Effect of Climate Change
on Built Heritage

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Effect of Climate Change on Built Heritage

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Table of Content

Preface

WTA-2010 Colloquium - Effect of Climate Change on Built Heritage

When (according to the legend) in August of the year 356 snow was falling in the eternal city of Rome, this was not considered a result of climate change, but a miracle and the pope decided to built a church, whose plan he was able to draw in the freshly fallen snow. The church, Santa Maria Maggiore -also named Santa Maria ad Nives (of the Snow)- is one of Rome's most important basilicas……

Climate change can be defined as a change in the average climate (more specifically the average temperature and precipitation) over a certain period. And, looking at climate data, it is clear that our climate indeed has changed during the 20th century.

Since the beginning of the 20th century average global temperature increased with 0.74 °C. For the Netherlands the increase since ca. 1950 was even much faster. IPCC, the Intergovernmental Panel on Climate Change attributes the increase in temperature to human activities, more precisely to the production of greenhouse gases. Model calculations have predicted a temperature rise of 1.1 to 6.4 °C from 1990 to 2100. This prediction implies enormous changes for man and environment, amongst others desert formation on one hand and changes related to sea water level and landslides on the other hand. With nowadays already 15-20% of the country located under sea level, it will be clear that consequences for the Netherlands could be enormous.

Although there is little doubt about the fact that the climate has changed indeed, the debate has become quite polarized on the causes of change. There is a majority view, as expressed by the IPCC reports, which clearly points at greenhouse gases as the main cause of global warming; a scientific minority has doubts and gives alternative interpretations of the facts. The relative slowing down if not even decrease of global warming over de past 10 years (2000-2010) is still not fully understandable on the basis of IPCC models. As the debate is further confused by possible political and/or economical interests it is clear that we are facing a rather difficult matter.

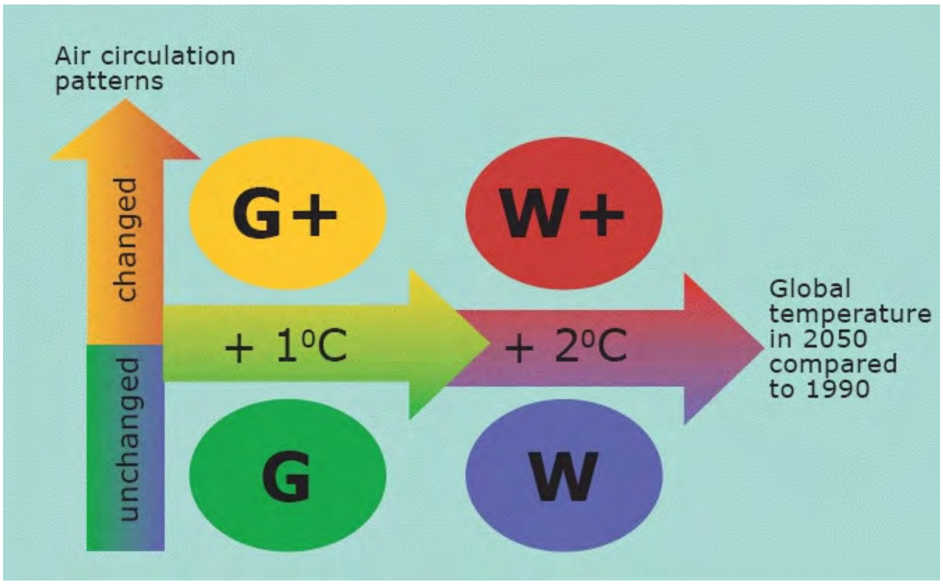
Internationally the Kyoto Protocol urges governments to reduce CO_2 production and the Kopenhagen Climate Conference of 2009 should have renewed both protocol and criteria. After the political discords that have prevented the establishment of a new climate agreement in Kopenhagen, very recently even IPCC reports have come under fire because of mistakes like the one on the melting Himalaya glaciers.

Whatever the causes of climate change may be, most scenario's of future climate change still show clear effects in next decennia in terms of temperature, precipitation, etc.. Resulting changes in exposure conditions would certainly affect building materials and, by consequence the need of understanding of the impact on the built cultural heritage. We may expect growing importance of preventive conservation, in order to deal with this impact in a cost effective way. Preventive conservation is the systematic maintenance and monitoring of a monument stock in a sustainable way, in order to prevent expensive technical restorations.

WTA considered the effects of climate change to the built cultural heritage a very actual and important theme and therefore has decided to dedicate this year's international WTA colloquium to this theme.

Important contributions will be given by international experts in this field and will range from History of climate change and the results of the EU project Noah's Ark to Impact on indoor climate and Damage development due to increased salt load of materials. Apart from these, also contributions on subjects like Production of low CO_2 binders for mortars and concrete form part of the discussion WTA would like to stimulate on the theme of Climate Change.

Prof. Rob P.J. van Hees
Chairman WTA NL-VL



Chapter 1: Climate Change and Cultural Heritage - General Approach

"Effect of Climate Change on Built Heritage",
WTA-Colloquium, March 11-12, 2010, Eindhoven, The Netherlands,
WTA-Schriftenreihe, Heft 34, 3–4 (2010)

Climate Change in Europe

Arie Kattenberg
The Royal Netherlands Meteorological Institute, De Bilt

Abstract

This contribution deals with the process of global warming according to the Intergovernmental Panel on Climate Change (IPCC). Based on different scenarios defined by working groups of the IPCC global climate projections have been calculated. Selected results of these calculations are presented and discussed in this presentation. In a second part regional climate projections are given which shows uncertainties. Finally, scenarios are presented in which is predicted what could happen in Europe with a view on the „Built Heritage".

Arie Kattenberg,

Arie Kattenberg studied mathematics, physics and astronomy at Utrecht University. In 1981 he obtained his PhD in Utrecht, defending a thesis in the field of solar astronomy. In 1983 he became climate researcher at KNMI. He specialized in climate research using computer models, initially aimed at understanding the El Niño phenomenon (rapid climate oscillation in the tropics), later more generally investigating the role of the oceans in the climate system. At the end of the 1980ies and in the early 1990ies he developed a computer model for the upper, wind stirred 'mixed layer' of the oceans.

In 1994 Kattenberg was detached to the secretariat of IPCC working group I (which has the physics of the climate system as topic) in the Uk, to work as editor and lead author on the Second Assessment Report of IPCC, which was published in 1995. In the end of the 1990ies Kattenberg was involved, on behalf of KNMI, in the 'climate debate' in the Netherlands, a.o. with the Parliamentary Investigation lead by politician Middelkoop.

Between 1999 and 2006 dr. Kattenberg was 'Head International Relations' of KNMI, involved in the international organisation of world meteorology.

Recently Kattenberg became involved in climate research again, and as climate policy adviser he is now responsible for the 'marketing' of the expertise and knowledge on climate of the KNMI.

"Effect of Climate Change on Built Heritage",
WTA-Colloquium, March 11-12, 2010, Eindhoven, The Netherlands,
WTA-Schriftenreihe, Heft 34, 5–16 (2010)

Historical Records as Evidence in the Climate Change Debate

Christian Pfister
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Abstract

Our knowledge of pre-instrumental temperature trends in Europe has considerably improved over the last two decades thanks to several EU projects of which the 6th Framework Program Integrated Project "Millennium" - European climate of the last Millennium" is the latest. In the context of this program Dobrovolny et al presented calibrated monthly temperature trends for Central Europe from documentary evidence over the last 500 years. Luterbacher et al. succeeded in producing spatial reconstructions of temperature and air pressure for the whole of Europe back to 1500 on a seasonal and back to 1659 on a monthly basis. Some ten years ago, changes in the frequency and severity of pronounced extremes for Switzerland back to 1500 were analysed. Results for the medieval period back to about 1170 are far more limited according to the sparsely of the documentation and the higher effort for its interpretation due to uncertain dating. Provisional reconstructions include pronounced warm and cold anomalies back to about 1170 based on documentary and tree-ring data which include the so-called Medieval Warm Period.

Our knowledge of past precipitation is far more limited for two reasons: Firstly, EU programmes did so far focus on temperature and secondly, patterns of precipitation are spatially far more limited than those of temperature and would require a much higher density of evidence. At least, extreme patterns of drought and wetness are known back to the Middle Ages. In this presentation long term trends and extremes of monthly and seasonal temperature, both cold and warm (-dry), are outlined in order to point to the maxima and minima that are so far documented. Examples of effects on building structures will be demonstrated from case studies of extreme floods and severe windstorms. In order to deal in some more depth with the issue of climate damages to built heritage climate historians would need more specific information on effects which are known to be particularly damaging.

Christian Pfister

Christian Pfister studied history and geography (M.A.) at the University of Bern and in 1974, completed his PhD in history. In 1982, he finished his Habilitation (postdoctoral lecture qualification) at the University of Bern's Institute of History and became associate professor and then extraordinary professor at the Institute of History. After working as a research professor for environmental and climate history at the Swiss National Science Foundation, he now is professor for economic, social and environmental history at the Institute of History.

Pfister has led numerous projects in climate and disaster research, e.g. the work package "Climate Risks " of NCCR Climate (2005 - 2008) and a work package within the 6th EU framework programme's project "Millennium - European Climate of the last Millenium" (2006 - today). From 2006 he has also been a member of the "Scientific network for the investigation of historical disasters across cultures" (funded by Deutsche Forschungsgemeinschaft DFG). In 2000, he was awarded the Eduard Brückner-Award for interdisciplinary achievements in Climate History.

He has published more than 220 articles in books and journals on population, climatic change, nature-induced disasters, agrarian, forest, environmental and population history. Furthermore, he has published 5 monographs and 11 (co-) edited books, e.g. Mauch, Christof / Pfister, Christian (Ed.): Natural disasters, cultural responses: case studies toward a global environmental history. Lanham 2009.

1 Introduction

The forces of nature remain unnoticed by the general public until they disrupt its daily routines. The scientific world is then expected to integrate extreme events into a larger system and give its interpretation of them. Historical records have a very important role to play in this context. The climate of the past has left its traces all over the globe, and these are researched by many scientific disciplines. Historical climatology mainly assesses data from anthropogenic archives, which contain two types of information:

- Direct data, including qualitative descriptions of the weather and, from the late 17th century, early measurements using instruments
- Indirect data, also referred to as proxy data, i.e. quantifiable descriptions of biological or physical occurrences that act as climate indicators

2 Historical climate observations in Western Europe

In Western Europe, climate observations from historical documents date back to Carolingian times (approx. 800). Thanks to the scope, completeness, and temporal resolution of this material, the 1,200 years down to the present day can be divided into five periods:

Figure 1: The oldest British weather hut in Antarctica (Port Lockeroy).

