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VULNERABILITY OF CULTURAL HERITAGE TO CLIMATE CHANGE

Report

by

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Executive summary

Europe has assumed a leadership role in establishing research projects (e.g. NOAH's ARK) on the impact of climate change on cultural heritage, in an era of improving urban air quality. The work performed has taken a uniquely quantitative approach, and established the great importance of water as a threat to heritage, despite temperature being so often identified as the key aspect of climate change. The threat from water is revealed as intense rain, flood, or storm surges. Increased rainfall can overload roofing and gutters, penetrate traditional materials (e.g. thatch, cob, wattle-and-daub, etc) or deliver pollutants to building surfaces, while flooding brings catastrophic loss. In a more subtle, yet more pervasive way, changes in humidity affects the growth of microorganisms on stone and wood, and the formation of salts that degrade surfaces and influence corrosion. Despite the intense periodic nature of future rainfall, drier summers overall will increase salt weathering of stone, and desiccate the soils that protect archaeological remains and support the foundations of buildings.

Future research work required in the area of climate change and cultural heritage is clustered under 5 themes, namely:

1. understanding the vulnerability of materials to climate, to reliably assessed future impact
2. monitoring change, especially on decadal and even century-long time scales
3. modeling and projecting changes in heritage climate at high spatial and temporal resolution, with a estimate of reliability
4. developing tools to manage cultural heritage in a changing climate
5. preventing damage by developing long term strategies.

INTRODUCTION

In a world where climate is changing, our heritage will be faced with a range of new pressures that are quite different to those experienced in the past. Management practices will have to evolve to reduce the impact of novel threats and to recognise the need for a shift from damage mechanisms like air pollution, towards a different biological and physical process that will give rise to damage forms that are expected to be different from those of the last century.

The present Report is based on the results achieved within the project Noah's Ark on "*Global Climate Change Impact on Built Heritage and Cultural Landscapes*". funded by the European Commission under its 6th Framework Programme for Research.

In addition to the Deliverables produced within the Noah's Ark project (http://noahsark.isac.cnr.it/deliverables.php), the following documents have been taken into account:

- Report n° 22 of the UNESCO World Heritage Centre: «*Climate Change and World Heritage Report on predicting and managing the impacts of climate change on World Heritage and Strategy to assist States Parties to implement appropriate management response*» Paris, May 2007, 55 p.; (http://whc.unesco.org/en/activities/474/)

- The Report entitled «*Climate Change and the Historic Environment: Adapting Historic Environments to Moisture-Related Climate Change*», M. Cassar (2005). (http://www.eprints.ucl.ac.uk/archive/00002082/01/Publish_Climate_Change_Report_05.pdf)

- Report « *Engineering Historic Futures Stakeholders Dissemination and Scientific Research Report*» M. Cassar (2006) http://www.ucl.ac.uk/sustainableheritage/ehf_report_web.pdf)

The present Report will include the state of the art, future developments and recommendations.

1. ACTIONS BY INSTITUTIONS IN FACING THE RISK OF CLIMATE CHANGE TO CULTURAL HERITAGE

1.1. UNESCO

One of the most intractable problems facing those responsible for world heritage is that of climate change, especially for the 878 natural and cultural world heritage properties (as on 20th September 2008), listed for their outstanding universal value following the adoption of the Convention on the Protection of the World Cultural and Natural Heritage http://whc.unesco.org/archive/convention-en.pdf) by the General Conference of UNESCO at its seventeenth session Paris, 16 November 1972. They include 679 cultural, 174 natural and 25 mixed properties in 145 state parties to the Convention.

The issue of the impact of climate change on World Heritage natural and cultural properties (UNESCO, 2007), was brought to the attention of the 29th Session of the World Heritage Committee in Durban in 2005 by a group of concerned organisations and individuals, including environment groups. The said group petitioned the Committee that climate change threatens the continued existence of five key World Heritage sites: the Belize and Great Barrier Reefs, glaciers in Waterton-International Peace Park (in the US and Canada), Mount Everest and the Peruvian Andes. The World Heritage Committee requested the World Heritage Centre of UNESCO, in collaboration with its Advisory Bodies (IUCN, ICOMOS and ICCROM), interested State Parties and the petitioners who had drawn the attention of the Committee to this issue, to convene a broad working group of experts on the impact of climate change on World Heritage. The Committee took this decision noting "that the impacts of Climate Change are affecting many and are likely to affect many more world heritage properties, both natural and cultural in years to come".

The Committee requested the broad working group of experts to:

- review the nature and scale of the risks posed to World Heritage properties arising specifically from Climate Change;
- jointly develop a strategy to assist State Parties to implement appropriate management responses; and
- prepare a joint report on Predicting and Managing the Effects of Climate Change on World Heritage to be examined by the World Heritage Committee at its 30th session in Vilnius in 2006.

The expert meeting took place on 16 and 17 March, 2006 at the UNESCO headquarters in Paris and resulted in the preparation of a report on predicting and managing the effects of climate change on World Heritage, as well as a strategy to assist States Parties to the World Heritage Convention to implement appropriate management responses. A case study publication was also produced by the World Heritage Centre to raise awareness of this issue (UNESCO, 2008a).

At its 30th session in Vilnius in July 2006, the World Heritage Committee reviewed these two documents and took the decision to request all the States Parties to implement the strategy so as to protect the outstanding universal values, integrity and authenticity of the World Heritage sites from the adverse impacts of climate change.

The Committee also requested the World Heritage Centre, the Advisory Bodies and States Parties to develop and implement pilot projects at specific World Heritage sites, especially in developing countries, so as to define best practices for the implementation of the strategy. The World Heritage Committee further requested the World Heritage Centre to develop, through a consultative process, a policy paper on Climate Change and World Heritage, which was presented to it at the 31st session in Christchurch in 2007 (UNESCO, 2008b).

