and those expected in the *Paris region*.

In *Fontainebleau*, a first chronology of $\delta^{18}O$, from 1596 to 2000, was established from living oak woods from the forest and oak beams from the castle ("Salle de Bals, Clocher, Théâtre, Petites Ecuries") [9, 10]. It was completed during the study of droughts in France since 1326 [11] , from drilling oak beams of three buildings of the castle corresponding to three different periods of construction: "Porte Dorée, Chapelle, Petites Ecuries" whose wood probably comes from the surrounding forest. *Fig. 1* gives a representation of the temperatures of northern France deduced from the measurement of the cellulose of the Fontainebleau oaks. Average maximum temperatures in the April-September period (Tmax ^{AMJJAS}) are the most strongly correlated with temperatures measured since 1880. The Little Ice Age, from the 14th to the beginning of the 19th centuries, interrupted by a few more lenient decades in the 16th and late 17th centuries, is well highlighted. The same is true of the current warming, unmatched by its duration and magnitude.

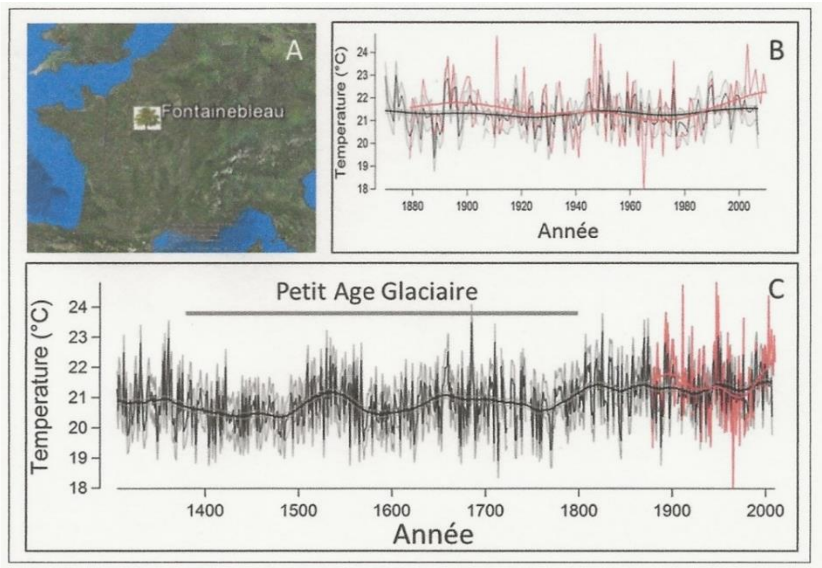

Fig. 1 - Re-establishment of temperatures in the northern half of France from the $\delta^{18}O$ of the oaks of Fontainebleau, France (Etien et al. [9], 2008; Etien et al., 2009 [10] and unpublished data). A) Location of the study site. B) Comparison of changes over time in average maximum temperatures over the April-September period (Tmax ^{AMJJAS}) calculated and measured. In red: instrumental temperature; in black: temperature reconstructed from the $\delta^{18}O$ of the cellulose of the oaks of Fontainebleau. The fine lines correspond to interannual variations, the thick strokes to slippery averages over 11 years. The grey shaded area represents the area of uncertainty calculated for reconstructed temperatures. C) Reconstruction of temperature variations over the past 7 centuries. (Same legend for colors and features as in Figure B.) (Extract from Daux, 2013 [9]).

The curves obtained in Fontainebleau (*Fig. 1*) and Angouleme (*Fig. 2*) reveal similar climatic trends in the two regions [14] , this suggests that they have a representative value of the climate of western France under oceanic influence over a long period of time..

Two groups of oaks from the Forest of La Braconne, located 15km east of *Angoulême*, were used to establish a first chronology of $\delta^{18}O$, from 1860 to 2004 [12]. This chronology was extended until 1326 using the trees of the oldest previous group and oak **beams of historic buildings** in the Angouleme region: the House of the Count of Angouleme, the Church of Poullignac (31km to the south) and the Château de La Rochefoucauld (21km to the north-east), as part of the same study as in Fontainebleau on summer droughts in France since 1326 (*Fig. 2*). The provenance of the beams is not documented, but is most likely local.