1. Before 1300: mainly descriptions of anomalies and natural disasters. The more extreme an event, the more frequent and detailed the accounts we have.
2. 1300–1500: nearly continuous description of weather conditions in summer and winter, sometimes in spring, rarely in autumn.
3. 1500–1800: virtually complete description of the weather month by month, and day by day in places.
4. 1680–1860: measurements using instruments on an individual basis; the first short-lived meteorological networks.
5. Since 1860: instrument measurements within the scope of national and international meteorological networks.

The older data types were overlaid by more recent ones, though not entirely supplanted. The following is a brief introduction to the evidence.

Records of daily weather were given a boost from the close of the 15th century on thanks to the rise of astronomy, which became the leading branch of science, and to the invention of the letterpress. Astronomical calendars looked forward one to two decades and presented calendar data and the pre-calculated positions of the planets for each day. Each month was given a double page, the right-hand page having one line left empty for each day. In these empty lines, personal notes were made, including brief weather observations. From the 16th century, 33 such weather diaries are known for central Europe. Starting with the 17th century, the weather descriptions became more detailed (cf. p. 29). Weather diaries can be analysed by counting and averaging phenomena like rain, snow, and frost and comparing them with the corresponding average values of nearby meteorological stations. A few years ago, within the scope of the EU project CLIWOC, work started on a methodical evaluation of shipping logbooks, which usually contain systematic observations of wind direction and weather. Thousands of these exist. The CLIWOC database mainly covers the region of the North Atlantic for the period between 1750 and 1850.

Most authors of chronicles and weather diaries were aware that their description had a subjective tinge. In order to improve the inter-subjective and inter-temporal comparability of their data, they wove into their descriptions observations of natural phenomena which were known climate indicators. In the warmer half of the year, these included particulars on the quantity and the sugar content of must and observations on the flowering and harvest times of (cultivated) plants. Placidus Brunschwiler, the abbot of Fischingen Monastery (Canton Thurgau), for example, describes the summer of 1639 as follows: “In the month considered here [May], until the 17th day of August, there was hardly ever a really warm day, but more rain and cold winds, so that we did not harvest hay and corn until the 17th day of August, which is usually done around St James’ Day [25 July].” A grain harvest delayed by three-and-a-half weeks was shown for the instrumental measurement period only in the “year without summer” (1816) > Smolka, p. 50, so that this points to a temperature anomaly on the same scale for 1639.

Figure 2: Mercury thermometer according to Réaumur, 1780: The oldest instrumental measurement series commence in the second half of the 17th century. From the second half of the 18th century on, meteorological instruments spread quickly. This thermometer, made in Mannheim in 1780, has a scale based on that of the French physicist René-Antoine Réaumur: water freezes at 0°C and boils at 80°C. Today's Celsius scale has been used in Germany since 1924. .

In the winter months, the common climate indicators were snowfall frequency, the duration of snow cover, the time and duration of ice cover on bodies of water, the occurrence of frost, and – in warm winters – the activity of flora and fauna. Recordings of annually recurring events in the winter months were less frequently systematic: since the late 15th century, the books of the city of Tallinn, Estonia, have recorded the day on which the first ship entered its port after the ice cover thawed in spring. Using a whole host of documents, Gerhard Koslowski and Rüdiger Glaser have established the extent to which the western part of the Baltic Sea was frozen after 1501. To record the level of flooding on an inter-subjective basis, high-water marks were mounted on bridges and buildings. In 1597, Galileo Galilei built the first known instrument to determine air temperature and started to take instrumental measurements. Among the pioneers of observations using instruments, the Parisian physician Louis Morin deserves special mention: between 1665 and 1713, Morin took thermometer and barometer readings three times a day and was the first observer to systematically record the direction of cloud movement. In the 18th century, meteorological instruments spread more rapidly.

With a view to finding a common denominator for these meteorological activities, Karl Theodor, Elector of Palatinate, established the Societas Meteorologica Palatina in 1780. This international scientific society provided its members with uniform instruments, issued guidelines for carrying out measurements and published the results. The society's meteorological network extended from Greenland to Rome, from La Rochelle to Moscow. It was broken up by the armies of the French Revolu-

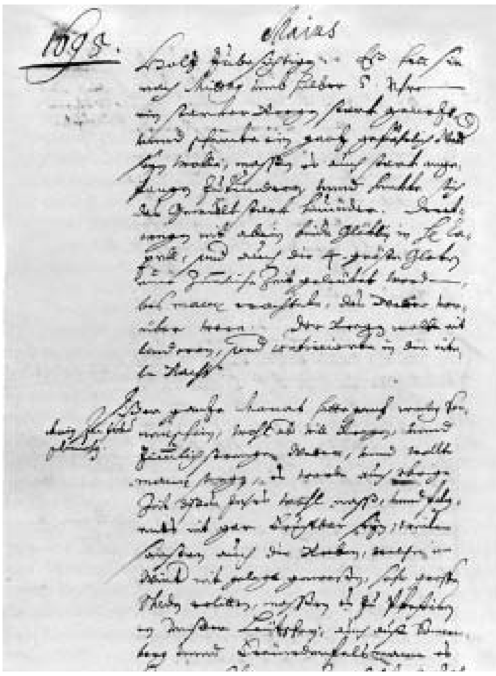


Figure 3: Weather description by Father Josef Dietrich (1645–1704) at Einsiedeln Monastery (Switzerland). Father Josef kept the monastery journal from 1672 until 1695. Not infrequently, the weather description for a single day extends over several lines and is surprising in its wealth of meticulously detailed observations. Dietrich already distinguished between four types of cloud and classified precipitation by duration and intensity. The movement of a cold front on 29/30 May 1695, for example, is described as follows: “We found a very wet morning because it had rained incessantly all night and was still raining in the morning. Higher up, there was a little snow. Toward midday, the rainy weather stopped again, and it looked much brighter; by 3 o’clock, there was even a bit of sunshine.”

tion. Large databases like Euro-Climhist, HISKLID and CLIWOC already store hundreds of thousands of descriptive and early instrument-based data. Millions of other documents are awaiting discovery in archives. When evaluating documented data, a check is first made as to the spatial consistency of all the direct and indirect data available for a given period of time, using meteorological criteria. In accordance with the informational robustness of the various data types, the seasonal or monthly data fields are analysed to derive numerical indices for temperature and precipitation. These indices have seven tiers, ranging from –3 (extremely dry or extremely cold) via zero (“normal”) to +3 (extremely wet or extremely warm). Any interpretation must be adapted to a continuously changing data environment and take account of sourcespecific, ecological, and individual aspects. It cannot be formalised in mathematical terms, but the results can undergo statistical vetting.

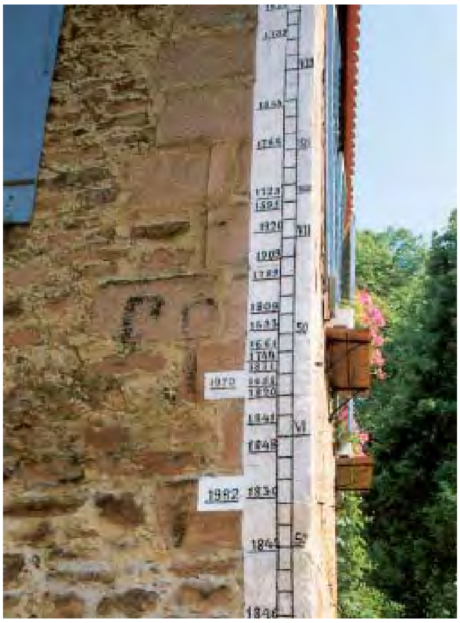
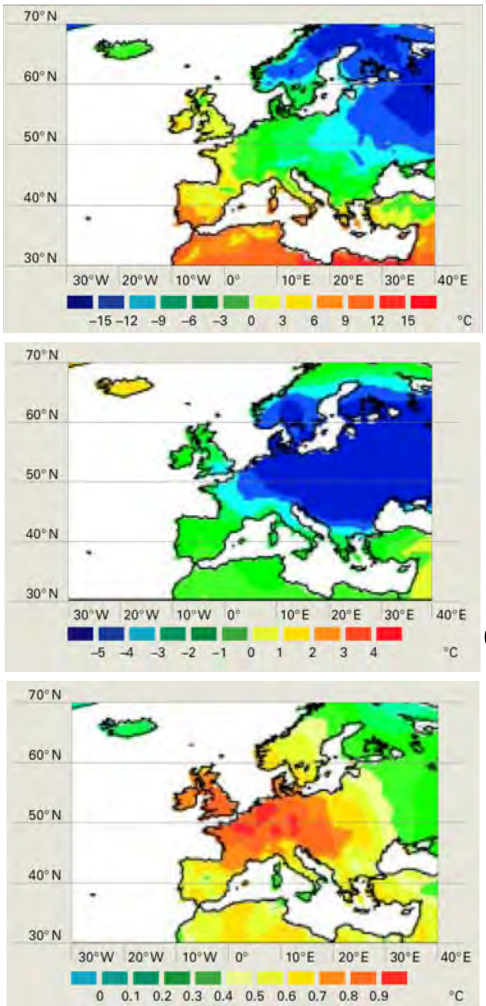


Figure 4: To document the level of severe floods for posterity, high-water marks on buildings were used to indicate maximum levels.
On this house in Wertheim at the confluence of the rivers Tauber and Rhine, 24 high-water levels are documented. Tens of thousand of high-water marks were destroyed in the 20th century.

How can index series be further evaluated? To start with, a statistical comparison of index series and measurement series can yield regression equations which, in turn, can be used to estimate temperature and precipitation. Also, using these indices as starting material, it is possible to model the impact of climate on climate-sensitive sectors, such as pre-industrial agriculture, but also the effect of climate fluctuations on eco-systems in the past. Finally, studies have shown that a few geographically well-distributed series of measurements for temperature, precipitation, and air pressure suffice to estimate the sea-level air pressure field and the spatial patterns of temperature and precipitation for the whole of Europe.

On the basis of such considerations, Jürg Luterbacher, Heinz Wanner, et al. (University of Berne) have reconstructed spatial changes in air pressure, temperature, and precipitation for more than 5,000 grid points throughout Europe using statistical models. Until 1658, seasonal and, subsequently, also monthly reconstructions were made (Fig. 6). On this extensive spatial basis, the significance of climatic influences for the price of grain, the business cycle, and the outbreak of epidemics in recent centuries is currently being investigated systematically for the first time.