The policy paper, prepared at an expert meeting held at the UNESCO World Heritage Centre in Paris in February 2007, included considerations of the synergies between the Convention and this issue, the identification of future research needs, legal questions on the role of the World Heritage Convention with regard to suitable responses to climate change, linkages to other UN and international bodies, including the IPCC, and alternative mechanisms, other than the List of World Heritage in Danger, to address international concerns such as climatic change. The World Heritage Committee meeting in Christchurch in July 2007 accepted this policy document in its Decision 31 Com 7.1 2007 (UNESCO, 2008c).

1.2. European Commission

In the 6th Framework Programme for Research and Development, the European Commission approved and financed a project on the topic of climate change: *Noah's Ark* («Global Climate Change Impact on Built Heritage and Cultural Landscapes», 2004-2007, http://noahsark.isac.cnr.it). The project will be described in § 2.3.

At the time of the preparation of the present report no announcement has been made regarding the 2nd call of 7th Framework Programme, which deals with "Development and application of methodologies, technologies, models and tools for damage assessment, monitoring and adaptation to climate change impacts (excluding extreme events)". This, together with the potential national programmes such as the AHRC/EPSRC Science and Heritage Programme in the United Kingdom, offers the opportunity for new research on both the fundamentals and application of research results to management practice.

1.3. European Parliament

On 10 September 2007 the coordinator of the Noah's Ark project was called to give evidence on "Global climate change impact on our cultural heritage" to the European Parliament Temporary Committee on Climate Change for the first public hearing on "Climate impact of different levels of warming".

1.4. Council of Europe

Climate change is cited among the strategic orientations by Robert Palmer, Director of Culture and Cultural and Natural Heritage (http://www.coe.int/t/dg4/cultureheritage). With the present report, this international institution is directly and specifically engaging with the effects of climate change on cultural heritage. It has however done so previously in an indirect way through its involvement in sustainable development. This is the case of the Convention on Cultural Heritage formulated on initiative of the Council of Europe, that of Faro (2005), on the Value of Cultural Heritage for Society.

In 2008, the interest of the Council of Europe in the problematic was renewed by the Executive Secretary of the European and Mediterranean Major Hazards Agreement who organized a side event entitled "Cultural Heritage and Risk: some European experiences" within the International Disaster and Risk Conference held in Davos, Switzerland, where a oral presentation was given concerning the "On-going initiatives to assess the impact of climate change on Cultural Heritage".

The Council of Europe sustains and funds the activities of the European University Centre for Cultural Heritage, Ravello, Italy, especially in the organisation of courses on the risks of climate change for cultural heritage (see §1.7 below).

1.5. Centre for Sustainable Heritage (University College London)

In 2005 the Centre published a report by May Cassar, titled "*Climate Change and the Historic Environment*"(Cassar, 2005), which was commissioned by English Heritage. The central body of the report analyses the answers to a questionnaire sent out to British cultural heritage managers and decision-makers.

This first report was followed in 2006 by a second, based on British national research, entitled "*Engineering Historic Futures Stakeholders Dissemination and Scientific Research Report*" (Cassar and Hawkings, 2006).

The spirit of these studies and many of their results were integrated into the Noah's Ark Project, financed by the European Commission, in which the Centre played a major role. It is therefore unnecessary to discuss the earlier findings here. Suffice it to say that the Centre for Sustainable Heritage continues to be highly active in Europe on issues relating to climate change and cultural heritage.

1.6. EU Noah's Ark Project

This project brought together the main European scientific laboratories engaged in research on cultural heritage in the context of climate change, together with an international insurance company and a private company specialising in recovery from environment disasters. The scientific publications that have already been published (Sabbioni et al., 2006; Brimblecombe et al. 2006, 2007; Grossi and Brimblecombe, 2007; Grossi et al. 2007; Blades et al., 2008) and those to follow, will report the results of this important study, the first on this series of issues. Those involved were research teams engaged for many years in the study of the degradation of cultural heritage due to air pollution, who have transferred their experience to climate change. They therefore have an excellent knowledge of materials, and some of them, also of atmospheric and climatic phenomena. They are :

- *Istituto di Scienze dell' Atmosfera e del Clima of the National Research Council* (ISAC-CNR, Bologna, Italy): Cristina Sabbioni (project coordinator), Alessandra Bonazza, Palmira Messina;
- *Centre for Sustainable Heritage, University College London* (UCL, London, UK): May Cassar, Phillip Biddulph, Nigel Blades;
- *University of East Anglia, School of Environmental Sciences* (UEA, Norwich, UK): Peter Brimblecombe, Carlotta Grossi;
- *Corrosion and Metals Research Institute* (KIMAB, Stockholm, Sweden): Johan Tidblad;
- *Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences* (ICSC, Kracovia, Poland) : Roman Kozlowski, Lukasz Bratasz, Slawomir Jakiela;
- *Institute of Theoretical and Applied Mechanics, Czech Academy of Sciences* (ITAM, Prague, Czech Republic): Drdacky, Zuzana Slizkova;

- *Instituto de Recursos Naturales y Agrobiologia, Consejo Superior de Investigationes Sceintificas* (CSIC, Seville, Spain): Cesareo Saiz-Jimenez, Juan M. Gonzales Grau;
- *Norsk Institutt for Luftforskning* (NILU, Kjeller, Norway): Terje Grontoft, Gaute Svenningsen;
- *Ecclesiastical Insurance Group* (EIG, Gloucester, UK): Ian Wainwright, Chris Hawkings;
- *Biologia y Medio Ambiente*(BMA, Barcelona, Spain): Ariño Vila Xavier, Antonio Bolea.

Thus, the project’s participants represent a strong body of experts in materials, atmospheric and climate sciences, who are dedicated to continuing to investigate these issues in their research projects. This presumes that institutions financing research are willing to build on existing knowledge and expertise in research in the said field.