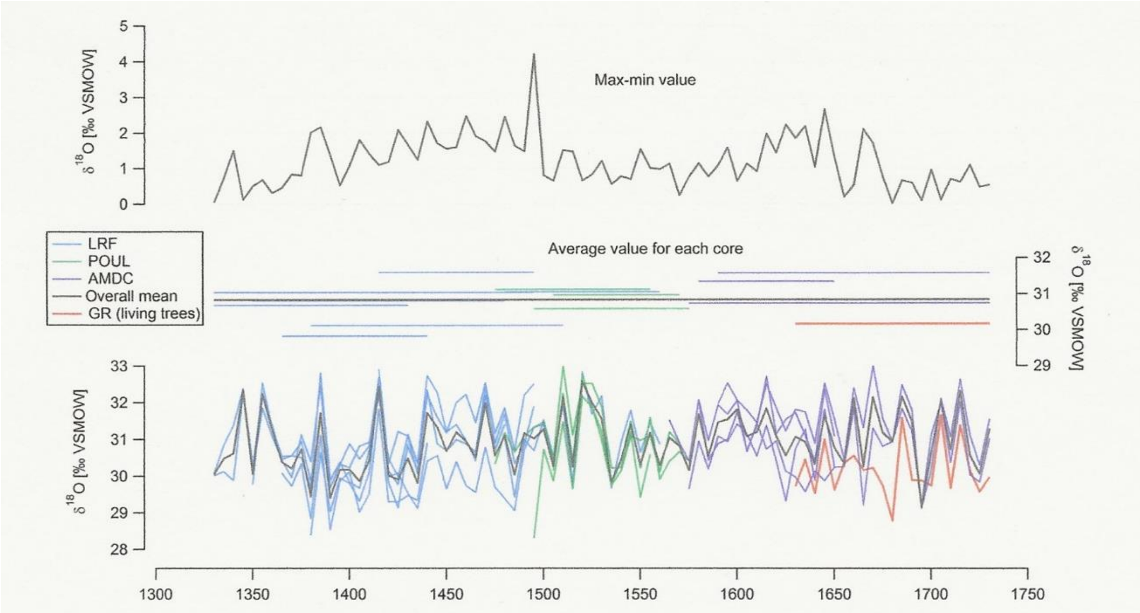

Fig. 2 – Chronology of $\delta^{18}O$ in the Angouleme region. Bottom: $\delta^{18}O$ measured every 5th year for individual timber cores from different buildings in Angouleme (LRF: Château de La Rochefoucauld, POUL: Church of Poullignac and AMDC: House of the Count of Angouleme). The orange line shows the $\delta^{18}O$ of living trees (GR). Middle: time spans and average $\delta^{18}O$ values for the respective cores. The thick grey line is the mean $\delta^{18}O$ of all timber cores over the whole period. Top: range of measured values for each year (maximum minus minimum value) (Extract from Labuhn et al., 2016 [11])

The wood frame of *Notre-Dame de Paris* was sampled in 1991 for its dendrochronological study [13] . The fire on the roof of the cathedral, on 19 April 2019, unexpectedly opened a field of research on the recent history of climate and environment in the *Paris region* by the *dendroclimatological* study of the unburnt remains of the frame of the cathedral [14]. The results of this study are likely to be similar to those obtained at Fontainebleau, because the probability that at least some of the oaks used in Paris come from this forest is not zero: the Fontainebleau Forest and Paris are on the banks of the Seine, which facilitates the flotation of timbers already suggested by historians. This study, as part of the Casimodo project [15], is expected to shed new light on the climate around the year 1000 and on the medieval climate optimum, as well as on the climate in Paris itself, incorporating a possible effect of Urban Heat Island that would remain to be evaluated. Thus, Notre-Dame could contribute to the reconstruction of the climate for a period (the year 1000) during which it did not yet exist (it was built from 1163 to 1345). It would be a great example of cultural heritage's contribution to climate history.

The results of the dendroclimatological studies carried out on the forest oaks and beams of the Château de Fontainebleau [8, 9, 10, 11] (*Fig. 1*) have already shown that data on *temperatures and precipitation in Paris* have been traced from 1300 to 1500, in a study focused on Notre-Dame [16] (*Fig. 3*).

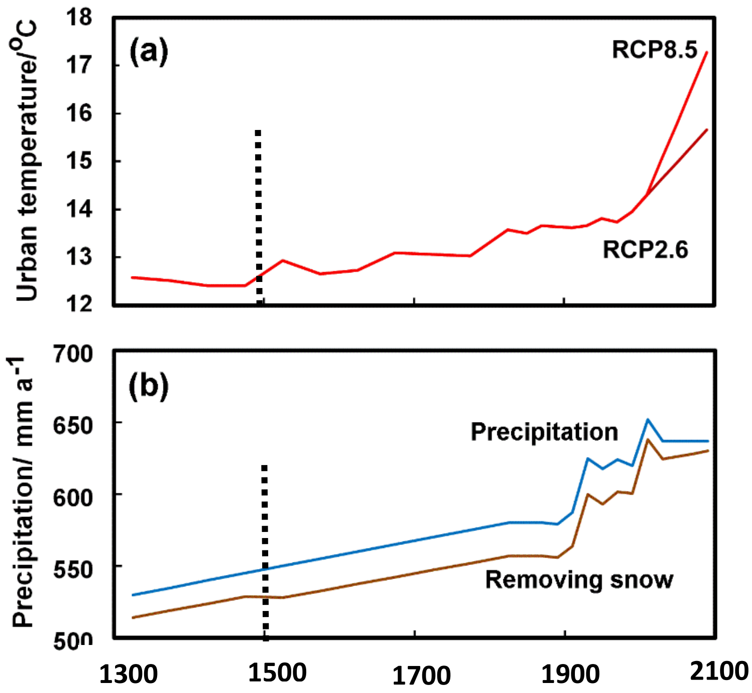

Figure 3 - Evolution of temperatures and precipitation in Paris from 1300 to 2100, using dendroclimatological and historical data, current surveys and, for the 21st century, the Aladdin-Climate and GAINS models in the IPCC RCP2. 6 and RCP2.5 scenarios [1 6].