Presented below are some of the results of historical climate research which have become important in recent discussions about anthropogenic climate change. The



(a) Temperatures in the record winter of 1709 in Europe

(b) Deviations from the mean, 1901–1998

(c) RE temperature

Figure 5: For the record winter of 1709, statistical methods were used to estimate seasonal and monthly temperatures, with the support of early instrument-based measurements and temperature indices, for 5,000 grid points in Europe. In eastern central Europe, this most extreme winter of the last 500 years was as much as 6°C too cold. In the night from 5 to 6 January 1709, France was reeling under a cold-air front advancing at a speed of 40 km/h, bringing a temperature drop of some 20°C. On the morning of 6 January, the cold air had reached the Mediterranean and caused untold damage to frost-sensitive plants.
The RE (reduction of error) values are a statistical measure of the quality of the reconstructions. The higher the RE value, the higher the confidence in the quality of the reconstruction. /7/

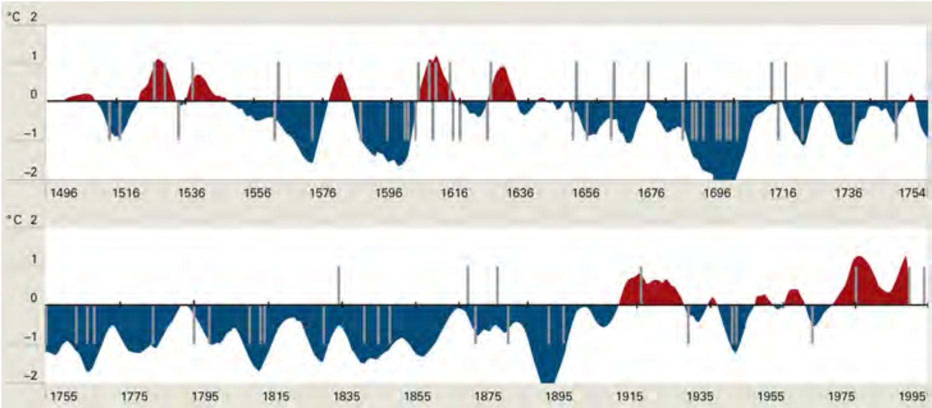


Figure 6: Fluctuations in winter temperatures in Switzerland's Mittelland region (1496–1995) /8/
For the period before 1755, figures have been estimated using temperature indices. Thereafter, they are based on measurements: the winters of the "Little Ice Age" (until 1895) were 0.5°C colder in the long term than those of the 20th century, and as much as 2°C between 1675 and 1700.

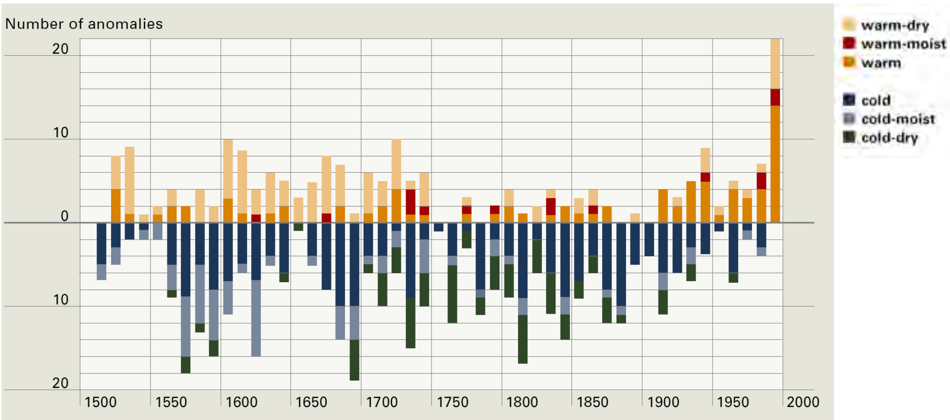


Figure 7: Sum of the extremely warm and extremely cold months (anomalies) per decade (1501–2000), classified by precipitation conditions /11/
The "Little Ice Age" stands out owing to an accumulation of cold anomalies, and the present-day greenhouse climate owing to the 22 extremely warm months in the 1990s, a number unprecedented since 1500.

outstanding climatic anomaly in recent years was undisputedly in the summer of 2003. Across Europe, the summer was the warmest in the last 500 years. In southern central Europe, it put all record temperatures observed since the start of instrument-based measurements (1755) well into the shade. The only analogous case from the last 700 years was possibly the summer of 1540, when grain and vine ripened at the same time as in 2003, which points to similar temperature conditions. Still, the drought of 1540 was much more serious. From mid-March to the end of September, large areas of (central) Europe were under almost continuous high pressure. In these six months, a little rain fell on only a few days. Numerous wells dried up, and the smaller rivers between the Rhine and the Carpathian Mountains ran dry. At some points along the Rhine, it was possible to wade across the river. Many people had to travel long distances at night to fetch their water in wine kegs, which were carried by pack animals. Forests went up in flames, and the fires were so numerous that a veil of smoke settled over wide areas of the continent. Can this severe analogous case of 1540 be cited as a fact which invalidates the significance of the summer of 2003 as evidence of the greenhouse effect?

An answer to this is provided by the chart below: for each decade in the period 1501 to 2000, it shows the number of extremely warm and extremely cold months (anomalies). The measurement series (since 1755) were converted to index data. The colour scale shows the nature of the precipitation in the various, thermally extreme months (very wet, “average”, very dry). Three phenomena stand out:

1. Extremely cold and dry months (with dominating winds from north to east) occurred more frequently between 1570 and 1890 than since then. Such anomalies are regarded as indicating the “Little Ice Age”, which started in central Europe around 1300 and ended in the late 19th century.
2. In the years 1901 to 1990, an average of five cold and four warm anomalies were measured. In the 1990s, cold extremes did not occur at all, while the number of much too warm months has risen five-fold compared with the average values in the period 1901–1990. The maximum value of 22 warm anomalies (1991–2000) is more than twice as high as the maxima in the period 1501–1990.
3. 3 The analogous case of 1540 must be assigned to a different environment in climate history than the extreme summer of 2003. The Mediterranean summer of 1540 was followed two years later by a cold and wet summer, during which the much-battered glaciers were able to recuperate. The summer of 1947, also cited occasionally as a case similar to that of 2003, was preceded by a cold winter in which the Rhine froze in Germany.

The greenhouse-effect scenarios assume that, as average values rise, the spectrum of extremes will shift. Cold extremes will vanish: what was deemed normal in the past, will now become “cold”, and what used to be “warm” will become normal. And, beyond the record heat figures measured hitherto, so the thinking goes, we will have to face what are literally unprecedented extremes. The developments in the last 15 years in central Europe are largely in line with this scenario. The very cold extremes, which were a firm component of our climate for centuries, have disappeared entirely since 1988. Instead, the warm extremes in the 1990s occurred five times more often than in the entire “warm” 20th century. And, with the summer of 2003, we have been given a taste what might lie ahead. It is the remit of scientists (and science historians) to fit present-day events and developments into a larger context. This is true not only of political events but, in an age of global warming, also – and increasingly so – of climate anomalies and natural disasters. Historical climatology is able to provide arguments for discussion in this area.

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Mapping Heritage Climatologies

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Abstract

The NOAHs ARK project established a need for key meteorological parameters affecting cultural heritage and cartographical representations of potential damage to materials in the form of an atlas. This brought an increasing pressure to define Heritage Climatology. Classical climatological maps, such as those of Köppen, can be applied to heritage, but often miss some of the environmental pressures that affect monuments, buildings and sites. The heritage climate needs to be projected into the future to allow strategic management of heritage through the 21st century. However, the way we express climate change impacts on heritage and the reliability of model outputs and predictions of damage remain difficult.

Peter Brimblecombe

I was born in Australia, but went to university in Auckland, New Zealand where my PhD concerned atmospheric chemistry of sulphur dioxide. I remain interested in atmospheric chemistry and currently work on the thermodynamics of aerosols, particularly water soluble organic substances. My studies of long-term changes in urban air pollution and climate and its effects on health and building damage are also an important activity: the historical aspects of subject resulted in my book, The Big Smoke. This encouraged an interest in the relationship between air pollution and architecture, literature and even cinema. My research on material damage by air pollutants has not been restricted to outdoor environments. I have worked on the museum atmosphere and have a continuing interest in the process of damage to cultural materials by air pollutants. I have increasingly co-operated with conservators in the National Trust, English Heritage and Historic Royal Palaces on management issues; focussing on accumulation of dust, but have recently become interested in the balance between climate and access. The practical context of my research work means that I am frequently an invited speaker at conferences, interviewed by the media and teach on advanced courses. In 2005 I received a gold medal from the Italian Chemical Society for contributions in environmental and heritage chemistry and with the NOAHs ARK team the Europa Nostra Grand Prize in 2009. I am a Professor and an Associate Dean at the University of East Anglia and senior editor of the leading international journal Atmospheric Environment (8000 pages annually; impact factor ~3).

1 Weathering

The role of environment in damaging building materials was recognised in classical times by writers such as Herodotus or Vitruvius. Early writers describe weathering by frost, the role of salts and other climate factors. Biological growth and the effects of air pollution were also known along with the blackening of buildings by smoke, which provoked frequent comment in the ancient world e.g.

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

Odes and Carmen Saeculare
Horace

The role of air pollution became dominant in the early 20th century through the sulfation of surfaces from sulfur dioxide, derived mostly from coal smoke. The deposition on stone facades and subsequent oxidation and its oxidation to sulfuric acid caused much damage through the formation of gypsum crusts. However, significant decreases in air pollution that typified urban areas from the 1960s and 1970s meant a decline in the rate of damage from traditional acidic air pollutants such as sulfur dioxide. Coarse particles from smoke also decreased, but these pollutants began to be replaced by photochemical oxidants in smog: ozone and nitrogen oxides. The increasing use of diesel vehicles in Europe meant greater blackening from fine particles and a change in the organic content of deposited soot /1/.

Although the controlling influence of the major acidic pollutants was apparent in the mid 20th century this declined and even though these pollutants were replaced by others they were less aggressive towards stone /2/. However, it may be that some more modern materials such as polymers could be more susceptible to attack in modern oxidative atmospheres /3/. The much reduced impact of air pollution has raised the potential of increasing damage from traditional forms of weathering especially in a century likely to experience marked climate change. The Intergovernmental Panel on Climate Change (ICPP) delivered its Climate Change 2007: Synthesis Report, which showed that the century-long trend (1906-2005) suggested an average global increase in temperature of 0.74 °C per century. Best estimates of the rise in global surface temperature by the end of the current century under a set of emissions scenarios (A1/2 and B1/2) suggest increases that range from 1.8 to 4.0°C. There will very likely be precipitation increases in high latitudes and decreases in most subtropical land regions continuing recent observed trends. Thus it seems that over the next 100 years will likely have a range of direct and indirect effects on the natural and material environment, including the historic built environment. Important changes will include alterations in temperature, precipitation, extreme climatic events, soil conditions, groundwater and sea level. This concern lay behind the European commissions desire to fund projects such as NOAH's ARK /4/ and more recently CLIMATE FOR CULTURE /5/.