1.7. European University Centre for Cultural Heritage (Ravello, Italy)

The Centre intends to include climate change and its effects on cultural heritage among its main concerns in the future. Currently, only two cycles of courses have dealt with this new problem, and this only recently, in 2007, the cycle on Risks, and that on the Sciences and Materials of Cultural Heritage.

In the cycle «*Cultural Heritage and Major Risks* », a course was taught in 2007, which described the foreseeable risks to cultural heritage in the context of climate change and in 2008 the focus was on strategies for prevention against major risks including climate change.

The courses of the cycle «*Sciences and Materials of Cultural Heritage*», in 2007 were entirely devoted to the topic « *Global Climate Change and Cultural Heritage* », notably with the participation of three key figures from the Noah’s Ark project: Cristina Sabbioni, May Cassar, Milos Drdacky. This course is expected to run again in 2009.

2. RISK ANALYSES

2.1. General methodology

The Intergovernmental Panel on Climate Change (IPCC) has stated that present day weather conditions in Europe reveal vulnerabilities that can only be exacerbated by climate change, particularly at a regional level. Overall the adaptive potential of Europe should be relatively high because of well-developed political, institutional and technological support systems.

- Current pressures on water resources and management are likely to be exacerbated by climate change
- Flood hazard is likely to increase across much of Europe – except where snowmelt peak has been reduced
- Half of Europe's alpine glaciers could disappear by the end of the 21st century, so preparations for rescue excavations will be needed
- Soil properties will deteriorate under warmer and drier climate scenarios in southern Europe, leading desertification and changes in soil chemistry affecting archaeological sites
- Timber harvests are likely to decrease in the Mediterranean, with increased drought and fire risk
- Some agricultural production systems in southern Europe may be threatened by the risk of water shortage
- The insurance industry faces potentially costly climate change impacts through property damage but there is great scope for adaptive measures if early steps are taken
- Human settlements concentrated on coasts exposed to sea level rises and extreme events will need protection or removal
- Heat waves are likely to reduce the traditional peak summer demand at Mediterranean holiday destinations and less reliable snow conditions will adversely impact on winter tourism
- Risk of flooding, erosion and loss in coastal areas will increase substantially, with implications for human settlement and tourism. Southern Europe appears to be more vulnerable, although the North Sea coast has a high exposure to flooding.

		Flood Incidence[1]	
Region	**1990 Exposed population (millions)**	**1990 Average number of people experiencing flooding (1000s/year)**	**2080s Increase due to sea-level rise, assuming no adaptation (%)**
Atlantic Coast	19.0	19	50 to 9000
Baltic Coast	1.4	1	0 to 3000
Mediterranean Coast	4.1	3	260 to 120000

[1] Estimates of flood incidences are highly sensitive to protection standards and should be interpreted in indicative terms only

2.2. Impact of climate factors on cultural heritage

Climate parameters, risk factors and identified impacts are summarised in the table[1] below:

Climate parameters	**Climate change risk**	**Physical, social and cultural impacts on cultural heritage**
Atmospheric moisture change	• Flooding (sea, river) • Intense rainfall • Changes in water table levels • Changes in soil chemistry • Ground water changes • Changes in humidity cycles • Increase in time of wetness • Sea salt chlorides	• pH changes to buried archaeological evidence • Loss of stratigraphic integrity due to cracking and heaving from changes in sediment moisture • Data loss preserved in waterlogged / anaerobic / anoxic conditions • Eutrophication accelerating microbial decomposition of organics • Physical changes to porous building materials and finishes due to rising damp • Damage due to faulty or inadequate water disposal systems; historic rainwater goods not capable of handling heavy rain and often difficult to access, maintain, and adjust • Crystallisation and dissolution of salts caused by wetting and drying affecting standing structures, archaeology, wall paintings, frescos and other decorated surfaces • Erosion of inorganic and organic materials due to flood waters • Biological attack of organic materials by insects, moulds, fungi, invasive species such as termites • Subsoil instability, ground heave and subsidence • Relative humidity cycles/shock causing splitting, cracking, flaking and dusting of materials and surfaces • Corrosion of metals • Other combined effects eg. increase in moisture combined with fertilisers and pesticides

[1] 'Principal climate change risks and impacts on cultural heritage' in *Background Document UNESCO WORLD HERITAGE CENTRE in cooperation with the United Kingdom Government 'World Heritage and Climate Change' for the broad working group of experts at UNESCO HQ16-17 March 2006* and in Working Document 30 COM 7.1 prepared for the 30th Session of the World Heritage Committee, Vilnius, July 2006 which can be found at http://whc.unesco.org/archive/2006/30com-en.htm

Temperature change	• Diurnal, seasonal, extreme events (heat waves, snow loading) • Changes in freeze-thaw and ice storms, and increase in wet frost	• Deterioration of facades due to thermal stress • Freeze-thaw/frost damage • Damage inside brick, stone, ceramics that has got wet and frozen within material before drying • Biochemical deterioration • Changes in 'fitness for purpose' of some structures. For example overheating of the interior of buildings can lead to inappropriate alterations to the historic fabric due to the introduction of engineering solutions • Inappropriate adaptation to allow structures to remain in use
Sea level rises	• Coastal flooding • Sea water incursion	• Coastal erosion/loss • Intermittent introduction of large masses of 'strange' water to the site, which may disturb the metastable equilibrium between artefacts and soil • Permanent submersion of low lying areas • Population migration • Disruption of communities • Loss of rituals and breakdown of social interactions
Wind	• Wind-driven rain • Wind-transported salt • Wind-driven sand • Winds, gusts and changes in direction	• Penetrative moisture into porous cultural heritage materials • Static and dynamic loading of historic or archaeological structures • Structural damage and collapse • Deterioration of surfaces due to erosion
Desertification	• Drought • Heat waves • Fall in water table	• Erosion • Salt weathering • Impact on health of population • Abandonment and collapse • Loss of cultural memory
Climate and pollution acting together	• pH precipitation • Changes in deposition of pollutants	• Stone recession by dissolution of carbonates • Blackening of materials • Corrosion of metals • Influence of bio-colonialisation
Climate and biological effects	• Proliferation of invasive species • Spread of existing and new species of insects (eg. termites) • Increase in mould growth • Changes in lichen colonies on buildings • Decline of original plant materials	• Collapse of structural timber and timber finishes • Reduction in availability of native species for repair and maintenance of buildings • Changes in the natural heritage values of cultural heritage sites • Changes in appearance of landscapes • Transformation of communities • Changes in the livelihood of traditional settlements • Changes in family structures as sources of livelihoods become more dispersed and distant