In conclusion, written documents and weather records are classic sources of data on France's past and recent climate. For its part, *dendroclimatology applied to the woods of cultural buildings* is a new and original quantitative approach in the heritage field, very promising to document this ancient climate, the objects concerned being very numerous and generally well dated, which should allow a good calibration of the results over time and highlight possible reemployment in the absence of other signs on the frames such as notches, holds, mortises, ankle holes, assembly marks. Recently, campaigns on cathedrals in *Beauvais* or *Bourges* have harvested woods [16]. Their dendroclimatological study would probably be of great interest. Together, these results should contribute to the verification of the robustness of the climate models proposed for the 21st century.

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4th Part:

The impacts of Climate Change on Monumental Heritage to be tackled in France

The potential impacts of climate change described below, which are not yet discussed in France, but which deserve to be, are either extrapolations for France of the results of studies concerning Cultural Heritage at European level (*metals, the effects of the freeze-thaw, interior environments*) or studies not specifically concerning Cultural Heritage but whose results can be reasonably transposed to it (*the stability of buildings on clay soils*).

The effects of freeze-thaw on Cultural Heritage materials and climate change

The frost damages porous materials when they are wet: the volume of water increases in the pores of the material and causes it to burst. This change in water phase occurs at a specific temperature (0°C) and the effects of temperature changes related to climate change, even if small, can have amplified effects on materials.

A *"wet frost" index* was developed in the European project Noah's Ark [1]: it is expressed by the number of days of rain per year at positive temperatures, followed immediately by days with an average temperature of less than -1°C. The results suggest that most of temperate Europe, thus France, will see a reduction in frost in the future (*Fig. 1*). This could mean that the porous stones used in monuments in temperate regions, therefore in France, would be less vulnerable to frost in the future [1,2]; but there is a risk of late frost after wetter winters. Only a few parts of the Alps, at high altitudes, should be affected by a thaw of the local permafrost, resulting in landslides or at least falling rocks embedded in the ice that will melt.

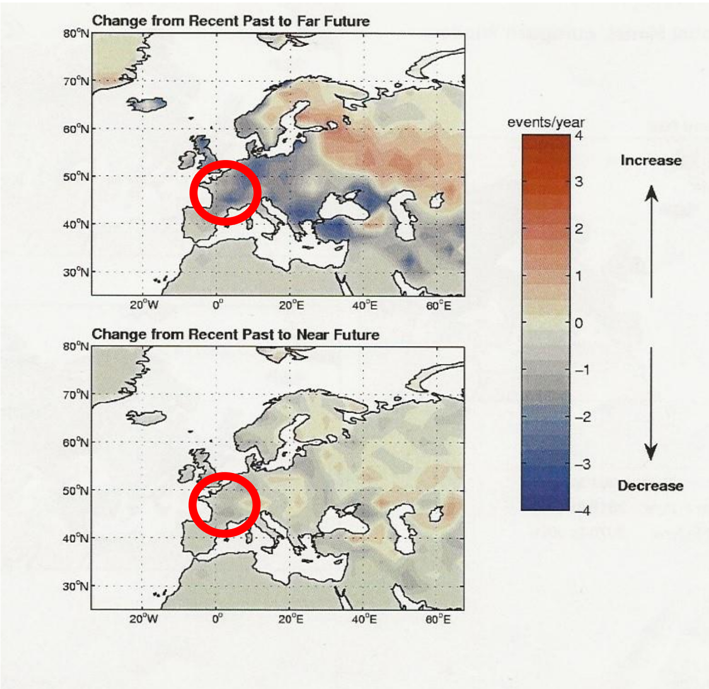

Fig. 1 - Changes in Europe and France in the number of positive-temperature rainy days per year, followed immediately by days with an average temperature of less than -1°C (number of events/year) between the recent past (1961-1990) and, at the bottom, the near future (2010-2039) and, at the top, the far future (2070-2099), according to the English model HadRM3 in scenario A2 of the 4th IPCC Report, mapped in the Noah's Ark project [1]

The European Cultural HEritagE Risks and Securing activities (CHEERS) project (2018-2021) [3], of which the French Bureau of Geological and Mineral Research (BRGM) is a partner, is interested in safeguarding alpine Cultural Heritage in the face of natural hazards: *"Cultural Heritage is at the heart of the identity of alpine territories and represents a strong economic challenge for them. However, these territories, by their geographical and topographical location, are subject to multiple natural hazards whose consequences on heritage properties* *can prove disastrous...* ». The study of the influence of climate change among the hazards mentioned is not clear in the early work of this project, but will certainly be addressed in the wake of these, in particular the impact of the freezing and thawing of materials, as highlighted in the IPCC Special Report on Oceans and Cryosphere [4].

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The indoor climate of museums, libraries, collections, archives and reserves facing pollution and climate change

Risks generated by an increase in temperature or a decrease in relative humidity in museums, libraries, archives and reserves, and on the objects and collections they house, are generally considered negligible (apart from extreme events such as floods and fires). This is probably due to the lack of risk models, itself due to the relative novelty of heritage sciences, the small number of researchers and the means at their disposal, hindering the evolution towards "green museums, green archives and green libraries" [1]. Efforts have focused mainly on heating and cooling systems in order to adapt them to the current climate and reduce their pejorative effects. But little is done in terms of projections towards the future climate.

As noted above, libraries and archives are the places where historical records are preserved, allowing a reconstruction of France's past and recent climate, until the appearance of weather records in the 17th century.