2 NOAH'S ARK Project

The NOAH's ARK Project examined how climate change might affect Europe's built heritage and cultural landscapes over the next century. Mapping was an especially important element and led to display of the results as a Vulnerability Atlas /6/. This was aimed at heritage managers to assess the threats of climate change in order to take a strategic view of the impact of future climate scenarios on built heritage and cultural landscapes. The results should allow a better response to the protection of materials and structures of the historic built environment to future climate scenarios on a European scale.

It was recognised from the outset that some processes of heritage damage will be accelerated or worsened by climate change, but others might be less important and this could affect long term strategy and planning. The impacts on individual processes have often been described, but it is has been far less common to account for the risk posed by climate change. Models of future climate have improved rapidly and allow global changes to be linked to the response of materials, historic structures, archaeological sites and cultural landscapes.

The NOAH's ARK Project also developed guidelines that outlined a descriptive context to the scientific findings to communicate the potential heritage relevance of climate change to policy makers and heritage managers. The scale of the mapping promoted its use at a strategic level rather than that of an individual site. Much of the advice relates to adaptation to climate change and ensuring that heritage is resilient to novel environmental threats.

3 Critical parameters for cultural heritage

The NOAH'S ARK Project recognised that only a subset of meteorological parameters would be relevant to heritage, so first considered those most critical to the built heritage. For example, the effect of a few degrees change in temperature on the deterioration process might be seen as relatively slight, because stone or metal in themselves insensitive to temperature. However there are ways small changes can be amplified. Higher temperatures give longer frost free periods, decreases in snow cover and a lengthening of growing season that lead to a broad range of phenological impacts,. These can be most noticeable in spring: e.g. earlier breeding or singing of birds, flowering of plants or spawning of amphibians. These responses reveal a “coherent pattern of ecological change across systems” /7/. Hallet et al /8/ have shown the benefits of large scale climate indices as predictors of ecological change. In the case of both biological systems and cultural heritage, frost is an important factor in damage. Freezing and thawing is common in climates with winter temperatures close to zero. Increasing winter temperatures may make frost damage less frequent in future in mild climates such as that of Britain /9/, but potentially more frequent in colder climates /10/.

Freezing represents a phase change for water. Such changes are important in causing damage to materials, such that when water freezes or salts crystallise the volume changes can impose mechanical stress on materials. Phase changes are sensitive to climate as they occur at discrete values of temperature or relative humidity. This means even slight changes in climate can allow phase boundaries to be crossed more or less frequently. As suggested above the frequency of freeze-thaw events is likely to decrease substantially in many culturally important sites in temperate Europe, even though the winter temperature change is only a few degrees /10/.

Other critical factors were readily identified in NOAH's ARK. It was especially clear that the water interactions withf heritage materials was especially important. The presence of liquid water is linked to temperature, which frequently increases in colder climates. This often comes about through prolonged times of wetness, which for metals leads to higher rates of corrosion or higher deposition rates of pollutants and more favourable conditions for microbiological activities, greater salt mobilisation. In the vapour phase water is also responsible for deterioration. This is usually described in terms of relative humidity. When this increases most materials show enhanced rates of deterioration . Changes in RH lead to crystallisation and dissolution processes within porous stone and the pressure exerted can be high enough to disrupt the stone in a process known as salt weathering.

Increased precipitation can increase the damage caused by wet deposition by dissolution of surface layers of materials. Changes in the chemical composition, especially pH, can affect the deterioration rate. Wind can increase eddies and turbulent flows around historical buildings and alter the deposition rates of both gaseous and particulate pollutants. It can strengthen the effect of driving rain and abrasive windblown sand /11/. A very serious effect may be the increased transport of sea salt inland /12, 13/.

4 Heritage climatology

The study of weather across the globe is called climatology, which deals with the spatial distribution of weather averaged over time. One of the most influential systems for classifying climate is that of Wladimir Peter Köppen developed at the end of the 19th century. He was attracted to the study of climate through a fascination with environment especially the relationship between plants and the climates in which they flourish. The importance of weather on the many aspects of our environment is recognised by the subsequent development of specific climatologies. In biology, ecological climatology /14/ has come from an integration of ecology and climatology to gain an understanding of the way terrestrial ecosystems function and bioclimatology deals with the relationship between climate and life. Building climatology looks at achieving a comfortable building climate together with energy-saving structural designs /e.g. 15/. Brischke et al /16/, use the notion of material climate, while the more specific need for a heritage climatology was strongly felt in the NOAH's ARK project, which defined climate parameters critical to the protection of heritage (Brimblecombe et al., 2006). This later led to a desire for a climatology tuned to heritage. Cristina Sabbioni, the project coordinator of NOAH's ARK said: "We quickly realised we would have to develop our own cultural heritage climatology" /17/.

It was recognised that classical meteorological parameters may not be especially relevant to heritage as it was clear that combinations were very important. As an example wind driven rain, which causes moisture to penetrate deep into building is a combination of precipitation and wind-speed. Additionally some effects accumulate over time and classically this is seen as degree-days in agriculture or pest control. In the case of heritage the increasing number of frost-free days could be important in disrupting frozen middens (mounds of domestic waste) at Viking sites in Greenland as shown in Fig. 1.

Similar arguments can be made for the variation in meteorological parameters or the number of cycles or events. As noted before when temperature cycles below and above freezing point were discussed it induces a phase change in the water within porous building materials, which results in frost shattering. In a similar way salts within porous building materials can crystallise from brines as the relative humidity decreases. Only slight changes in the thermo-hygrometric climate can lead to large changes in the number of brine-crystal transitions. Thus phase change might be seen as amplification mechanism through which small changes in climate can markedly change the number of transitions.

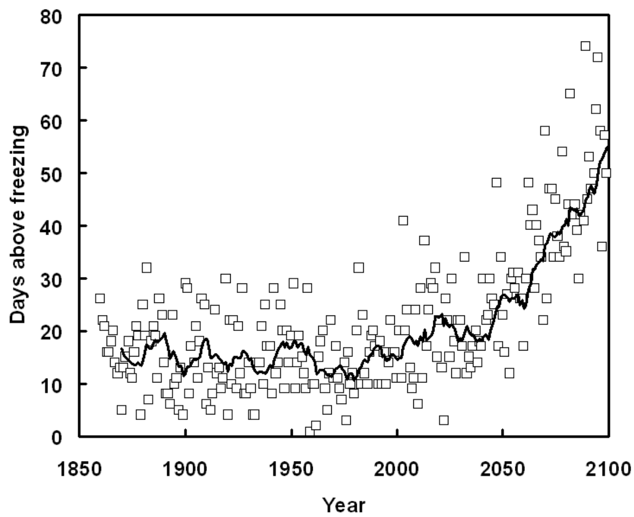

Figure 1: Predicted number of days each year in Southern Greenland when temperature is above freezing point (HadCM3A2 output). Line shows an 11-year running mean.

Damage /e.g. 18/ or dose-response functions /e.g. 19/ are widely used to describe the relationship between air pollution and the rate of alteration of the material. They are less common for describing the impact of climate on heritage, but an example would be thermal stress /20/ or frost weathering /10/. Such functions can also be useful to make estimates of risk /21/ and beyond this it is important to reflect that this is displayed in terms of sociological or artistic perceptions and provokes management responses that may have to balance these with economic reality.

5 Köppen climate maps

The approach of Köppen-Geiger to climatology leads to maps of the kind typically found in many atlases. Although these were initially tuned to an interest in vegetation, we can see how readily they might be adapted to understanding the relationship between heritage and climate. The example of frost damage to crops and vegetation mentioned above has some similarities with the need to track freezing events in terms of damage to porous stone. Additionally maps were central to the NOAHs ARK project. Recently the classical approach of Köppen has been updated by Kottek et al /22/ to allow ready digitisation. It also makes it possible to incorporate data that shows evidence of recent shifts in climate. A simplified Köppen-Geiger categorisation of climate for Europe /23/, modified from Kottek is presented as a map in Fig. 2. The number of Köppen-Geiger climate types has been reduced so it shows only the broadest changes for our discussion.
The Köppen-Geiger scheme describes climates in terms of codes. The first letter describing the broad groups of climate : A through to E. These can be subdivided into further types. The Köppen-Geiger scheme describes climates of relevance to cultural heritage. In terms of European climates this might be seen as /23/:

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 insolation. 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 leads to less salt damage, and some potential for frost weathering. Some potential for thermal stress on materials exposed to strong insolation.

Cfab – warm fully humid climate with warm to hot summers: damp conditions and variation in humidity that cause salt damage, occasional freezing events present

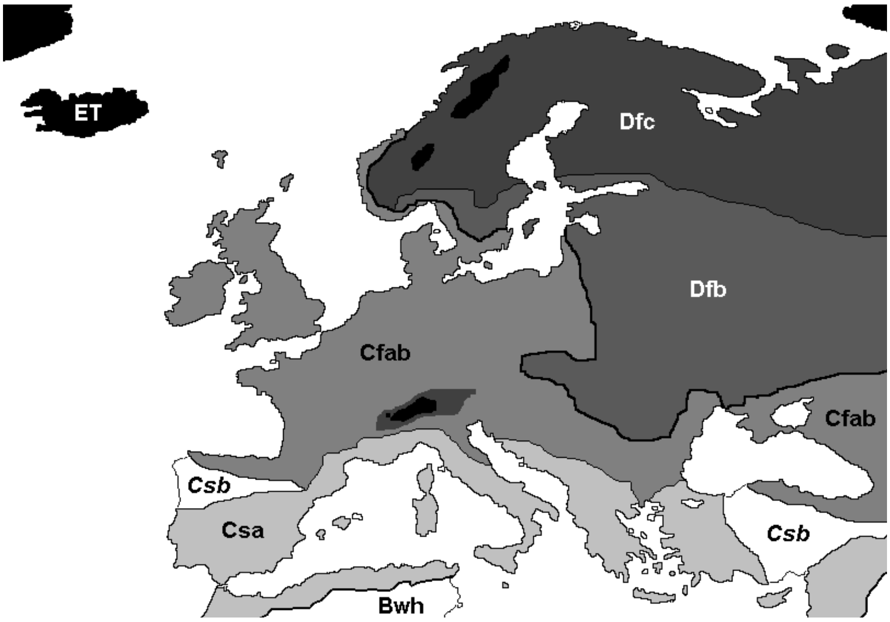

Figure 2: European climate regions following the Köppen-Geiger scheme as applied by Kottek et al /22/.

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

ET – polar or montane climate: conditions so cold that ground may remain frozen. This is a potential problem if temperatures increase as there can be frost heave, disruption of soils and archeological sites.