2.3. EU Noah's Ark Project

2.3.1. Methodological approach

The climate parameters critical to the built cultural heritage were selected and the respective climate data from the General Climate Model (HadCM3) and the Regional Climate Model (HadRM3) of the Hadley Centre (UK) were derived. The HadCM3 General Model has a grid resolution of 295 x 278 km (each cell: 2.5 x 3.75 degrees at 45°N latitude). The HadRM3 Regional Climate Model encompasses a European region at a higher resolution based on a grid of equal-area cells of 50 x 50 km (each cell: 0.5 x 0.5 degree at 45°N latitude).

The model output used for mapping relied on the A2 scenarios (IPCC SRES Emission Scenarios used in TAR and FAR). The A2 scenario storyline and scenario family describe a very heterogeneous world. The underlying theme is self-reliance and preservation of local identity. Fertility patterns across the covered regions change slowly, which allows for a continuously increasing population. Economic development is primarily regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in other storylines.

The selected geographical area was centred on Europe (i.e. a region of 33.75°W-67.50°E longitude and 80°N-25°N latitude for the general model, and 30°W-55°E longitude and 72°N-35°N latitude for the regional one).

Air pollution data for gases, such as SO_2, HNO_3, O_3 concentrations and pH precipitation, were processed in order to produce future scenarios. Regarding future emission levels, two scenarios were developed for 2020 (using the dataset available for Europe within the Convention on Long-range Transboundary Air Pollution-CLRTAP and EMEP) and for 2085 (from Clean Air for Europe Program-CAFE, Maximum feasible technical reduction-MFTR scenario).

Yearly means of SO_2, HNO_3 and O_3 air concentrations and pH precipitation for the years 1990, 2020 and 2085 over the European area were used, with a grid resolution of 0.4 x 0.4 degrees.

Parameterisations for future climate variables were developed based on:
- temperature derived parameters: temperature range, thermal shock, freeze-thaw cycles. One early result was an indication of decline in the frequency of freezing over the 21st century and a lower potential for frost damage outside the Artic and high mountain areas;
- water derived parameters: precipitation amount, total number of rainy days, extreme rain events, consecutive number of rainy days, mean relative humidity, relative humidity range, relative humidity shocks. Particularly noticeable in early outputs were the dry summer months in central Europe;
- wind derived parameters: wind speed, wind speed counts, wind driven rain, wind driven sand;
- pollution derived parameters: SO_2, HNO_3, O_3 and pH precipitation.

The climate data derived from HadCM3 and HadRM3 were transformed into parameters relevant to cultural heritage problems. Special attention was devoted to developing novel climate parameterisations of future climate variables that are of special relevance to heritage materials. The parameters are termed "heritage climate parameters" and include:

- Wet frost, i.e. days of rain followed by frost

- Sheffer-type indices – for fungal growth
- Evaporation – soil moisture, desiccation and water table
- Thermohygrometric shock
- Directional wind driven rain – damp penetration and redistribution of deposited atmospheric particles
- Decreasing temperature and increasing humidity – hydrated salts

In the early part of the project it became clear that *temperature changes would not have particularly critical impacts on cultural heritage*. Even when temperature effects were amplified through freeze-thaw cycles, these would be much reduced in most of Europe of the future. However, *warmer temperatures look set to affect archaeological sites in the permafrost regions***.** Hydro meteorological parameters seemed likely to be most critical, and it was noted how *increased heavy rainfall would be critical for increased flooding and loading on roofs***.** Additionally, dry summers look likely to increase the impact of humidity cycles (via salt crystallisation), and potentially lead to the drying out of unfired building materials and soils.

The following key outputs were obtained:

- Climate change is subtle and occurs over long timescales. However, some climate parameters, such as freezing, humidity cycles and wind driven rain can change very considerably. In particular, phase changes in freeze-thaw cycles and salt crystallisation will be amplified, becoming sensitive to reduced or increased frequency in the presence of quite modest changes in climate.
- Different parts of Europe will experience different changes in heritage climate. For example, a large change in salt crystallisation will be likely under a drier regime across areas of Europe dominated by medieval Gothic architecture. There is a potential for wetter frosts in future Ukraine, Romania, Austria, Hungary and Slovenia.

2.3.2. Description and prediction of the global impact of climate change on building materials and structures

The first objective was to develop models for the impact of global climate changes on the deterioration of different cultural heritage materials, including both meteorological and pollution parameters.

Models were adapted or developed for stone and masonry materials, metals, wood, and glass (with composition representative of mediaeval stained glass windows). The models included meteorological (temperature, relative humidity, etc) and pollution (SO_2, rain pH, etc) parameters. For stone materials, a wide range of effects was considered, including chemical attack, soiling/blackening, thermal shock and freeze-thaw cycles. For wood, both mechanical damage due to variations in relative humidity and decay by wood destroying fungi were considered. A chloride deposition model, as a function of climate change and wind speeds, was also proposed. Chloride deposition will be active particularly in increasing the corrosion of metals and in causing the degradation of stone materials due to salt crystallisation cycles.

