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Climate change critical to cultural heritage

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ABSTRACT: Although modellers have established the type of climate expected in Europe over the coming century, they have not been concerned with the combination of meteorological variables most important to building damage. We have identified the climatic parameters most likely to be critical for architectural surfaces and structures. They have been loosely grouped as: (1) Temperature derived parameters – range, freeze thaw, thermal shock (2) Water derived parameters – precipitation, humidity cycles, time of wetness (3) Wind derived parameters – wind, wind driven rain, sand and salt. We also looked at pollution derived parameters such as SO_2, NO_2, elemental carbon and pH, but neglect these in this analysis which focuses on a European situation with much reduced air pollution forecast for the future. As expected a future Europe will experience less frost damage to porous stone, although higher temperatures can enhance fungal growth on wood. Drier summers seem likely to increase structural problems from desiccated soils and salt weathering of porous stone. Our work hint at likely heritage management strategies for the future.

1 INTRODUCTION

Our built heritage is exposed to the atmosphere over long periods of time. This means that it is exposed to changes that occur on long timescales and accumulated damage from this exposure. The very choice of the term weathering to describe damage to buildings reflects the view that climate is a key factor in damage, despite the fact that the earliest uses of the word in the 1500's tend to reflect the positive benefits of exposure to weather or a sense of drying. However, architects and geologists, saw the more negative aspects of weathering in its ability to wear and disintegrate, such that three hundred years ago architects were convinced that buildings were destroyed by "time, smoke and weather" (Brimblecombe 2000).

The blackening effect of air pollutants had long been known and the poet Horace was able to write in his *Odes and Carmen Saeculare* of the temples of Ancient Rome:

> "Your fathers' guilt you still must pay,
> Till, Roman, you restore each shrine,
> Each temple, mouldering in decay,
> And smoke-grimed statue, scarce divine"

John Evelyn in17th C London wrote in detail in his book *Fumifugium* (1661) of the damage that air pollution causes to our monumental heritage. The adoption of coal as a fuel led to increased concentrations of sulfur dioxide in urban atmospheres and from the 17th century there were complaints of the way this damaged stone buildings. Sir Christopher Wren claimed that the sulfate encrustations on London buildings were inches thick in places. Coal became widely adopted as the main fuel across Europe in the centuries that followed (Brimblecombe 1999) such that these sulfate layers became ever more widespread.

The 20th century saw a profound shift in the nature of urban air pollution. The adoption of the private automobile increased the concentration of volatile organic compounds in urban air and as coal was replaced by gas and electricity in cities it declined. Governments adopted increasingly well structured environmental regulations, perhaps beginning with the *UK Clean Air Act* (1956) through to the European Union's *Air Quality Monitoring and Management Directive* (1996). Although this legislation derived from health concerns, there are doubtless benefits for building materials from the reduced pollution loads. The reduction in sulfur dioxide concentrations in urban air that paralleled the declining use of coal has reduced the damage from acid gases and the production of gypsum layers (Brimblecombe 2000).

The urban fabric still shows dark damage layers, but these are increasingly the result of soot from diesel engines (see Bonazza et al. 2006, Grossi et al. 2006).

These layers show the potential for a level of organic chemistry and biological activity that was not known in sulfur dioxide dominated atmospheres. Despite the potential for novel chemistry in dark crusts on buildings in the 21st century, the role of pollution in building damage is likely to be much reduced. There is evidence that erosion rates in the last decades of the 20th century in major cities such as London were much reduced (Trudgill et al. 2001).

Reduction in the damage from gaseous air pollutants and a decrease in some components within acid rain have meant that climate factors, which have hitherto been largely ignored, may become more important determinants of building damage. This is not to say that the potential impacts of frost, rain or wind have not been appreciated, but the changing balance of these factors as a result of climate change have largely been ignored. Buildings have to survive centuries such that they will confront increasing changes in climate. Historic buildings were designed to confront a climate very different from those in the future. Some of these problems have been of interest to a project *Engineering Historic Futures* coordinated by the University College London's (UCL) Centre for Sustainable Heritage (Cassar 2005). In the UCL project, the difficulties faced in managing historic buildings, archeological sites and parks and gardens. The report noted many different concerns although the increased frequency of heavy rain or flooding was a general worry.