This Köppen classification is essentially thermo-hyetal, i.e. including both temperature and precipitation. We can see the way in which it might work with pressures on heritage in the potential for salt damage in Spain developed in the work of Grossi et al /24/ . The map shown in Fig. 3 shows broad agreement with the low resolution Kottek et al map /22/ in so far that it captures the differences of Asturias (and Galicia) very well and the high frequency of transitions in the sodium chloride

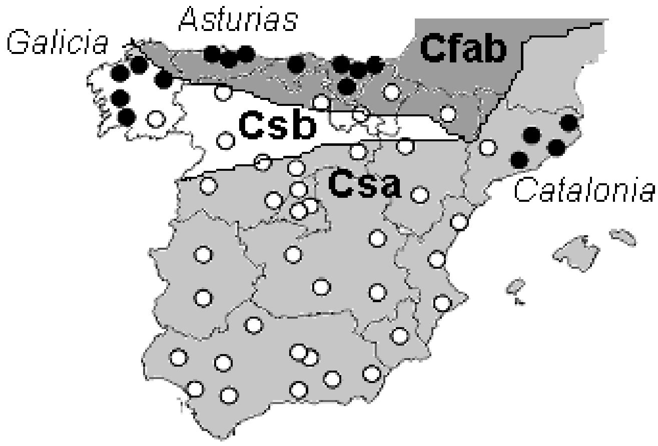

Figure 3: Salt transitions in the sodium chloride system in contemporary Spain /24/ showing the distribution of sites with climates imposing a higher annual frequency of sodium chloride transitions as filled circle. Sites with lower frequency of transitions and dry summers causing these to occur mainly in winter are shown as open circles. The superimposed climate types are taken from the coarse resolution map of Fig. 2

system there /24/ because of the fluctuating oceanic climate along the northern coast separated from inland Spain by the Cantabrian mountains. However, there are subtle differences and in the east. In Catalonia the Mediterranean climate also induces a higher potential for salt weathering. Higher resolution expressions of salt weathering in Spain are mapped in Grossi et al /24/. Strictly speaking the Köppen classification fails to address humidity directly, but the implication here is that rainfall can be something of a surrogate and argue that rainfall gives guidance to humidity.

It is not just the lack of local detail in the Köppen-Geiger scheme that makes it incomplete. Its focus on temperature and precipitation means that some climate parameters are missed. Relative humidity (except as rainfall) and wind, for example are not considered in the Köppen-Geiger climate scheme. This means that the coastal regions where wind blown salt might be important or storms or wind driven rain which might damage buildings are neglected. Sand in dry regions can also be driven against buildings by wind.

Perhaps even more notably the scheme does not account for air pollution which was such an important driver of damage in 20th century cities. Air pollution brings out further problems, which relate to maps of damage. Spatial gradients in pollution are often very steep. An important example of this would be roadside pollution generated by vehicles, which leads to a rapid rate of blackening of buildings close to the road-side, but the rate falls off rapidly with distance from the road. (Brimblecombe and Grossi, 2005). The same problem occurs with the decline in salt deposition with distance from the coast. Beyond this we have to accept that climatology treats average weather so does not provide a satisfactory account of extreme events, which can cause catastrophic damage to historic buildings.

6 Future heritage climates

Combined with the idea that great buildings are meant to survive many centuries it places our consideration of damage on a hundred- or thousand-year timescale. Furthermore the climate is likely to change considerably across the current century, which makes it necessary to predict heritage climates over considerable periods. The NOAHs ARK project used predictions at a coarse resolution (hundreds of km), although 50km was used for the conditions at the end of the 21st century.

Such long term predictions raise numerous issues. Most discussed tends to be concerns over the accuracy of the model in terms of the future world it describes. Temperature is often seen as most reliable and precipitation less so. Parameters such as relative humidity, all important for heritage, seem poorly handled in the model, such that Grossi et al /24/ calibrated the Hadley output against contemporary with the aim of making it more reliable for future predictions of the impact of future climate on heritage. There are also struggles with issues of scale. Clearly the spatial scale of the models creates problems, even when we improve the scale from 100's km to 10s of km, as heritage objects and sites are yet smaller. Time resolution can be a problem also because some impacts of relative humidity need predictions at hourly intervals to understand the importance of changing water content on objects in terms of imposed stress.

Beyond these problems of modelling we have also to consider the problems in conveying results to heritage managers in a form that allows them to take action. Some of the advice seems relatively simple and for example the National Trust in the UK has enlarged some of the guttering and down-pipes on some historic house to cope with the increased rainfall intensity predicted for later this century. As yet little attention has been given to the way to express the uncertainty of the modelling in terms of the advice. These may involve probabilistic approaches, perhaps using Boolean statistics or more contentiously fuzzy logic. However, such approaches are for the future and not to be treated here, so we restrict ourselves to the problem of representing the changing impact of climate on heritage.

Let us imagine a structure of information in a form that might be required or is desired by managers. This could be expressed in four stages: (i) at the simplest and most qualitative level there is a need to know the climate parameters relevant to heritage. (ii) Moving beyond the static view, further decision making requires the idea of the direction of climate change and whether the impact will increase or decrease in future. (iii) The next stage is to be able to gain a sense of the size of the imposed risk with perhaps (iv) an estimate of reliability.

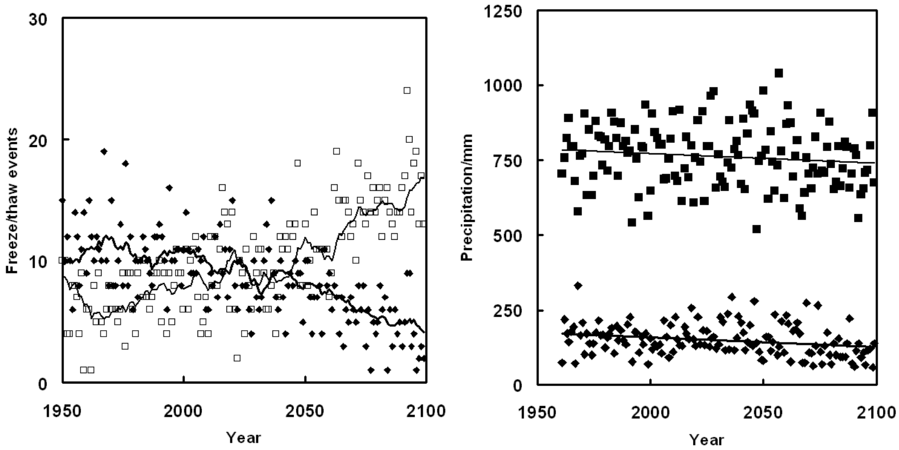

Figure 4: (a) Annual number of freeze thaw cycles predicted to be experienced in England (as filled diamonds) open and squares Southern Greenland (as open squares) across the period 1960-2100. (b) Rainfall for England (as filled squares) and an area centred on Araouane in Mali (as filled diamonds). The lines are simply determined by linear regression.

The first stage of defining relevant meteorological parameters to heritage was a task within the NOAH's ARK Project as described in Section 3. Frosts are familiar drivers of weathering in porous stone. The potential for damage from this process can be parameterised as they were within NOAH's ARK as shifts from 1 to -3 oC (there are other potential parameterizations as discussed in /10/). This is shown in shown in Fig 4a that displays the number of freeze thaw cycles predicted for England across the period 1960-2100 (as filled diamonds). We can see here that the warmer climate through the current century leads to a decline in the number freeze thaw cycles (parameterised by determining subsequent daily temperatures cross of zero degrees). However, in some colder locations increased warmth leads to an increase rather than decrease as shown in Fig. 4a as open squares for Southern Greenland. Figure 4b shows declining rainfall for England (as filled squares) and on the same figure from the Sahara desert rainfall for Mali in an area centred on Araouane (as filled diamonds). These figures give a sense that changes in the climate pressures on heritage are vitally important in understanding the impacts on heritage. However, change is not always that easy to represent. The NOAH's ARK Project typically chose to use the absolute differences between the 1961-1990 and 2070-2099 means in parameters. This gives a reasonable picture perhaps for the freeze thaw cycles at various sites and this can be shown for Europe in Fig. 5a, while Fig. 5b as discussed later begins to express the statistical reliability of such change.

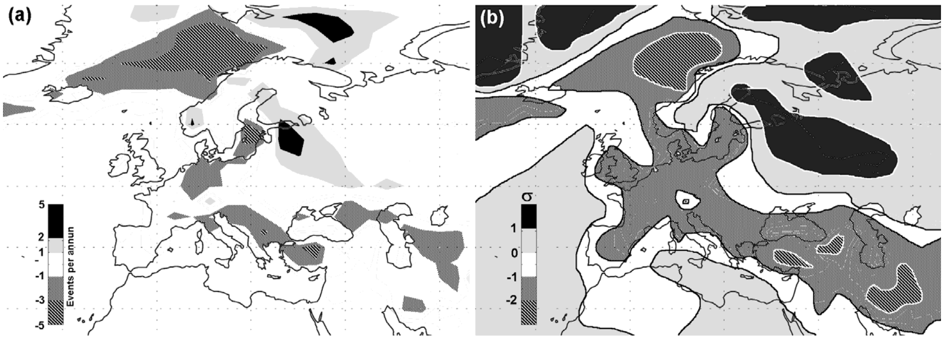

Figure 5: (a) A map of the differences in the annual number of frosts between 1961-1990 and 2070-2099 using HADCM3A2. (b) A map of the differences in the annual number of freezing events by 2070-2099 in terms of standard deviations above or below the 1961-1990 mean.

However, with other climate parameters absolute differences can be more problematic. Take for example rainfall when looking at the changes in damp-maritime England as compared with the aridity of northern Mali in Africa (Fig 4b). The decline in precipitation at both sites are about 32 mm per century (whether calculated by least square regression or as a Sen slope). However, the decline is more significant in Mali where annual rainfall in the 1950s is estimated at 175mm, but by 2100 almost 125mm, a substantial reduction. In England the change from about 800mm to 750mm is in a relative sense much smaller. This example shows the importance of considering whether relative or absolute differences are relevant when expressing the change in potential impact on heritage.

The changes displayed in Fig. 5a give a sense of both the direction change and the magnitude of the change. However, this fails to give a sense of how likely or reliable is the estimate of change. One attempt /10/ at showing this is given in Fig. 5b, where we can see the changes in terms of standard deviations above or below the 1961-1990 mean number of annual freeze-thaw cycles and that for the end of the 21st century (2070-2099). We can see that high levels of statistical certainty can be given to the increases in freeze-thaw cycles found in Northern Europe, notably Russia. In southern Norway there is little change and over much of the rest of Europe there is a decrease in the annual number of freeze-thaw cycles (Fig. 5a). A high degree of certainly can be given to the decreasing number of freeze-thaw cycles likely to be experienced in a swath stretching from England and western Europe down through the Balkans and Turkey into Iran (Fig. 5b). This would suggest a decreased risk from frost shattering, although the actual size of this change is large only in limited portions of the swath (see Fig. 5a), notably Northern Germany, the Balkans, Turkey and Turkmenistan.