The models were of different types, including:

- damage functions based on real field data obtained from large exposure programmes.
- damage functions based on a literature survey and further developed for the Project's purpose based on an analysis of the dominant effects;
- damage functions based on original laboratory investigations performed within the Project.

In total, the developed set of damage functions represents a significant achievement and a substantial advancement of the state of the art.

The second objective was to use the models to assess and quantify the impact of past and future climate changes on important materials employed in cultural heritage objects in different scenarios.

The models that were developed were used to quantify the impact in three periods: recent past (1961-1990), near future (2010-2039) and far future (2070-2099). As mentioned above, for meteorological parameters, the A2 scenario was considered, while for pollution parameters, a more optimistic reduction scenario and a more pessimistic constant pollution scenario were used.

With regards to materials *damage functions* and *dose-response functions* were used and integrated with the variations predicted in climate models. An example of *damage function* is the Lipfert function for surface recession on calcareous stones (Lipfert, 1989). The function integrates the solubility of calcite, rainfall intensity and pH, the deposition speed and concentrations of SO_2 and HNO_3 in the air. The *dose-response functions,* which relate the amounts of pollutants deposited on a material to its response, were used for the corrosion of metals (steel, zinc, copper, bronze, lead) and the alteration of stained glass. These functions have the crucial property of being *mappable,* in the same way as climatic factors.

Organism growth on monuments deserved particular attention, both as an agent of aesthetic change as well as its possible role in contributing to stone deterioration or protecting against deterioration. Biomass production was correlated with climate conditions, the main parameters defining bioclimate being precipitation and temperature. Changes in these parameters affect organism activity, and hence changes in the biomass.

Experimental work on materials sensitive to extreme dynamic climate events was performed with the main purpose of determining a climate risk index for sensitive historic materials. Two materials particularly vulnerable to moisture – wood and clay-containing sandstones – were investigated to determine potential modes of material damage induced by climate change.

Two principal damage mechanisms causing the deterioration of historic wood structures and objects were studied, and a range of experimental methods and computer-aided numerical simulation was applied: mechanical damage due to relative humidity variations and attack by wood-destroying fungi. The former was relevant to historic wooden objects inside buildings, the latter to wooden structures exposed to the outdoor weather. Furthermore, swelling and shrinkage of the clay binder induced by cycles of wetting and drying in outdoor exposure to atmospheric precipitation were determined as the principal mechanism by which clay-containing materials deteriorate.

To formulate a risk index for indoor wood, numerical modelling was used to trace the evolution of the moisture content gradient and the stress field resulting from the restrained differential dimensional response across a wooden cylinder, simulating sculptures, in response to variations in temperature and relative humidity (RH). The material properties of lime wood were used in the modelling, as this wood species was widely used historically. Allowable RH variations, below which mechanical damage will not occur, were derived as functions of the amplitude, time period and starting RH level of the variation. The risk of environmentally induced mechanical damage of wood was described as a yearly number of RH variations exceeding 30% between 2 consecutive days, since such variations revealed considerable damaging potential, according to the results of the modelling that was performed.

An improved climate risk index for the fungal attack was also developed. Moisture transport into wood was determined using a scanning Nuclear Magnetic Resonance (NMR) technique. A model of two-stage infiltration, interpretable in terms of very rapid transport through the vessels with a simultaneous slower infiltration into the denser surrounding material, was used to interpret the results. Profiles of moisture penetration into wood could then be numerically simulated for any precipitation event. Following the fungal growth models, the moisture penetration profiles could be recalculated into “events of fungal growth risk”, which were subsequently agglomerated into the quarterly “time of fungal growth risk”. The effect of temperature was also taken into account.

Acoustic emission (AE) monitoring was employed to investigate direct tracing of mechanical damage in Salamanca sandstone from Spain – representing a clay-containing material – due to the restrained dimensional change in response to cycles of wetting and drying. AE, defined as energy released due to fracturing of the stone structure, was recorded for each episode of wetting and drying and related to the total energy corresponding to mechanical destruction of the specimen. In this way the percentage of the total damage per each cycle could be established and consequently the critical number of cycles corresponding to severe damage of the material – 10 for the Salamanca sandstone - was investigated. Based on the damage development that was determined and the infiltration of water into the sandstone that was modelled, the risk index of climate-induced damage was defined as the thickness of the outer layer of stone within which the number of wet-dry cycles was greater than 10 during a given time interval (one quarter in the present calculations), and simultaneously the ambient temperature was above 0 °C.

2.3.3. Mitigation and adaptation strategies options for climate change impacts

The development of strategies and measurements for mitigating and adapting to the impact of global climate change on the built cultural heritage focused on structural and drying out damage.

Concerning structural damage, analyses were carried out on climate data recorded, and damage and failures experienced as a result of climatic and disastrous loads and actions. Subsequently, the cultural heritage elements, objects and sites were ranked into five sensitivity categories within four groups of climate hazards. They include weather action, floods, landslides and winds. In addition, a database of scientific references on mechanical damage and failures of historic structures due to weather effects was created, and relevant adaptation strategies and measures were suggested.

The impact of wind action on historic structures and art objects was developed in two parallel ways. Several typical shapes for historic roofs and structures were selected, mostly of old town towers. The three-dimensional model that was developed is suitable for investigating complex situations, and has been validated and calibrated using results from tests on reduced scale models in wind tunnel. The innovative methodology and the application of hybrid analysis of air flow around complex architectural forms of historic towers represent a pioneering effort in the field.

Landslides and floods due to heavy rains were studied in the second task. A map of important active and stabilised landslide events in the Czech Republic was compiled. Combined with information on geological composition, it allowed the identification of materials which are most prone to landslide deformations. A review of important case histories where buildings of a historic value have undergone landslide damage was performed, revealing the most problematic materials to be fine-grained materials, clays and clay stones. Further research focused on the development of mathematical constitutive (material) models for fine-grained soils. A notable development was made in the development of models based on hypoplasticity theory. For risk assessment and adaptation measures, a thorough study was made of existing methods of identifying and protecting landslide-prone areas. This part of the project resulted in several theoretical studies of fundamental importance for their contribution to more general theory and numerical modelling in soil (Milos, 2007).