The European project NOAH's ARK (http://noahsark.isac.cnr.it/) aims to assess the overall risk posed to monumental heritage by climate change. The project title alludes to the biblical story regarding the protection of what we value in times of great climatic stress. It is a broad project that intends to go beyond academic researchers to include practitioners and additionally the insurance industry, which has to confront the costs of climate in a very direct way. The project has excited considerable interest in the media because it seems to include threats that the public find real. This has ranged from worries about the effect of increased rainfall on the traditional English pub with its thatching and wattle and daub walls, through to concerns about climate impact on icons such as the Eiffel Tower in Paris or the *Torre del Oro* in Seville.

As welcome as such media attention has been, the project has broad interests that go beyond concerns over individual monuments. This is because the project is concerned with the pressures on European monumental heritage as a whole. Individual monuments are of course, exemplars of the processes that may be underway in the future, but these sites are not the focus of our study. The output from NOAH's ARK will be a damage atlas for Europe, often couched in terms of risk to particular materials: stone, brick, clay rich materials, metals and wood.

Table 1. The meteorological parameters thought critical in the NOAHs ARK project. Subdivided into groupings – in temperature, water, wind and pollution derived parameters.

Parameter	Definition and meteorological parameter
Temperature	1. range: $\max(T_1..T_n) - \min(T_1..T_n)$; T = daily mean 2. thermal shock:$(T_{max} - T_{min}) > X°C$; Counts for X = 7, 10, 15, 20 3. mean: $\text{mean}(T_1..T_n)$; T = daily mean
Freeze-thaw cycles	1. number of freeze-thaw cycles: Cycle (1 cross) $T(i) > 1$ ^$T(m) < -3$ ^ $T(n) > 1$ i,n,m are intervals of time 2. Frost damage: Crack length ~ $-0.14\ T^2 - 2.54T- 8$, where T $-4°C <T> -15°C$ and Fr Frost Index : $I_g = \Sigma_0^{360.30} T\ (-5)/30$
Sun hours	1. mean: mean $(S_1..S_n)$, S = daily sun hours
Precipitation	1. rainy days: Consecutive number of rainy days, (>0.1 mm): days of rain/time period 2. Extreme events: Z (mm/t) >200 mm /day 3. sum of precipitation
Relative humidity	1. range $RH_{max} - RH_{min}$ 2. mean RH
Humidity cycles	1. number of cycles crossing RH = 75% 2. daily RH shocks (RH(n) − RH (n + 1) > 25%
Wind	1. Wind speed : mean $(W_1..W_n)$; W = daily mean 2. Wind direction: Distribution of daily directions for 8 compass points 3. Extreme events: days v > 7.5, 10, 15, 20 m/s
Wind driven rain	1. v.p; where v = wind speed; p = amount of precipitation (daily)
Wea salt	1. salt deposition inland wind speed (see wind)
Gas (SO_2, NO_x), particulate	1. stone recession by dissolution of carbonate 2. blackening of materials 3. corrosion of metals 4. influence on bio-colonisation
pH precipitation	1. stone recession by dissolution of carbonate: Modified Lipfert function: Carbonate Stone = f (solubility of Calcite in equilibrium with $[CO_2]$, rain, $[H^+]$)

The changes examined in the project can in principle be subdivided into the following main categories (see Table 1):

- Temperature derived parameters: Range, freeze thaw, thermal shock.

- Water derived parameters: Precipitation, humidity cycles, time of wetness.
- Wind derived parameters: Wind, wind driven rain, wind driven sand, salt.
- Pollution derived parameters: SO_2, NO_2, particulates and pH – largely neglected in this paper.