Such qualitative maps are useful in the strategic assessment of future risk to heritage, but presentation remains a problem because it needs to combine the notion of the direction of change, the size of the change (relative or absolute) and the reliability. It is particularly important, and a potential focus of future research on heritage management to develop approaches to decision making that are robust in the face of climate and risk predictions that have variable reliability.

7 Conclusions

Some response of cultural heritage to climate can be found in classical maps such as that of Köppen-Geiger. However, this scheme does not account for wind, air pollution and perhaps even relative humidity. Additionally it treats average conditions and that does not account for extreme events. Climate pressures can be translated into potential for damage through dose-response or damage functions, although these are not as well defined for climate as they are for air pollution. The potential for damage can be mapped to provide information for strategic decision. However, there are problems with such representations and particularly how to project them into the future. Predictions of future damage also involve issues of error and reliability which have yet to be explored in terms of cultural heritage.

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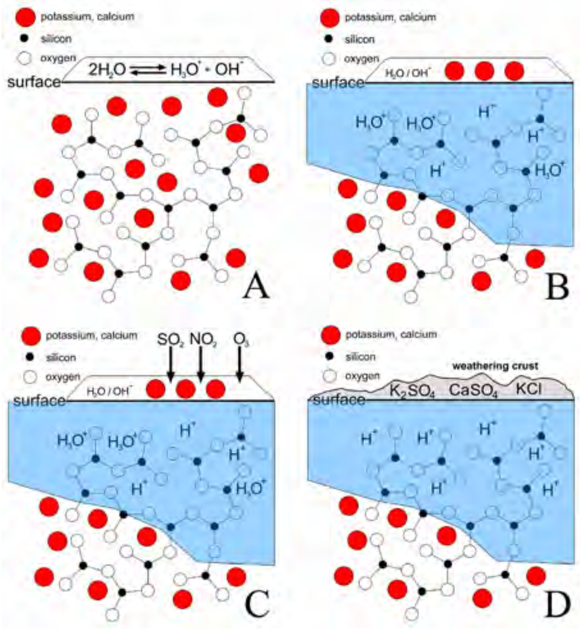

Chapter 2: Impact of Climate Change on Materials and Building Constructions

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Evaluation of the Effects of Expected Climate Change Scenarios for the Netherlands on the Durability of Building Materials

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Abstract

Regardless causes of climate change, changing climate parameters, such as higher temperature, amount and intensity of precipitation, different wind regime, will affect the durability of materials used in the building envelope, either individually or combined. The current paper evaluates possible trends and tendencies arising from these changing climate parameters on the durability of building materials in the Netherlands, based upon four scenario's of climate change developed by the Royal Netherlands Meteorological Institute, KNMI.

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1 Introduction

Whatever the causes of climate change are, future scenario's of climate change show clear effects in next decennia in terms of temperature, precipitation, etc. /1-2/ . Resulting changes in exposure conditions will inevitably affect building materials and, by consequence, the (preventive) conservation of built cultural heritage. Preventive conservation is the systematic maintenance and monitoring of a monument stock in a sustainable way, in order to prevent expensive technical restorations. Accepted values of monuments include, besides the material aspect, - either original or originating from continuous changes in course of history -, relationships within the cultural and physical contexts, with surroundings and landscape /3/. The last three will also be affected by climate change. Understanding of changes in exposure conditions is essential to develop strategies for preventive conservation.

This paper focusses on effects of climate change on the durability of materials in the building envelope, with emphasis on porous building materials (brick and natural stone masonry, concrete), timber and coatings. The effects of flooding are commonly discussed in literature, e.g. the effects on Venice /4/, assessment of the long term effects on brick masonry of temporary exposure to sea water during the disastrous flood of 1953 in the Dutch province of Zeeland /5/ and the guidelines developed by English Heritage /6/. The current paper concentrates on other effects of climate change, such as higher temperatures, increased precipitation, (locally) increased ground water table and increased salt concentration of ground water, etc. For the Dutch situation, four scenario's of climate change have been developed /1/ and recently evaluated again /2/ by the Royal Netherlands Meteorological Institute, KNMI. These are denominated G – moderate (more or less unchanged), G+ – moderate, but with changing air circulation patterns, W – warm, and W+ – warm in combination with changing air circulation patterns, respectively. General tendencies in all four scenarios are:

- Temperatures will increase, resulting in a higher frequency of more temperate winters and warm summers.
- Winters will, on average, become wetter, and extreme amounts of precipitation will increase.
- Intensity of severe rain in the summer will increase, but, in contrast, the number of rain days in summers will decrease.
- Changes in wind regime will be small compared to current natural variation.
- Sea levels will continue to rise.

Details of each scenario are summarized in table 1. The current situation, i.e. effects of climate change over the past century /1/ shows that average temperature in the Netherlands has risen 1.2 °C over the period 1900 – 2005. Temperatures for 2100 are expected to increase 1 to 6 °C worldwide, relative to 1990, with,

Table 1: Summary of effects of four possible scenario's for the Netherlands in 2050, relative to 1990 /1/.

Scenario		1990	G	G+	W	W+
	Summer					
Mean temperature	ºC		+ 0.9	+ 1.4	+ 1.7	+ 2.8
Yearly warmest day	ºC		+ 1.0	+ 1.9	+ 2.1	+ 3.1
Days 25 ºC NW Netherlands		8	11	14	16	22
NE Netherlands		20	27	30	34	41
Central Netherlands		24	30	34	39	47
SE Netherlands		28	36	41	44	53
Mean precipitation	%		+ 2.8	- 9.5	+ 5.5	- 19.0
Wet day frequency	%		- 1.6	- 9.6	- 3.3	- 19.3
Mean precipitation on wet day	%		+ 3.4	+ 7.6	+ 6.8	+ 15.2
Mean precipitation on 1% wettest days	%		+ 12.4	+ 6.2	+ 24.8	+ 12.3
	Winter					
Mean temperature	ºC		+ 0.9	+ 1.1	+ 1.8	+ 2.3
Yearly coldest day	ºC		+ 1.0	+ 1.5	+ 2.1	+ 2.9
Mean precipitation	%		+ 3.6	+ 7.0	+ 7.3	+ 14.2
Wet day frequency	%		+ 0.1	+ 0.9	+ 0.2	+ 1.9
Mean precipitation on wet day	%		+ 3.6	+ 6.0	+ 7.1	+ 12.1
Mean precipitation on 1% wettest days	%		+ 4.3	+ 5.6	+ 8.6	+ 14.7
	Yearly					
Yearly max. daily mean wind speed	%		0	+ 2	- 1	+ 4

probably, a slightly higher increase in Europe. For the Netherlands, scenarios vary from an increase in 2050 of 0.9 to 2.3 °C in the winter, and 0.9 tot 2.8 °C in the summer, relative to 1990 (Table 1). There is also a strong regional variation, as illustrated by the number of days with maximum temperature 25 °C (Table 1).

The amount of annual precipitation in the Netherlands has increased by + 18 % since 1906, with + 26 % in the winter, + 21 % in the spring, + 3 % in the summer and + 26 % in the fall. The amount of rain in prolonged 10 day rain periods also increased by + 29 % since 1906 /1/. Extreme precipitation is likely to increase /2/. In addition to the climate scenario's, significant regional differences may appear, in particular with respect to extreme precipitation. In current climate, such differences already exist /7/. Future regional precipitation patterns may change due to a warmer North Sea and drying over the European continent /2/.

KNMI scenario's depict that the expected effect of climate change on maximum wind speed in the Netherlands is rather small, within natural variation /1/. The number of storms in the Netherlands has decreased by 20 – 40 % since 1962 /1/; at the same time, the number of storms at Düsseldorf airport, not that far from the border with Germany, has roughly increased by 70 % from the 1960's into 1990's, accompanied by an increase in mean wind velocity /8/. Other studies also indicate a possible shift of storms with very high intensity from the Atlantic to northwestern Europe /9/.

The KNMI scenario's only assess the direct climate characteristics. Several other effects relevant to the durability of building materials that have not been assessed by the KNMI, include specific and relative humidities and the amount of solar radiation. In the UK situation, for example, specific humidity is likely to increase, whilst relative humidity may decrease, especially in the summer; the amount of solar radiation is likely to increase./10/.

2 Possible effects of climate change on building materials

2.1 Introduction

Below, general trends or tendencies of individual climate parameters affecting building materials are concisely discussed. The paper identifies the major trends in risks for building materials, due to climate changes. A quantitative estimate of the potential effects cannot be given as major data relating impact, specific materials and effects are lacking.

2.2 Higher temperatures

Higher temperatures will result in faster biocolonization, involving other species than currently encountered in the Netherlands, and increased biodegradation, as more periods with optimum temperature will occur /11/. A salient example is the recent shift of the habitat of wood-eating termites towards more northern directions, from southern Spain to the middle of France. Other genera will develop that are typical for the Mediterranean area in the West-European maritime climate, causing accelerated biodeterioration; a typical example is the (booming) occurrence of *Trentepohlia odorata* on (calcium silicate) masonry.

2.3 Higher precipitation

Higher precipitation (especially in the winter), more extreme precipitation and wind driven rain may result in deeper penetration of moisture in a façade, affecting (combined thermal) hygric expansion with accompanying stresses /12/. Deeper penetration may, especially by small dimensions, result in water sepage through walls. The effect of a higher potential run-off is difficult to assess.

2.4 Combination of higher temperature and higher precipitation

Higher mean winter temperatures will result in less freeze-thaw cycles in the winter; in practice, this effect might be limited, as the decrease in the number of freeze

– thaw cycles in northwestern Europe by the end of the 21st century (2079 - 2099) is less than one cycle compared to the period 1961 - 1990 /13/. However, at the same time, porous building materials may be more wet due to higher precipitation in the winter, possibly resulting in more intense damage upon frost.

Higher temperatures and higher precipitation will influence atmospheric and relative humidities, with direct effects on salt damage to porous building materials, those in built cultural heritage in particular. The number of dissolution and re-crystallization cycles at the surface of salt laden masonry may strongly increase and cause damage /14-15/.

Biocolonization patterns will change, with manifest effects on biodeterioration and biodegradation. Higher temperature and precipitation will cause faster development of microorganisms (e.g. higher germination power rates), and affect the species of microorganisms occurring. Likely, a shift will occur from algae to cyanobacteria and fungi (moulds) as in the Latin American situation /16-17/. The latter may result in development of more pronounced aesthetical damage on stony, cement-based and polymeric building materials.

Especially the availability of moisture is, together with the availability of organic nutrients, a controlling factor in biocolonization. Analysis of the microclimate of the city of Rome over the period 1850 – 1980 has shown that a decrease in precipitation, -i.e. the opposite of what is expected in climate change scenarios for the Netherlands-, and 10 % decrease in relative humidity, accompanied by an increase in temperature of 0.5 to 1.5 °C as well as increasing air pollution, resulted in a decrease of microflora diversity (especially affecting lichens), but did not significantly reduce the total biomass on stony materials /18/.