To investigate drying-out adaptation strategies, a case study on the Church of St Michael the Archangel in Dębno south Poland was performed to understand the impact of climate on building materials. This provided data for the validation of a new heat and moisture (HAMT) transfer model, to simulate a building material's response to temperature and RH changes. The model was used to investigate the effects of climate change on the moisture content of building materials and the effects of different drying-out strategies. The HAMT model has received international validation and has been accepted as a sub-model of the widely used EnergyPlus© software.

The methodologies adopted involved the use of existing data and software to construct a verified software model of a cultural heritage building. The approach was to use the constructed model to understand the effects of climate change on the integrated building, thus providing an understanding of the external and internal contributions to moisture within the building fabric. The simulations provide state-of-the-art insight into the behaviour of materials under different conditions. The research into drying-out strategies, in particular, has implications for the present methods employed to dry out buildings (whether culturally important or not). Wood is particularly sensitive to rapid drying techniques, and this research shows that a drying regime using natural ventilation complimented by small amounts of controlled mechanical dehumidification may offer faster over all drying, reducing the risk of mechanical stress and biological attack.

2.3.4. Dissemination of information on climate change effects and adaptation strategies on the built heritage and cultural landscapes

For each chosen climate parameter, the General Climate Model (HadCM3) 30-year mean value maps were developed, as they are more climatologically significant. They were produced for the recent past (1961-1990), near future (2010-2030) and far future (2070-2099), and show how the scenarios of a particular parameter evolve.

Additionally, difference value maps between the far future and recent past, and near future and recent past, were produced in order to better quantify the changes with respect to the present scenario.

The regional model (HadRM3) far future values were also plotted with higher resolution. The far future period is crucial in climate investigations, since it is estimated that the most significant changes will occur in this period.

The following materials were selected for processing: marble, compact limestone, sandstone, brick, steel-iron, bronze, zinc, copper, lead, wood, glass.

A Vulnerability Atlas was produced gathering together different types of maps and research outputs of future scenarios, and linking climate science to the potential damage to cultural heritage within the following sections:

- *Climate Maps*: climate change is mapped in terms of the traditional climate parameters relevant to cultural heritage (e.g. annual precipitation, frost). They represent the basis of the other types of maps and are functional to their preparation.
- *Heritage Climate Maps*: they are obtained by the combination of climate parameters, with the aim of producing specific heritage climatologies (e.g. salt crystallization obtained from the events occurring per year of relative humidity cycles = 75.5%).
- *Damage Maps*: they are a further step forward in the use of climate parameters. They are based on damage functions, which quantitatively express the damage induced by climate parameters on building materials in future scenarios (e.g. surface recession of carbonate stones, metal corrosion).
- *Risk and Multiple-risk Maps*: they show areas of increasing/decreasing risk for one (risk maps) or more (multi-risk maps) deterioration process of materials in different regions of Europe. They are the summary of the previous maps and have the purpose of informing decision-makers on the type of risk likely to be most prevalent in a particular region.
- *Thematic pages*: have been used in cases where the production of maps is not possible and alternative methods are required to investigate future change of a particular type of damage (for example, in the case of soiling, where the local processes involved are closely linked to specific buildings). They summarise the results obtained on specific damage typologies, applying climate science in the context of European cultural heritage.

The research activity that was performed highlighted the great importance of water as a threat to heritage. Despite the fact that temperature is often considered the most recognizable agent of climate change, water seems to dominate when European monuments are considered. This may be water as experienced in times of intense rain, flood, or storm surges. In a more subtle, yet more pervasive, way it can be seen in the way increased rainfall can overload roofing and gutters, penetrate into materials or deliver pollutants to building surfaces. Water is also involved in the humidity change that affects the growth of microorganisms on stone and wood, and the formation of salts that degrade surfaces and influence corrosion.

A Europe with heavier rainfall may experience greater water penetration (especially into vernacular architectural materials such as unfired bricks, or thatching) and surface flooding. However, drier summers overall threaten to increase salt weathering of stone, mortar, frescos and wall paintings and the desiccation of soils that protect archaeological remains and support the foundations of buildings and monuments.

In addition, more specific results relating to the different damage processes considered can be advanced:

- Surface recession on carbonate stones, such as marble and compact limestone, is expected to increase in northern Europe reaching values as high as of 35 μm/y.
- Cycles per year of relative humidity around 75.5%, with consequent increase of salt crystallisation events, are likely to increase throughout Europe, particularly dangerous for porous materials such as porous limestone, sandstone and brick.
- An increase in iron and bronze corrosion in the urban areas of northern Europe is forecast. The trend is dominated by the effect of average annual temperature, where a maximum corrosion effect is observed at 10°C.
- Zinc corrosion is expected to increase in European areas affected by high chloride deposition.

- A slight decrease in stained glass leaching all over Europe is predicted, meaning that mediaeval glass will remain at risk in many areas.
- The Mediterranean Basin will in general continue to experience the highest level of thermoclastism risk.
- Europe in general will experience a reduction in frost damage (porous stones), with the exception of northern and mountain areas.
- Decay by wood-destroying fungi occurs in warm conditions in the presence of excess moisture. As north and eastern Europe become warmer in the future, with high precipitation levels, greater attention will be required in the protection of wood structures against rainwater effects.
- Sandstones containing clay will experience in the future more than 10 cycles at a depth of several centimetres in the North of Europe and in the mountains, mainly because of high precipitation. Drier areas–Spain, Italy, Turkey and North Africa–will be less endangered.

Guidelines offering adaptation strategies for cultural heritage management in the face of climate change were also produced, with the main aim of assisting heritage stakeholders, owners and curators of historic buildings and collections, public policy-makers and national heritage organizations to deal with future climate change pressures.