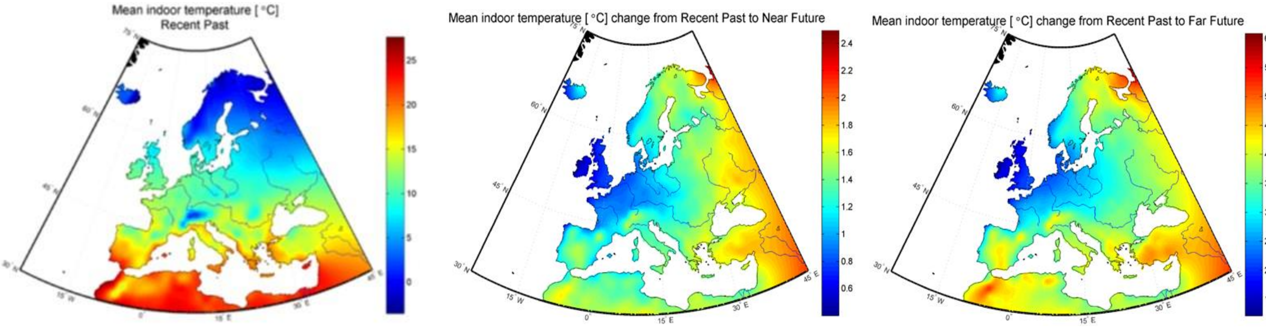
The concept of "*Historical Climate*" [2] was introduced to take into account the climatic variations to which objects have had to adapt in buildings over time. The conflict between, on the one hand, indoor climate change, the thermal comfort of the public and staff, and, on the other hand, conservation needs is constant: it requires a compromise between these various needs.

Mass tourism, by concentrating crowds, leads to disturbances in the temperature and relative humidity of museums, in addition to an increase in waste volumes, increased energy and water consumption. It represents a major physical danger to works exhibited in museums and premature wear of the monuments visited.

A simulation of the *effects of the past, present and future external climate on the interior of an unheated and un-air-conditioned model church* encompassed the French territory [3, 4]. This indoor climate simulation was constructed from sets of historical data (over 100 years), data from the present (less than 50 years) and projections of the REMO external climate model in scenario A1B of the 4th IPCC Report, for the next 100 years. The simulated indoor climate is coupled with damage functions to predict the risk of biological, chemical and mechanical damage to objects. The witness monument has been virtually placed in 468 locations in Europe. Projections for France can be deducted from the cards obtained (*Fig. 1 to 5*):

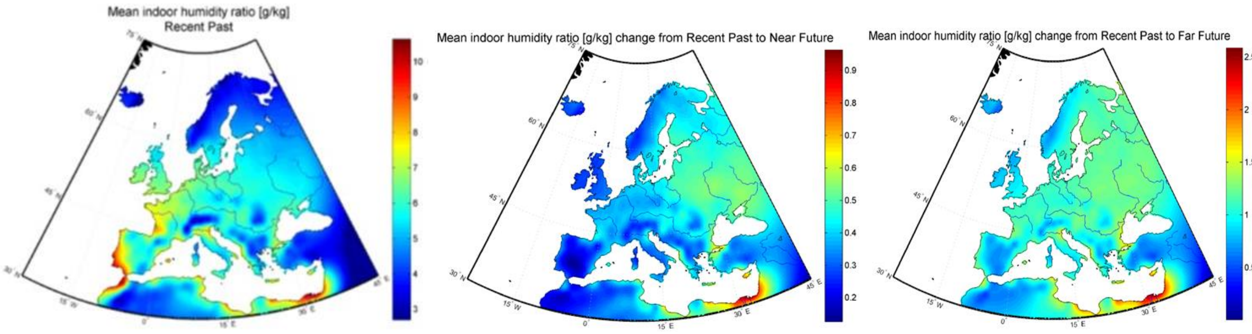
- An *increase in temperature* (*Fig. 1*), in the near future (*Fig. 1b*), more pronounced in the far future (*Fig. 1c*);
- An *increase in relative humidity* (*Fig. 2*) in the near future (*Fig. 2b*), more important in the far future (Fig. 2c);
- A stability of *mould growth* in the near and far future (Fig. 3);
- A possible *mechanical degradation of wood* (*Fig. 4*);
- A mechanical *degradation of a pictorial layer* likely in the distant future (*Fig. 5*).

However, the level of uncertainty in these risk maps is so high that deterministic approaches have severe limitations and research is needed to assess the levels of uncertainty introduced at each stage of modelling [5].



a) ***b)*** ***c)***

*Fig. 1 - **Average temperature** (°C) inside an unheated, un-air-conditioned **witness church** when placed virtually across Europe: a) in the **recent past**; and variation b) from the **recent past to the near future** and c) from the **recent past to the far future** [3] (NB: Scales are different from map to map)*



a) ***b)*** ***c)***

*Fig. 2 - **Relative humidity rates** inside an unheated and, un-air-conditioned **witness church** when placed virtually across Europe: a) in the **recent past**; and variation b) from the **recent past to the near future** and c) from the recent past to the far future [3] (NB: Scales are different from map to map)*