2 MODELLING THE FUTURE

Past climate change can be examined by looking at the long term records collected by meteorologists over the last three to four hundred years. We have drawn on a range of older data sets, although for convenience have used the daily records from central England (Parker et al. 1992) and Prague most closely. Estimates of future climate of the 21st century is increasing available from modelled output. This allows us to consider the changes in a wide range of meteorological parameters often on a daily basis. In the current study we have relied mostly on output from the Hadley model (HadCM3, a coupled ocean-atmosphere global circulation model from the UK Hadley Centre, 'see for example Johns et al. 2003). We have paid particular attention to the modelled grid cell that covers central England – stretching from the Welsh borders to the eastern coast of England and includes London. This was chosen to represent a maritime climate. Additionally we have looked in detail at a grid square in the Czech Republic, that includes Prague, and represents a more continental climate. The HadCM3 grid, typical of global models is coarse (2.5 × 3.75 degrees), so the grid squares examined here cover a large area.

It is possible to examine the regional output from the HadRM3 model, but this covers a shorter time period (2070–2099) although at a finer spatial scale. The regional model output includes topography, increasing the validity of individual cell predictions. Most of the discussion here relates to the output from the global model.

Our analysis of future trends has relied mostly on the A2 scenario (IPCC SRES Emissions Scenarios – Version 1.1 – July, 2000). This scenario describes a very heterogeneous world in which the underlying theme is that of strengthening regional cultural identities, with an emphasis on family values and local traditions, with high population growth. It gives pronounced changes in future climate, so should result in strong signals in terms of future pressures on architectural heritage, that allows us to consider problems likely to be most critical. The daily output from HadCM3 has been used here to calculate the specific values required to assess the potential for material damage in Europe.

3 TEMPERATURE DERIVED PARAMETERS

Temperature is the most obvious parameter that will change in a world with greater greenhouse warming.

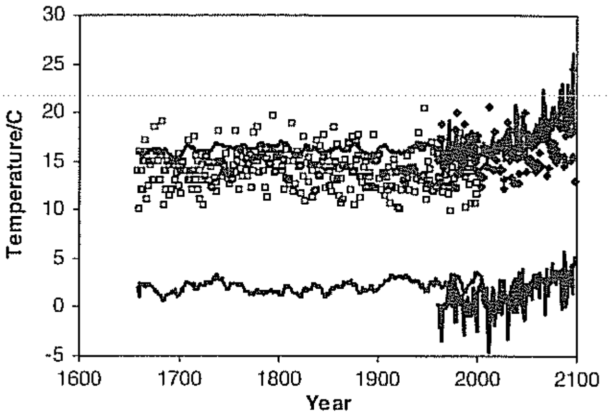

Figure 1. Long term monthly maximum and minimum temperature and annual temperature range in central England. The historical temperature range is marked by open squares and the range predicted from the Hadley model is in closed diamonds. The historical maximum and minimum values are shown as a smoothed line (11 year running mean). The Hadley model annual predicted values are shown by the jagged line.

Nevertheless temperature changes are often likely to be only a few degrees, so it is necessary to consider ways in which these relatively small changes are likely to affect building materials.

One of the rather slow changes in temperature that has the potential to affect large buildings is the annual seasonal change. Such structures can change in response to this annual cycle as a kind of breathing of the building. We have examined the annual temperature range as shown in Figure 1 for central England both from the period of historical instrumental measurements through to the modelled data that ends in 2099AD.

What we see from this figure is that although both summer and winter extremes in the monthly temperature increase in the future, the annual temperature range buildings experience remains fairly constant. Although our analysis is not complete for the rest of Europe, similar pictures of a relatively small change in the annual range over the next century becomes apparent. One should note the Hadley Model predictions for the minimum monthly temperature are rather lower than found in the overlapping historical record. This is probably the result of the warming effect of the North Sea not being well represented in the Hadley Model.

Frost is an important source of damage to wet porous building stone. Freezing leads to substantial volume changes that induce mechanical stresses in the outer layers of the stone. There are a number of ways of estimating the potential for frost damage, but here we adopt a very simple one and suggest that the damage would be related to the number of freeze-thaw cycles. These have been determined by examining the daily data from the Hadley Model output for points where