In case of timber, the decay of wood due to fungal attack directly relates to the climate:

$$\text{Climate index} = \frac{\sum \text{dec-jan}(T_{mean} - 2)(D - 3)}{n} \qquad (1)$$

in which T_{mean} is the mean monthly temperature in °C, D is the mean number of days in the month with 0.254 mm or more precipitation, and n is a scale factor to scale the index to a range of 0 to 100, n being 16.7 for the US and 10 for Norway, for example /19-21/. The relationship is valid for temperatures below 30 °C. Climate index < 35 indicates a low risk, 35 CI 65 a moderate risk and CI > 65 a high risk /19/. The relationship clearly illustrates that increasing rainfall and mean temperature will result in increasing risk of deterioration of timber structures and building parts due to wood-deteriorating fungi, which will also reflect variations in local microclimates. Besides fungi, timber will also suffer from faster growth of more devastating insects.

2.5 Higher precipitation in combination with wind load

At high levels, wind driven rain generally results in more weathering. Combined with a higher amount and intensity of precipitation, increased wind load may cause increased weathering of high-rise buildings /22/.

2.6 Increased solar radiation

Increased solar radiation may possibly lower durability of bituminous roofings, plastics, paintings and coatings as well as specific hydrofobic or antigraffiti coatings, whereas an increase in short-wave UV radiation will negatively affect the preservation of historic wall coverings and polychromy. Degradation of (painted) timber construction elements used on the exterior façades, such as cladding, window-frames, fences, etc. is also likely to increase, whereas untreated timber and wood products will be more prone to colour changes. In addition to the increase of solar ultraviolet radiation itself, the degradation potential of any UV-B environment is enhanced by higher temperatures and, possibly higher relative humidities.

2.7 Soil moisture contents and salinity

It is unclear whether and how higher precipitation will affect soil moisture contents. Given that ground and surface water in the Netherlands are controlled in most areas, any effect will strongly depend on measures taken with this respect. For example, in built environments such as cities, there is no regulation of the water level, and building owners are responsible for degradation on their wooden pile foundations.

Lower soil moisture contents may result in drying accompanied in shrinkage and resulting subsidence, which may result in cracking of foundations and walls; they may also expose wooden pile foundations, especially common in the historic city centres of most towns in the western provinces of the Netherlands like Amsterdam, to oxygen, due to lower ground water levels, resulting in degradation by fungi and finally failure, leading to uneven settlement. At the same time, there will be a lower the risk of damage due to rising damp.

Higher soil moisture contents will result in higher risks of damage due to rising damp, by higher moisture content of porous building materials, at onset of freeze – thaw cycles, or by increased transfer of water soluble salts from soil (and deicing) into the building shell.

The report by the Dutch government's Delta Commission /23/ describes several expected effects as a result of climate change, as well as proposals to accommodate these. Combined, these will affect both ground water table and salinity:

- Sea level rise and decreasing river transport towards sea during summer.
- Longer dry periods and penetration of salt water via rivers and groundwater

- Both increasing and decreasing ground water tables, depending on the part of the country.
- Increasing salt concentration in ground water
- The level of IJsselmeer will be increased by max. 1.5 m as one of the measures proposed by the Delta Commission /23/ will be put in practice.

Result will be higher salt loads on building materials, for example due to capillary rising damp from the soil. The higher salt load may lead to faster decay of building materials. Adequate measures, treatments and interventions will be necessary to prevent this fast decay and to protect valuable cultural heritage objects in particular.

2.8 Higher wind speed

An increase in wind load would have implications for the anchoring of cladding materials /24/. Otherwise, the effects on building materials in the Netherlands are expected to be minor.

2.9 Impact of climate change on durability of building materials in the Netherlands and adaptation possibilities

Above, the KNMI climate change scenarios for the Netherlands /1-2/ have been discussed in relation to relevant physical-chemical processes affecting the durability of building materials. Various lines of approach may be distinguished to adapt to the effects of climate change on building materials in the Netherlands, but any approach is complicated by the fact that climate change may affect degradation and durability of different building materials involved in opposite directions.

2.10 Biocolonization and biodegradation

The combined effect of higher temperature and higher precipitation is likely to speed up biocolonization and increase effects of biodeterioration and biodegradation, for stony materials, (organic) coatings and timber. Possible adaptation measures may range from the development and use of new, innovative materials with slow controlled release of biocides to selection of currently available and more sustainable materials. In the current case, materials with a low water retention will be less prone to biocolonization than those with a high water retention, which is favoured by a large amount of pores with diametres below 0.1 m. Hence, apparently the use of more coarsely porous building materials may serve as an adaptation measure. The use of water repellent treatments may also be considered /25/. The latter would, however, not be an option, given the risk of future damage by other processes, in case of the presence of salts or rising damp, which may be affected by climate change itself, whilst at the same time increased solar radiation is likely to speed up degradation of water repellent agents themselves.

2.11 Salt damage

Salt damage on fired clay brick and natural stone masonry in general, and in built cultural heritage in particular, may possibly increase. Besides higher temperatures will result in faster evaporation, water penetration into façades will be deeper, potentially dissolving more salts that may be transported and accumulated, giving rise to damage. This may happen, for example, in case of masonry made with an outer shell of higher firing temperature, harder bricks, and inner core of low firing temperature, sulfate-rich bricks. To what extent higher temperatures and higher precipitation will result in more relative humidity cycles in which the equilibrium relative humidity of water soluble salts is crossed, is yet unclear. Only a limited increase of such cycles, however, may have rather severe effects on salt damage to porous building materials /14-15/. Measures at the design level, affecting indoor climate, might help to adapt. In case of smaller objects, such as sculptures, desalination may be an approach of adaptation. However, for larger salt-loaded objects, such as entire façade walls, this is, with current techniques, not practical. Desalination systems like electro-osmosis /26/ and poultices /27/ deserve further research.

In case of materials applied during renovation, restoration or new construction, adaptation measures might be found in use of more salt-resistant materials, such as salt transporting or salt accumulating restoration plasters or bricks with a pore structure favouring salt crystallization at the surface (efflorescence) rather than behind that (crypto-efflorescence). A promising field might be the use of (restoration) mortars with mixed-in crystallization inhibitors /28-29/. As far as crystallization inhibitors are concerned also possible effects on health and environment may need attention, apart from their performance.

2.12 Freeze – thaw damage

Contrary to what might be expected, freeze – thaw damage, -not of major concern to concrete in the Netherlands, but rather to brick and natural stone masonry-, may not decrease. The expected decrease in the number of freeze-thaw cycles is small, whereas materials may be more wet at onset of frost, due to higher precipitation, with a possible increase in freeze - thaw damage. Enhancing frost resistance of masonry and, in particular, pointing mortars by use of air entraining agents or gap-graded sand /30/ may be an adaptation approach.

In case of concrete in civil infrastructure, the slightly lower amount of freeze – thaw cycles due to higher temperatures may possibly have a minor beneficial effect, not on freeze – thaw damage itself, but on rebar corrosion, as a more restricted use of deicing salts will limit chloride loads.

2.13 Increased solar radiation

The effect of increased solar radiation on plastics and coatings is likely to be compensated by the development of advanced light-stabilizer technologies, based on both conventional and improved photostabilizer systems /31/.

3 Conclusion

Evaluation of the climate scenario's developed by the KNMI for the Netherlands /1/ shows that the combined effect of different climate parameters is rather complex. Action of individual climate parameters may strengthen each other, such as higher temperature combined with higher precipitation, or may result in effects contrary to what might be expected, such as the combination of higher precipitation combined with only a slight decrease in the number of frost-thaw cycles.

Well known damage processes affecting building materials, such as salt damage, rising damp and biodeterioration, will probably intensify. Adaptation at a materials level may, depending on the material involved, consist of a different choice of already available materials or techniques, or new materials or methods currently being developed. However, also at a higher level of design (detailing, ventilation), measures should be considered to enhance durability of building materials in the future situation. New materials and techniques are generally not developed for conservation of built cultural heritage alone. Compatibility with historic materials is essential, and should be considered in both product development and application. A repair mortar with superior resistance to one or more damage mechanisms may result in accelerated deterioration of the historic mortar aimed to be conserved /32/. The impact of new materials on authenticity of materials, monuments and monuments in their broad context asks for evaluation. This may, however, not result in *a priori* exclusion of the application of innovative materials and techniques. Preventive conservation of built cultural heritages requires that possible acceleration of damage mechanisms has to be considered in future interventions.

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Developments in the Field of Cementitious Mortars for the Restauration of Monuments

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Abstract

A major part of CO_2 is emitted by the cement clinker production. This produced cement is used as a binder in mortars and concrete. In this paper it is shown that the cement content of mortars can be reduced by employing by-products in cement, such as stone waste materials. Furthermore, the cement content as such in mortars can be reduced, e.g. by including inert fines and a smart mix design concept. It will be seen that mortars with superior mechanical (e.g. strength) and physical (e.g. durability) properties can be produced that are low-cost and environmental friendly. An additional feature can be obtained by adding TiO_2 to the mortar. In this way, the mortar and surrounding stones will, due to the photocatalytic activity (self-cleaning effect), remain free of soiling. Besides this, the mortar contributes in removing NO_x from the air, the so-called air-purifying effect.

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1 Introduction

The application of eco mortars for the restauration of monuments requires the integration of new materials that are characterized by multifunctional properties. In the considered case, mortars that have low cement contents combined with the addition of photocatalytic acting materials seem to be a promising development in that field. Lowering the cement content in cementitious mortars and concrete is as such an ecological benefit since it contributes to a decrease in the CO_2 emission produced during the production of cement clinker which is as such a major part of the annual CO_2 emission around the world. The financial crisis of the year 2008/2009 resulted in a stagnation of the cement production while an increase, especially in the developing countries, is predicted for the coming years.
However, not only the emission of CO_2 forms a major problem in our modern society, but also the air quality in inner-city areas with high traffic loads is a serious issue. Limiting values can be easily exceeded during rush hour times. Here, the application of photocatalytic materials, such as titanium dioxide, results in a beneficial contribution to the overall reduction of nitrogen oxides (NO_x). The air-purifying property of these new building materials containing materials having photocatalytic properties is not the only interesting point, but also the preservation of a clean aspect offers different fields of new applications in façade systems. As these systems keep the original appearance over a longer period of time than classical systems, cleaning costs are reduced and less deleterious detergent are used. This self-cleaning effect offers a beneficial contribution to the overall aspect of eco mortars.