The compilation of the comprehensive set of guidelines for mitigation and adaptation to climate change represents the state of the art in this field. The approach was to use the research results and the augmented experience of the authors to provide meaningful and feasible strategies for coping with the most likely consequences of climate change on cultural heritage.

3. FUTURE DEVELOPMENT

The culmination of the deliberations of the UNESCO World Heritage Committee on climate change and cultural heritage was the decision (WHC-07/31.COM/7.1) taken at its Thirty first Session in Christchurch, New Zealand between 23 June – 2 July 2007. At this meeting issues related to the state of conservation of World Heritage properties concerning the impacts of Climate Change were discussed and the following research priorities for cultural heritage were agreed:

• Understanding the vulnerability of materials (indoor, outdoor, buried) to climate variables (for example, particularly too much or little moisture effects).

• Understanding how traditional materials and practices need to adapt to extreme weather events and a changing climate.

• Development of fail-safe methods and technologies for monitoring the impact of climate change on properties.

• Understanding climate change impacts causing changes in society i.e. movement of peoples, displacement of communities, their practices, and their relation with their heritage.

Future research required the area of climate change and cultural World Heritage have been clustered under 5 themes, namely:

• Understanding materials vulnerability
• Monitoring change
• Modelling and projecting climate behaviour
• Managing cultural heritage
• Preventing damage

3.1. Basic scientific research

A number of areas need to be explored at the level of basic research for creating the foundation of a climatology applied to cultural heritage protection.

A priority for basic research in the field of cultural heritage is the scientific determination of the climate parameters that are most critical to heritage buildings, collections and sites.

There are a number of climate models and they all need to be tested and validated for the prediction of impact on cultural heritage. Furthermore, a sense of the error in applying these models of future climate impact on heritage buildings, collections and sites needs to be obtained. There are particular problems in applying existing models as the right spatial and temporal scales are required. Although the spatial resolution of models has improved in recent years, this is not always true of temporal scales, as heritage research often needs data at daily and sometimes better than hourly time resolutions.

It is essential to develop and test damage functions for a wide range of heritage materials for past, present and future climates in indoor and outdoor environments.

An urgent priority for Europe is to explore the impact that sea level rise will have on cultural heritage protection.

3.2. Applied research

In order to bring home to heritage managers the importance of the underlying science to decision-making, it is important that the impacts on a group of the most significant world heritage sites and ensembles are developed in order to support the formulation of preventive conservation strategies.

The problems and model climate change impacts on cultural heritage in indoor environments need to be prioritised.

The changing condition of cultural heritage subjected to short term and medium term flooding and long term inundation needs to be measured. Guidance on sea level rise impacts for heritage managers need to be developed.

Adaptation strategies based on an early and cost-effective action including the balance between damage limitation, environmental control and energy consumption need to be developed.

Good policy, effective training and sustainable practice must all be built on the foundation of excellent scientific research.

4. RECOMMENDATION

These recommendations will be addressed at research, management, political and education levels.

4.1. Research

4.1.1. Funding

The peculiarities of the research on climate and cultural heritage, that include a broad range of vulnerable and aging materials, extensive exploitation for cultural tourism and concomitant financial benefits, fragility and remoteness, imbalance between the large number of sites compared to the small number of managers and conservation scientists, require specific concerted efforts for research in this area.

At its 30th Session (Vilnius 2006, Decision 30 COM 7.1) the World Heritage Committee requested all State Parties to protect the outstanding universal values, integrity and authenticity of the World Heritage Properties from the adverse impact of climate change. In order to fulfil this requirement, the following research gaps have been identified in the source document is WHC-07/16.GA/10 adopted by the 16th General Assembly of States Parties to the *World Heritage Convention* (October 2007) and described in the UNESCO Policy Document on the 'Impacts of Climate Change on World Heritage Properties' (2008, CLT-2008/WS/6, page 11, Annex 1 Specific Research Priorities) as: *uunderstanding materials vulnerability; monitoring change; modelling and projecting climate behaviour; managing cultural heritage and preventing damage.*

4.1.2 Cooperation and competitiveness

Europe was the first to create this novel research sector which combines scientific research on climate change with cultural heritage. In order to maintain this leadership, cooperation at the European level is vital to foster and consolidate European competitiveness in this sector at the international level.

The cooperation is also essential to prevent duplication of efforts and to improve complementarities and synergies both in *basic* research which requires bringing together a considerable amount of data and in *applied* research which needs the identification of common mitigation and adaptation strategies.

4.1.3 Critical mass

Because of the novelty and the demanding nature of this sector there are only a few scientists working in the field of climate change and cultural heritage. The three groups that exist are all based in Europe. For future research to thrive, it is important that projects and programmes are designed at a European level, not only to maintain the necessary critical mass but also to build on the essential datasets that have started to be developed on this scale. The development of a critical mass requires continuity of investment as a vital ingredient. The notion of spreading resources thinly appears to be fair but is in fact counter-productive.

4.2. Policy

Research must be converted into policy action, with the differences among countries addressed through international collaboration and knowledge transfer, in order to avoid recourse to inappropriate strategies and experiences. States with experience of the effects of a certain type of climate change on a cultural heritage could thus share their knowledge with those newly affected by similar conditions.

4.2.1 Global level

- Inclusion of the developing scenarios in future IPCC Reports and other international reports (e.g. UNFCCC) is essential.
- International cooperation particularly with developing countries (e.g. China and India), neighbouring (e.g. candidate countries, Mediterranean area) and industrialised countries (e.g. USA and Japan) must take place.

4.2.2 European level

For Europe there is a need to see:

- Inclusion of cultural heritage among the priorities in existing and forthcoming legislation and policies.
- Dissemination of knowledge and awareness-raising about the impact of climate change on our heritage among national, regional, local authorities, private sector (e.g. insurance) and citizens.