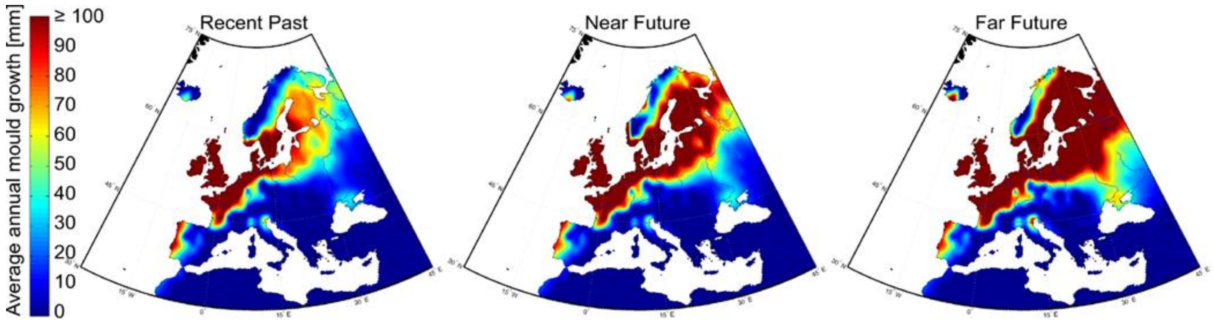


*Fig. 3 - Annual average growth (in mm) predicted of **mould** in the **recent past, the near future and the far future** inside an unheated, and un-air-conditioned **witness church**, when placed virtually across Europe [3]*

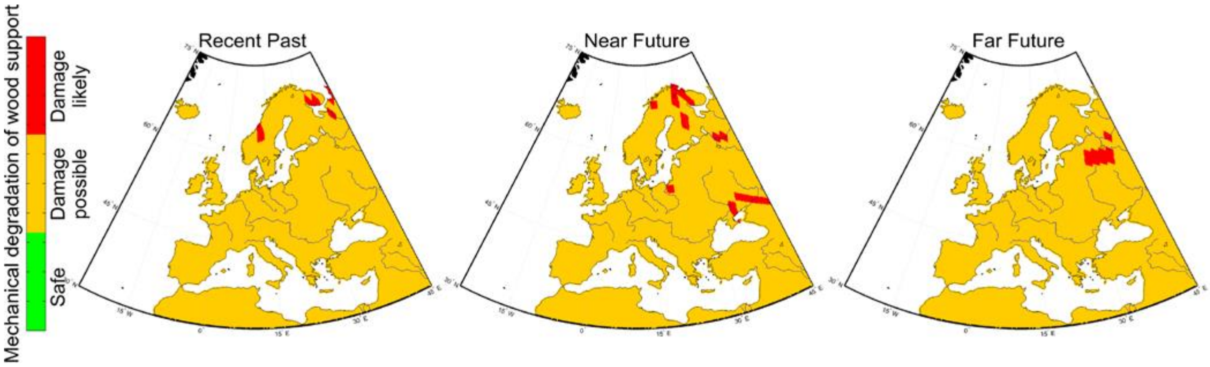


Fig. 4 - Prediction of the mechanical degradation of a ***wooden support*** *in* ***the recent past, the near future and the far future*** *inside an unheated, un-air-conditioned* ***witness church,*** *when placed virtually across Europe* [3].

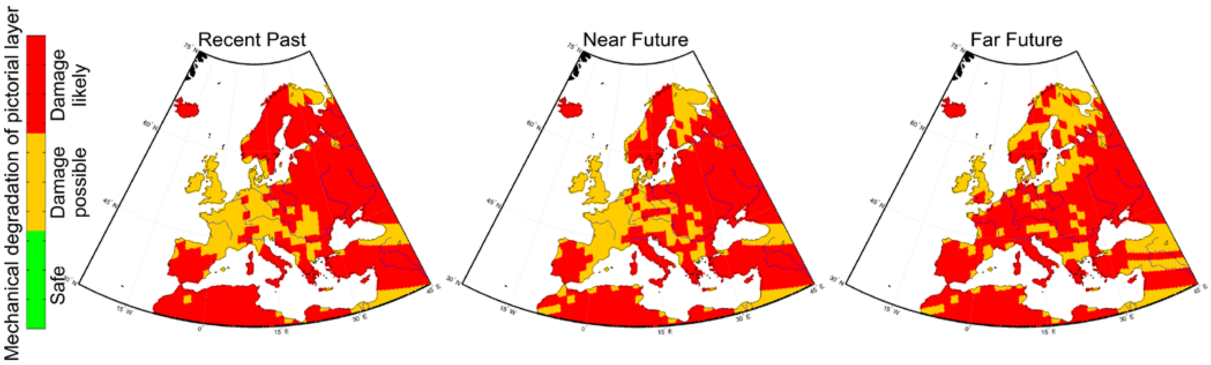


Fig. 5 - Prediction of the mechanical degradation of a ***pictorial layer*** *in* ***the recent past, the near future and the far future*** *inside an unheated and un-air-conditioned* ***witness church****, when placed virtually across Europe* [3]

A warmer climate is likely to potentially increase the number of *pests* in historic property and their movement northwards through less severe winters [6, 7]: "book lice" (*Liposcelis bostrychophila*), moth (*Tinea pellionella*), museum athrene (*Anthrenus spp.).* However, it is highly likely that insect abundance is not solely controlled by outside temperature: other factors such as food, habitat, access points, local maintenance and indoor climate can have an impact on insect numbers and property infestation.