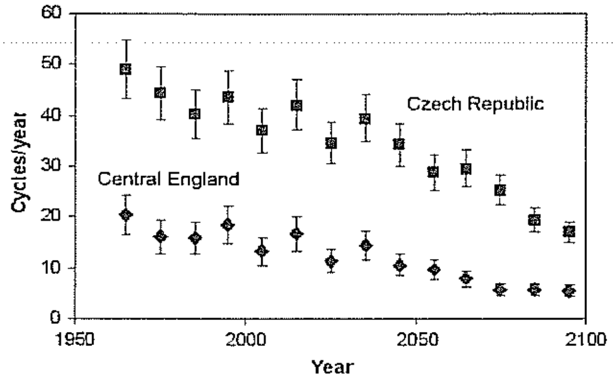

Figure. 2. Number of freeze-thaw cycles each year as predicted for Hadley grid squares representing the Czech Republic and central England. The values displayed are decadal averages.

the temperature crosses 0°C between one day and the next (see Fig. 2). More sophisticated approaches are possible. As seen in Table 1, we are interested in transitions between 1 and −3°C, but are also examining the particular temperatures reached and note in particular that crack propagation is especially important at about −10°C (Walder & Hallet 1985).

Figure 2 shows that the number of freeze-thaw cycles is likely to decrease in much of Europe in the future. It is also clear, the milder climate of England is subject to less freeze-thaw events throughout the period. In the far north, although there is a lower density of monuments, archeological sites are likely to experience an increase in the number of freeze-thaw cycles. This is a potential problem as it can perturb middens. At Narssarssuaq in Greenland early calculations from the Hadley Model suggest a four fold increase in the number of days above freezing.

There is a very significant change in the number of freeze-thaw cycles during a period when the average temperature changes only slightly (just a few degrees). This emphasizes the way in which small changes in a meteorological parameter can be amplified and have large effects on materials. In a similar way crops can be very sensitive to temperature, such as the length of the growing season, and also the amount of freezing, so there are also biological mechanisms for amplification.

Thus subtle changes of a few degrees increase in temperature or small percentages in precipitation might be able to affect buildings. Freezing and thawing is important because it represents a process where a phase change occurs at an exact temperature. Later we will see that phase changes induced by humidity can also be very sensitive to small shifts in climate. Overall Figure 2 suggests that increasing winter temperatures may make frost damage less frequent in future mild climates such as that of Britain (Brimblecombe 2000).

The temperature change on a greenhouse Earth might also be accompanied by an increase in solar irradiation. This may accelerate deterioration of organic materials such as paint coatings or materials used for consolidation of stone. Although the concentrations of 'traditional' air pollutants have declined, changing climate could enhance their effects: e.g. changes in wetting and drying cycles on building surfaces alter the deposition rate of acidic gases, longer sunlight hours increase photochemical degradation of polymers (e.g. as restoration elements).

The influence of temperature on the deterioration process for some materials, such as metals, is complicated. At low temperatures the deterioration rate increases with increasing temperature due to prolonged time of wetness. For some metals a maximum rate is followed by a decrease of the corrosion observed above about 9–11°C. However, this decrease is partly attributed to the faster evaporation of moisture layers after rain or dew periods. Additionally surface temperatures above ambient resulting from solar radiation reduce the time of wetness. It should however be mentioned that this phenomenon is not observed in marine locations where due to the presence of a surface moisture layer of hygroscopic chlorides. Here no maximum in the deterioration rate has been observed.

4 WATER DERIVED PARAMETERS

As we have seen in the section above temperature can also influence some aspects of the water balance and humidity relations of outdoor materials. The hydrometeorological parameters relevant to changing impacts on cultural heritage include: extreme precipitation events (a difficult parameter to predict, yet critically important in terms of predicting storm damage), saturation of soils and water loading on roofs and other architectural elements. For most materials an increasing relative humidity causes an increase in the deterioration due to a prolonged time of wetness, higher deposition rates of pollutants and more favorable conditions for microbiological activities.

The Hadley model suggests rainfall in general is often likely to decrease slightly in Europe over the next century, particularly in the summer months. However, this potential for drier summers may be a little of an illusion in terms of cultural heritage. If we look at the predicted maximum daily rainfall we find the future looks as if it may have individual days that are much rainier. Figure 3 shows that number of days each year with large amounts of rain (>10 mm) is to increase.