4.3. Training

4.3.1. Building scientific capacity

Public opinion, especially young people, is acutely aware of global climate change issues, particularly as a result of recent extreme events (storms, cyclones and tornados, floods, heatwaves, avalanches and landslides), which have received intense media coverage. In spite of this, there is less awareness of the specific character of the risks threatening cultural heritage. This is reflected also in the teaching and training of future conservators, restorers and researchers in the field and the remanents of reluctance in teaching of the physical and chemical sciences required to those who have been educated in the arts. . Therefore, there is an urgent need to introduce specific teaching concerning the issues of cultural heritage facing climate change in university syllabuses and in courses at schools providing specialised training for related professions, in particular those of architects, engineers, curators and conservators responsible for historic monuments.

Likewise, the organisation of periodic or permanent advanced training schools could be one of the specific actions of the Council of Europe, in parallel to those of the European Commission which is more focused on scientific research.

Another stimulating action of the Council of Europe could be the creation of an award dedicated to the protection of cultural heritage against climate change.

4.3.2. Knowledge transfer to practice

The transfer of knowledge must be increased because practitioners need to be able to convert research into practice, with support of protocols and directives. Cultural heritage is neither prepared nor adapted to our future climate. Information is necessary on how to make it more resilient to future disasters and how to survive them.

Few routes exist for disseminating this type of knowledge and there are few suitable journals in the area, which are not widely read by practitioners. There is a particular need to develop novel modes for transferring knowledge to practitioners.

Specialists are required in order to facilitate attenuation of climatic effects and explain adaptation to climate change. They are also required to extend appropriate management procedures to historic monuments, archaeological sites, landscapes and gardens. In the future such procedures must become routine.

5. REFERENCES

Blades, N., Cassar, M., Biddulph. P., 2008: Optimizing Dying Strategies to reduce Down Times for Actively-used Flood Damaged Historic Buildings. In: Saunders, D, Townsend, J.H, and Woodcock, S, editors. *Conservation and Access Contributions to the IIC London Congress,* 15-19 September 2008

Brimblecombe P., Grossi C.M., Harris I., 2006: Climate change critical to cultural heritage. *in*: Fort R, Álvarez de Buergo, M, Gómez-Heras C, Vázquez-Calvo C, editors. *Heritage, Weathering and Conservation.* Balkema, Rotterdam, 387-393.

Brimblecombe, P., Grossi C. M., Harris I., 2007: Future trends in surface wetness and relative humidity and potential impact on materials, *Pollution Atmosphérique*, n° spécial « Effets de la pollution atmosphérique sur les matériaux », 95-100.

Cassar, M., 2005: Climate Change and the Historic Environment. *University College London, Centre for Sustainable Heritage,* 98 p. http://eprints.ucl.ac.uk/archive/00002082/01/Published_Climate_Change_Report_05.pdf and

Cassar, M., Hawkings, C., 2006: Engineering Historic Futures Stakeholders Dissemination and Scientific Research Report, *University College London, Centre for Sustainable Heritage,* 158 p. http://www.ucl.ac.uk/sustainableheritage/ehf_report_web.pdf

Grossi, C.M., Brimblecombe, P., 2007: Effect of long-term changes in air pollution and climate on the decay and blackening of European stone buildings, in *Building Stone Decay: from Diagnosis to Conservation*, Prikryl, R; & Smith, B. (eds), Geological Society, London, Special Publications, 271, 117-130.

Grossi, C. M., Brimblecombe P., Harris, I., 2007: Predicting long term freeze-thaw risks on Europe built heritage and archaeological sites in a changing climate, *Science of the Total Environment*, 377, 273-281.

IPCC: *Climate Change Assessment Reports:* 1 (1990), 2 (1995), 3 (2001), 4 (2007) http://www.ipcc.ch/ipccreports/assessmentreports.htm

Lipfert, F.W., 1989: Atmospheric Damage to Calcareous Stones. Comparison and reconciliation of recent experimental findings, *Atmospheric Environment,* 23, 415-429.

Noah's Ark, 2004-2007: *Global Climate Change Impact on Built Heritage and Cultural Landscapes,* European Commission Project n° SSPI-CT-2003-501837. http://noahsark.isac.cnr.it.

Noah's Ark, 2007: *Global Climate Change Impact on Built Heritage and Cultural Landscapes, Vulnerability Atlas* (124 p.) *and Guidelines* (87 p.), Noah's Ark Project Final Int. Meeting, Rome, unpublished. http://nohasark.isac.cnr.it/deliverables.php

Sabbioni, C., Cassar, M., Brimblecombe, P., Tidblad, J., Kozlowski, R., Drdacky, M., Saiz-Jimenez, C., Grontoft, T., Wainwright, I., Arino, X., 2006: Global climate change impact on built heritage and cultural landscapes, in *Heritage, Weathering and Conservation,* Fort, Alvarez de Buergo, Gomez-Heras & Vazquez-Calvo (eds), Taylor and Francis Group, London, 395-401.

UNESCO, 2007: Climate Change and World Heritage, *World Heritage Centre Centre du Patrimoine Mondial,* Paris, Rapport n° 22, WHC-06/30.COM/7.1, 55 p. http://whc.unesco.org/en/climatechange/

UNESCO, 2008a: Case Studies on Climate Change and World Heritage, *World Heritage Centre,* CLT-2008/WS/6, Paris. http://whc.unesco.org/en/climatechange/

UNESCO, 2008b: The impacts of climate change on world heritage properties, *World Heritage Centre,* WHC-06/30.COM/7.1, p. 24, http://whc.unesco.org/en/climatechange/

UNESCO, 2008c: Policy document on the impacts of climate change on World Heritage Properties; *World Heritage Centre*, CLT-2008/WS/6, Paris, 32 p.. http://whc.unesco.org/en/climatechange/