Other measures can also contribute to *reduction of carbon foot-print*: reduction in the volume of waste in spaces open to the public and in workshops, reuse or recycling of materials, reduction of water consumption, insulation of floors and roofs, insulation from the outside (use of plasters and coatings highly insulating), installation of double windows or double glazing, installation of photovoltaic tiles... However, not all of these measures should alter the aesthetic value of historic buildings. Finally, the behaviour of users (employees and visitors) plays an essential role in the choice of temperature and ventilation of the premises.

Recommendations for museums, libraries, collections, archives and reserves facing climate change:

- Reduce *energy consumption* for winter heating, summer air conditioning, ventilation, and far transport of artefacts;
- Quickly exit the *use of fuel oil and fossil gas*;
- Expand the use of *LEDs* for lighting works, exhibition halls and places of worship;
- Remove permanently *candles* that emit soot that contribute to the blackening and soiling of artworks, especially murals, frescoes, tapestries and church stained glass;
- Make the *thermal assessment* of buildings housing cultural property;
- Make the *carbon footprint* of maintenance and restoration work to optimize the choice of materials and modes of transport;
- Achieve the *thermal insulation* of buildings and their roofs, at least by double glazing, respecting their history, architecture and aesthetics;
- Covering the *interior courtyards* of buildings with glass roofs that would reduce the surface area of buildings exposed to outdoor air by 40%:
- Develop and install *alert sensors* in monuments;
- Specifically protect materials that are fragile and vulnerable to changes in temperature and humidity: *wood, paper, textiles, polymers, films, contemporary artworks;*
- Protect collections from *biological infestations* that are favoured by rising temperatures;
- Raise *electric meters, power sockets and electrical appliances* in areas at risk of flooding.

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The stability of monumental buildings on clay soils in France

The structural stability of cultural monuments and buildings is an issue to be taken into account in the context of climate change. It can be compromised in certain situations: swelling and retraction of soil clays, landslides, river flooding, coastal erosion...

Under a construction, the evaporation of water from the soil can occur only on the periphery. There is then a gradient between the center of the building and its periphery, and differential movements follow. Unlike consolidation settlement phenomena, these effects do not subside over time, but increase when the structure loses its rigidity [1].

The swelling-shrinkage phenomenon only affects soils rich in expanding-retracting clay minerals (smectites). The evapotranspiration of trees plays a major role in triggering the phenomenon: the roots retained water and dry the soil deep. For its part, simple evaporation (in relation to air temperature, sunlight exposure, wind) affects a very superficial layer of soil (1 to 2 m) and results in water transfers. There is removal with horizontal cracking and above all vertical settlement (*Fig. 1*)[1].

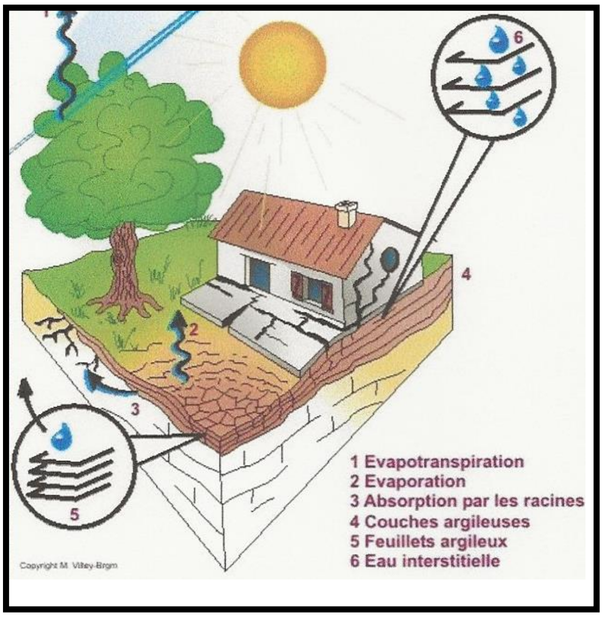

Fig. 1 - Cracking mechanisms of the walls due to the removal and swelling-shrinkage of clays in soil [1]

The French Bureau of Geological and Mineral Research (BRGM) is responsible for the development of *swelling-shrinkage hazard maps for clay soils* [1]. Built Cultural Heritage could be affected by this hazard and its census, as well as by the inventory of preventive measures to be taken in the context of climate change. However, according to the BRGM, this phenomenon is mainly manifested on light individual buildings, not deeply anchored, which is not the general case of large monuments, but could be that of small buildings of the vernacular heritage.

The BRGM's "*Swelling-Shrinkage Analysis and Impacts on Constructions*" (ARGIC) project [2] is a continuation of a general applied research effort that saw a marked resurgence of activity following the drought wave of the summer of 2003. A mapping of *ground movements* following drought and soil rehydration was drawn based on the number of natural disaster recognition recorded by French administration (*Fig. 2*) [3]. This map is superimposed on that of the distribution of the clay outcrops of secondary age (in blue and green) and tertiary (in yellow) on the geological map of France, mainly in the Paris Basin, the Aquitaine Basin, the Jura, the Limagnes of Loire and Allier, and the Maritime Alps (*Fig. 3*). Although nothing specific to the built Cultural Heritage appears on this map, it could be a useful guide to those responsible for this heritage, in the context of climate change, to inventory the risks and prevent the damage (cracks) already present or potential on monuments and cultural buildings located in the clay regions, these areas being already well located on this geological map.