The frequency of very rainy days is predicted to increase over the next century. Predicted maximum daily rainfall amounts also increase, although these are not illustrated here as extreme events are more difficult to represent in the Hadley model. These heavy falls of rain in the future are likely to overload roofs and guttering and have the potential to cause local

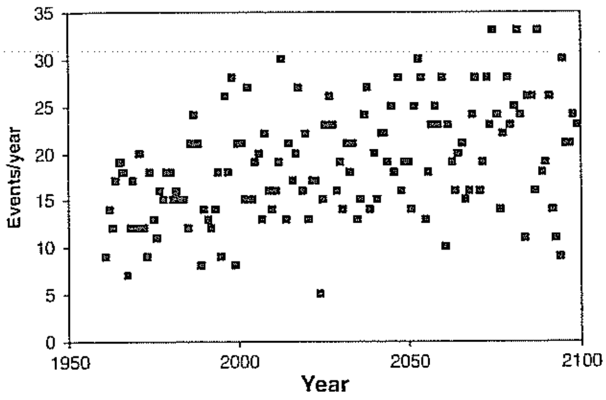

Figure 3. The number of heavy rain events (>10 mm) each year in the Czech Republic as predicted by HadCM3.

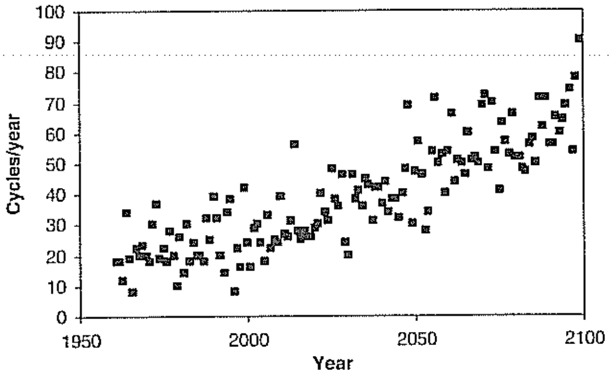

Figure 4. The number times each year the relative humidity crosses the 75.5% value as predicted by HadCM3 for the Czech Republic.

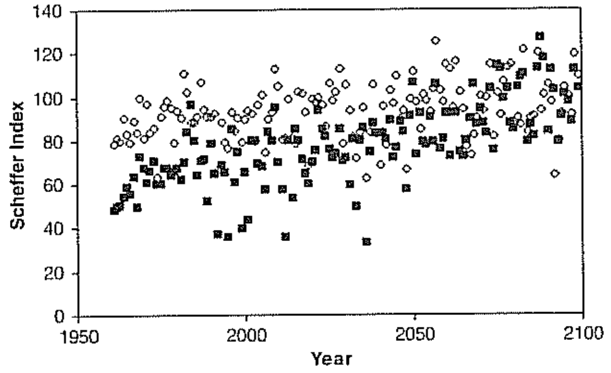

Figure 5. The Scheffer Index for fungal attack as predicted for Hadley grid squares representing the Czech Republic (closed squares) and central England (open diamonds).

surface flooding. These represent an important threat to the built heritage in the future. It may be a particular problem for vernacular architecture constructed on unfired materials such as wattle and daub, adobe or cob.

Precipitation can also affect the damage caused by wet deposition by dissolution of surface layers of materials. Erosion and delivery of acidity are important aspects of the role played by precipitation. Changes in the chemical composition and especially pH, can affect the deterioration rate of building material also.

We have already stressed that summers may have less precipitation. This also extends to relative humidity which is likely to be lower and changes the range of relative humidity cycles. Stone is especially vulnerable to relative humidity cycles. This arises because of damage caused by hygroscopic salts as they oscillate between high and low humidity. Lower humidity in the future means that the daily variations in humidity are more likely to cross critical values such as the 75.5% humidity where sodium chloride changes from a solution to a crystalline state. Figure 4 shows the number of times each year that humidity is likely to cross the critical 75.5% value that causes a phase change in sodium chloride in porous stone.

This suggests a significant increase in these phase changes in the Czech Republic over the next century. The picture for central England is almost identical and these observations illustrate a potentially important and dramatic change in the rate of salt damage from sodium chloride. As with freezing we see once again that significant changes in damage to materials can be induced where there are phase changes. These occur at discrete values of temperature or relative humidity. Thus even slight changes in climate can allow these temperature or relative humidity values to be crossed more or less frequently. We saw earlier that the frequency of freezing is likely to decrease substantially in most places in Europe, even though the winter temperature change is only a few degrees. Similarly just small decreases in relative humidity can cause a large change in the number of time salts will crystallize or redissolve.

However, drier summers might be favorable in reducing the time that building surfaces are wet, which could reduce the potential for pollution damage. Time of wetness has long been recognised as an important parameter in the action of pollutants such as sulfur dioxide. Humidity is also important in the degradation of organic materials, especially where biodeterioration is involved, with the Scheffer index- as a possible indicator of biological attack on organic materials (Wilcox & Dietz 1997). The Scheffer index, which is the sum of the monthly temperature minus twice the number of wet days minus three, divided by an adjustment factor of 16.7 (i.e. $\Sigma(T-2)(Dw-3)/16.7$). Figure 5 shows the change in the Scheffer Index for fungal attack for the Czech Republic and central England over the coming century.

Increasing temperatures and lower rainfall rates in future summers imply increased evaporation and a reduction in soil moisture content. Drier conditions also suggest that the desiccation of unfired building materials could become an important concern. This may also have structural implications for building foundations and archaeological sites. Lower water tables are being noted by archaeologists (Sauer 2005). When soils dry materials such as wood, which were waterlogged dry out and degrade very rapidly.

5 WIND DERIVED PARAMETERS

In gales stresses can cause elements of buildings to fail. Towers blow down and windows fall inwards. High winds blow rain almost horizontally and this wind driven rain can drive water deep into the fabric of buildings. In the same way close to the coast salt can be driven inland or in some areas abrasive sand can saltate and erode materials. These processes are complicated by the need to consider local winds, which are poorly predicted by existing large-scale models.

Changes in winds also alter the eddies and flows around historical buildings and can increase the deposition rates of both gaseous and particulates pollutants. This when combined with rain can redistribute deposited diesel soot on facades and disfigure the building.

Our initial analyses on a broad European scale have indicated only small changes in wind driven rain over the next century. However, it is likely that the relevant changes are being hidden by the coarse scale under consideration in HadCM3. One of the teams in the NOAHs ARK project is examining the effect of winds on towers, which may reveal the importance of changes in this parameter at a fine scale.

6 CONCLUSIONS

The NOAHs ARK project assumed a decline for much of Europe in the concentrations of SO_2, NO_2, O_3, HNO_3 and both primary and secondary particulates over the next century. A part of the project will test the validity of this assumption and see if the predicted pollutant concentrations will have effects under new climate regimes.

In the early part of the project it became clear that temperature changes appeared not to have especially critical impacts on cultural heritage as even when temperature effects were amplified through freeze-thaw cycles these would be much reduced in the future.

The early studies within the project have emphasized the importance of amplification mechanisms that allow quite small changes in temperature or relative humidity to significantly change the rate of damage to material. In particular we identified processes that are induced by phase change as important amplification mechanisms for heritage.

The work draws also attention to the need for us to construct more sophisticated climate parameters. As an example we have been exploring the future frequency of what we have termed *wet-frosts*. A wet-frost occurs when porous stone is saturated by significant rainfall only to have a freezing event on the following day. Our early analysis suggests there are some regions of Europe, perhaps around the Black Sea where this may increase across the next century.

Hydrometeorological parameters seemed likely to be more critical and we noted both increased heavy rainfall as critical for increased surface flooding and loading on roofs. Furthermore dry summers looked likely to increase the impact of humidity cycles (via salt crystallization) and potentially drying out unfired building materials and soils.

So far our work has gathered modelled output that suggests changes in meteorological parameters that are of importance to cultural heritage. However, these changes need to be translated into rates of future material damage and then to risk if the work is to be useful to managers and policy makers. Furthermore the output needs to be displayed as user-friendly maps of future damage in Europe rather than analysis of individual grid squares from the Hadley Model that have been adopted here.

ACKNOWLEDGEMENTS

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