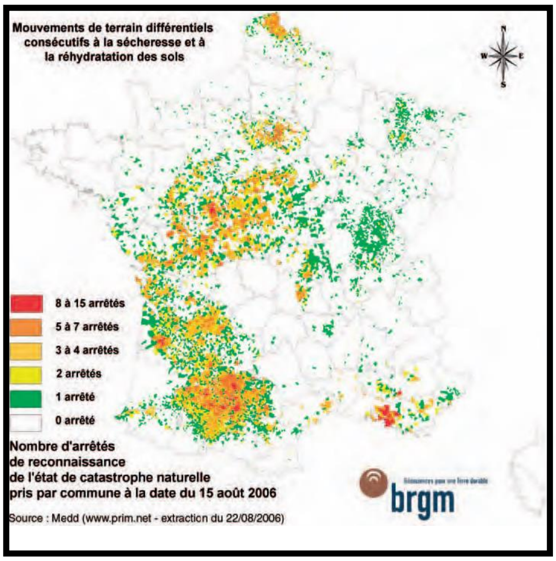

Fig.2 – Consecutive ground movements due to drought and soil rehydratation. Number of natural disaster recognition as for August 2006 [3]

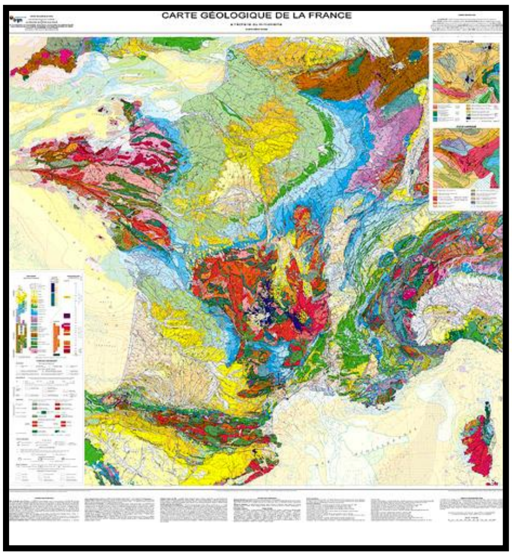

Fig. 3 – Geological map of France at 1:1,000,000 (BRGM ed.)

The scale of the losses attributed to this phenomenon is very large: more than 8,000 French municipalities affected in the summer of 2003 alone, which saw a severe heatwave and drought [3]. The likely worsening of droughts in France, as a result of climate change, will have effects on the water content of the foundation grounds and the surrounding vegetation, and will therefore affect the stability of the buildings.

The ClimSec project [4, 5,] carried out by the Climatology Directorate of Météo-France, has modelled these drought-climate relations according to several IPCC scenarios. It takes up the estimates of the French Insurance Association [6] based on two scenarios of the 5th IPCC Report. Under the RCP 4.5 scenario, annual damage from climate events is expected to double by 2050: climate change alone would account for 20%.

As the influence of climate change on the stability of buildings on clay soils, through drought affecting these soils, is very likely, there is no reason why it does not also affect cultural buildings, especially the most modest ones and especially those whose foundations are not deeply rooted.

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Summary of the potential impacts of climate change on French Cultural Heritage and maladaptation measures to be avoided

The French tangible Cultural Heritage is threatened mainly by the following ***slow impacts of climate change:***

- Increased *temperatures* and *CO_2 air concentration* increasing the acidity of the rain and thus the *dissolution of the carbonates* of the facades;
- *Thermoclastism* due to intense sunlight;
- Leaching and corrosion of old *stained glass windows*;
- *Salt-laden water raisings* in walls resulting in physical and aesthetic degradation;
- *Swelling-shrinkage of clays soils*, linked to alternating episodes of intense rainfall and drought, endangering the stability of buildings and monuments;
- *Floods* and river *low waters*;
- *Sea level rise* in coastal or island areas with coastal erosion and invasion of continental areas by salty sea waters;
- Increased *indoor temperatures* in museums, libraries and collections promoting biological infestations and disrupting all indoor climatology with implications for the conservation of artworks;
- *Corrosion of metals and concrete* (cement and metal frames);
- *Wood* degradation
- Migration of *climatic zones* with an impact on the distribution and seasonality of plants in parks, gardens and cultural landscapes...

However, the *effects of freeze-thaw on moist porous materials* will be **decreasing** due to temperature increases.

... but it is above all ***extreme events*** such as storms, tornadoes, heavy rains and associated submersions, flash-flow, heat waves, fires… that brutally attack property, especially cultural.

It will be necessary to ensure that any ***maladaptation*** that is produced is avoided, for example by:

- *massively vegetating* the facades and roof terraces of heritage buildings, thus altering their original aesthetics;
- touching on the architecture and decorative motifs of the facades during works *to insulate* buildings from the outside;
- using *dark* (low albedo) materials in new constructions, urban equipment and pavement;
- massively *watering* the foot of the walls to cool the surrounding atmosphere, resulting in salt-laden water rises;
- *watering* porous materials during freezing periods;
- significantly *removing away* the reserves of museums and archives, the restoration workshops, resulting in long and repeated transport, a source of emissions of pollutants and greenhouse gases;
- forcing *air cooling* systems in summer and *heating* systems in winter.

General conclusion:

Towards a French strategy to adapt Monumental Heritage to the impacts of climate change

We will conclude with *Recommendations* suggesting strategic measures to be taken in various areas of scientific and regulatory policy for an ideal adaptation of France's tangible Cultural Heritage to climate change. They were based on an analysis of the state of this heritage facing climate change and its predictable evolution outlined above in this brochure. Thus should be defined and applied:

A general policy of research on the adaptation of Cultural Heritage to climate change by first strengthening European cooperation (Joint Programming Initiatives Cultural Heritage and Climate, Heritage Portal, Programme H2020, Green Deal of the European Commission...) and worldwide (UNESCO, ICOM, ICOMOS, ICROM, Future Earth...).

Fundamental and applied research with many specific approaches:

- Develop in France researches on the *interactions between climate change and tangible Cultural Heritage*, which are still embryonic;
- Strengthen cooperation between on one hand the *disciplines of climate and air quality*, and those of *materials and restoration - conservation* on the other;
- Reconstruct *past climate series* from written archives, instrumental surveys and dendroclimatology on woods to validate predictive models of climate change;
- Apply the *various climate models* in the RCP and SSP-RCP *scenarios* of the 5th (2014) and 6th (2021) IPCC Reports;
- Use *Climate Services* (DRIAS and MétéoHD) to have regionalized projections;
- Develop *high-resolution climate maps* by downscalling;
- Draw *high-resolution risk and damage maps* for various materials, regions and cities in various models and scenarios;
- Apply models of *future pollutant emissions;*
- Develop *new Dose-Response and Material Damage Functions*;
- Develop specific research on the impacts of climate change on *metals and concretes* (carbonation of cement corrosion of metal frames);
- Develop research on predictive models of *outdoor-indoor transfers*;
- Combine *simulations* in the laboratory and at Cultural Heritage sites;
- Calculate the *Carbon footprint* of cultural buildings to reach *Zero emissions net.*

Teaching and training, essentially*:*

- Capitalize on the growing interest of *students in schools, colleges, high schools, and universities* for the protection of environment and climate (climate marches and strikes) and for heritage (European Heritage Days), illustrating it by the impacts of climate change on this heritage;
- Develop *initial training programmes* on climate change, its impacts and the adaptation of Cultural Heritage furniture and real estate, in Higher Education on Heritage, Architecture and Decorative Arts; in the Masters on Heritage, Environment, Geography and Urbanism; PhDs;
- Develop *ongoing training of heritage professionals* on the risks of climate change and adaptation.

A national and local, financial and economic policy. This includes:

- Contribute *to funding* European and national research programmes on adapting tangible Cultural Heritage to climate change;
- Generalize policies and budgets for *continuous maintenance* and *preventive conservation* of Cultural Heritage;
- Develop at the *local and operational level*, for example at the DRAC level, a constant concern about climate change for the future of Cultural Heritage;
- Establish *climate emergency plans* for cultural buildings;
- Assess the *socio-economic impact* of adapting Cultural Heritage to climate change;
- Assess the *cost* of adaptation.

The most important thing would be to catch up for lost time in France, compared to the Italian, English and German neighbours, in research on the impacts of climate change on Cultural Heritage. This is evidenced by the few examples and cases of studies that we have been able to cite concerning French heritage and the few French research teams dedicated to it. This would also bring more rigorous and precise results than generalities regarding these impacts at the global or European level.

In France, a great mobilization of the cultural sector is still lacking to show and understand the past history of the climate, its recent changes, future projections, cultural buildings in their territory, their resilience to past crises and their future in terms of conservation and restoration. The potential is immense, not only from a heritage point of view, but also from a socio-economic point of view in relation to cultural or mass tourism.

A sentence from the Dantec-Roux Report to the Senate in 2019 makes perfect sense here: "*We must stop believing that the impacts of global warming are too distant or uncertain to be necessary or possible to prepare for them."*

The restoration site, which opened in Notre-Dame de Paris following the fire on 15 April 2019, should be an opportunity to take into account the impacts of climate change on this emblematic monument, heritage and religious. A restoration is not only an architectural gesture, it is also giving new life to a building that is functional because frequented by many faithful and many tourists. The modelling of future outdoor-indoor exchanges in the cathedral in the context of climate change must be done, to provide for effective insulation of the future roof, after its materials and those of the frame have been chosen, and to design and size future heating installations in winter and air conditioning in summer. This Notre-Dame de Paris restoration should also serve as an example for fundamental and applied research concerning French Cultural Heritage as a whole in the face of the global climate imbalance.

Postface: acknowledgements

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Finally, I thank ICOMOS-France and ICOMOS-International, especially their directors Isabelle Palmi and Marie-Laure Lavenir, for offering this text the hospitality of their computer sites, thus ensuring a wide dissemination in the Cultural Heritage community.

I cannot resist reproducing to complete the answer that Stéphane Bern gave me in response to my questioning p. 6 of my Introduction: "*Stephane Bern thanks you for your very good analysis that he shares. He would like to tell you that he will try in the future to alert the leaders and owners of Historic Monuments to climate issues.*" Ideas are moving forward.