2 Development of eco mortars with low cement contents

The optimization of particle packing allows the design of cementitious mortars or concrete mixes that are characterized by a denser granular structure. Such a structure results in improved mechanical properties such as compressive strength or flexural strength. Not only the mechanical properties are affected, but also the durability of the designed mortar is improved due to the denser granular structure and the lower porosity of the cement paste.
The idea of optimized particle packing and its beneficial influence on the concrete properties forms the basis of a new mix design concept that is explained in detail in /1/. This new mix design concept can also be applied for the design of eco mortars. Here, two main aspects have to be pointed out. First, eco mortars can be designed that are characterized by lower cement contents. This can be realized due to the denser granular structure that results in improved mechanical properties such as higher compressive strength values. The higher compressive strength of the designed mortar allows a cement reduction. The second aspect deals with the replacement of cement by other materials such as by-products or stone waste powders generated by the natural stone industry. During the production of washed rock aggregates, high amounts of fine stone waste powders in slurry form are gener-

ated throughout the washing process. Also the production of ornamental natural stone slabs generates high amounts of fines as a by-product of sawing, polishing, etc.

Depending on the origin and the generation, two different options are possible for the application of the fine stone waste materials from rock production in cementitious mortars. The first option is based on the use of the generated filter cake, for instance as a re-dispersion of the remaining filter cake, in slurry form. This approach is suitable if the material is already generated or the generation of fine stone waste materials cannot be avoided (e.g. through cutting and polishing processes) The second option considers the direct use of the broken rock materials, hence including the fine fraction (< 125 m). In this case, the stone waste material will not be generated as the original product allows a direct use of the material in special types of concrete. This method involves a higher financial and environment-friendly aspect as an intermediate step in the production of broken rock aggregates is eliminated. Therefore, the direct use of this untreated product, its sand fraction here named Premix 0-4, is of major interest.

By characterizing this material and its properties (particle size distribution (PSD) and particle shape), Premix 0-4 can replace primary raw materials like limestone powder or clinker. The last results in a second benefit, as the clinker production requires a lot of energy and contributes to the emission of high quantities of greenhouse gases such as carbon dioxide. Also the production of limestone powders requires energy. Therefore, from an environmental and economical point of view, the use of these primary raw materials should be optimally deployed to meet the mechanical and durability requirements of cementitious mortars, and the application of the appropriate industrial by-products should be favored.

As discussed before, particle packing plays an important role in the mix design. Using the new mix design tool, mixes can be developed in which cement is partly replaced by the fines of the Premix 0-4 (see Figure 1).

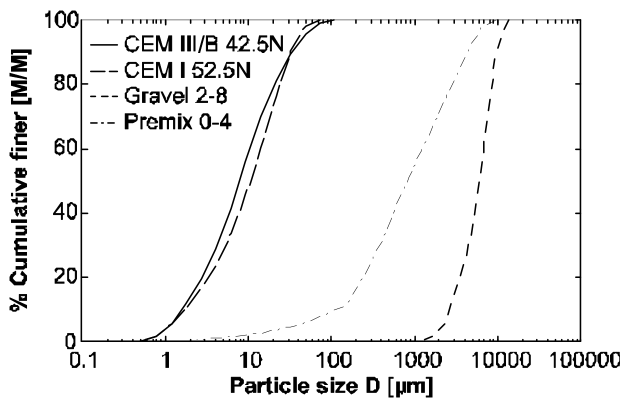

Figure 1: PSDs of aggregates and fines used (cumulative finer mass fraction).

Table 1: Composition of the tested mortars

Mix	CEM III/B 42.5 N	CEM I 52.5N	Premix 0-4	Granite 2-4	Water	SP [(a)]	w/c	w/p
	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m³]	[kg/m³]		
Premix C402	262.8	139.5	1462.3	178.9	173.0	2.00	0.43	0.33
Premix C363	254.3	109.0	1503.2	163.3	176.7	2.05	0.49	0.33
Premix C289	202.5	86.8	1649.7	133.0	157.9	1.86	0.55	0.33
Premix C252	176.4	75.6	1702.9	117.5	156.5	1.75	0.62	0.35
Premix C289	202.5	86.8	1649.7	133.0	157.9	1.86	0.55	0.33

(a) : SP: Superplasticizer

Four different mortar mixes have been selected based on the ideas of the new mix design concept. The designed mortars consist of premixed sand (Premix 0-4), containing both fine aggregate fraction and inert stone powder, in combination with varying cement contents. The cement content ranges from 252 to 402 kg consisting of a blend of 65% slag cement (CEM III/B 42.5 N LH/HS) and 35% Portland cement (CEM I 52.5 N). The cement reduction is compensated by increasing the amount of Premix 0-4 and granite as well. Owing to the high content of fines and low cement content in the mortar mixtures, the amount of water is maintained as low as possible in order to achieve w/c ratios around 0.50. This low w/c ratio requires the use of a plasticizer to allow a sufficient workability and compaction of the produced mortar samples under laboratory conditions. The detailed mortar composition is presented in Table 1.

The designed mortars are submitted to a compressive strength as well as a flexural strength. For testing the compressive strength, cubes of 50 × 50 × 50 mm have been produced and tested after 3, 7 and 28 days. The mean values of the compressive strength tests are depicted in Figure 2.

The compressive strength after 28 days of the samples having a cement content of 402 kg and 363 kg is not influenced by the cement content of the designed mix. Here, the mortar having a cement content of 363 kg achieves the same compressive strength after 28 days as the mix containing 402 kg cement. The optimum cement content for obtaining the densest possible packing seems 340 kg in this case.

It appears that a reduction in the cement content is not influencing the compressive strength when the original cement content is already higher than actually needed. In this case the additional cement acts as a kind of filling instead of a binding material. A reduction of the cement content highly influences the compressive strength in case the cement content is already below the necessary amount needed for optimum packing. A further reduction in the cement content is influencing the packing fraction of the granular structure in a negative way.

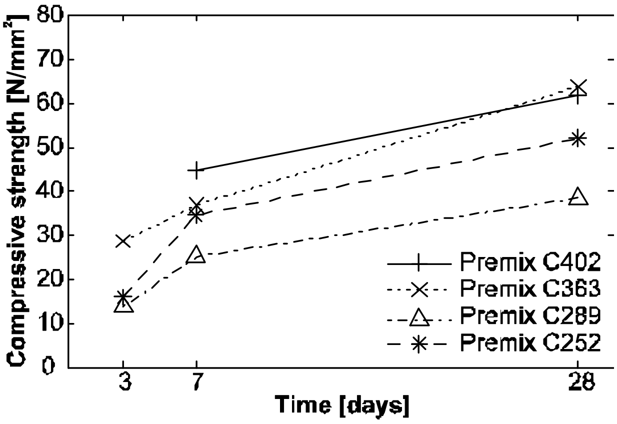

Figure 2: Development of the compressive strength for tested mortar samples.

Considering the mix proportioning as given in Table 1, the w/p ratio and the workability is constant for mixes having a cement content of 402, 363 and 289 kg. However, the w/p ratio was increased from 0.33 to 0.35 for the mix having a cement content of 252 kg. This slight increase in the water content improved the workability properties of the mortar and resulted in a denser granular structure of the hardened mortar. Therefore, the mix containing 252 kg cement achieved higher compressive strength values than the mix using 289 kg cement. The present results show clearly that cement can be used in a more efficient way when the packing of the granular materials is optimized.

The development of the flexural strength of the mortar samples was determined after 3, 7 and 28 days on prisms 40 × 40 × 160 mm . The results are presented in Figure 3.

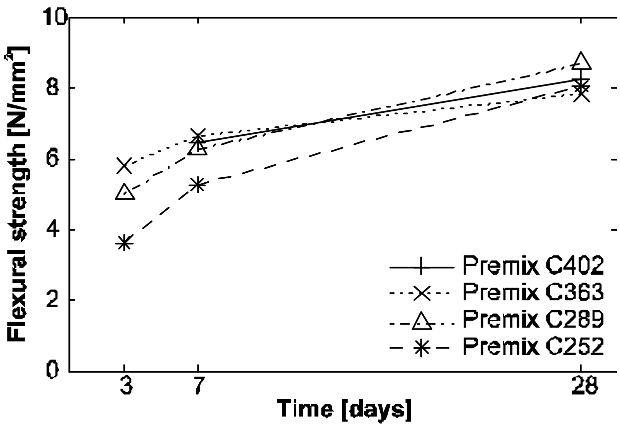

Figure 3: Development of the flexural strength for tested mortar samples.

Significant variations in the development of the flexural strength with respect to the mortar composition are noticed up to 7 days. To describe the effect of cement reduction on the results of the flexural strength after 28 days is hardly possible due to the high standard deviation. All tested series using Premix 0-4 showed after 28 days flexural strength values in the range between 7.9 and 8.1 N/mm^2.

3 Application of TiO_2 in cementitious mortar systems

3.1 Introduction

The application of photocatalytic active materials, such as titanium dioxide (TiO_2), in cementitious based construction materials allows the development of multi-functional building materials. The photocatalytic reaction at the material's surface provides the possibility to degrade inorganic and/or organic pollutants that are deposited on the surface. This allows for i) the degradation of air pollutants such as nitrogen oxides (NO_x) and ii) the prevention of surface soiling due to algae growth or other staining substances.

Another interesting application of photocatalytic active materials is related to their hydrophilic surface properties. Water droplets are not formed since the photo-induced super-hydrophilicity of the photocatalytic surface induces the formation of a uniform thin water layer. This thin water layer can easily flow under pollutants that adhere to the surface or can prevent the fogging of glasses. Due to the higher roughness of concrete surfaces compared to glass, the self-cleaning effect is of minor interest since a free flowing of the formed water layer is hampered. Therefore, the self-cleaning abilities of photocatalytic surfaces are mainly applied to glass and ceramic due to their denser surface texture.

3.2 General aspects

The photocatalytic effect of TiO_2 is known since the beginning of the 20^{th} century. The fading of paint materials containing titanium white was reported by /2/ and /3/. However, the extensive research on photocatalytic materials was initiated many years later by the photoelectrochemical cell for water splitting developed by Fujishima and Honda /4/.

After the discovery of the so called Honda-Fujishima effect, a lot of research was conducted on photocatalytic reactions due to an increasing demand for artificial systems capable to convert solar energy to chemical or electrical energy. Later the research focused mainly on the treatment of waste water. The photocatalytic oxidation (PCO) gained considerable attention regarding the removal of air pollutants during the last years. Since the middle of the 1990s efforts have been made, first in Japan, in large scale applications of this photocatalytic property for air-purifying purposes and self-cleaning applications. The construction industry provides several products containing photocatalytic materials on commercial basis. These products are, for example, window glass and ceramic tiles providing self-cleaning features. The utilization of the self-cleaning abilities of modified blends of cement was

Figure 4: Church "Dio Padre Misericordioso", Rome, Italy (Source: Richard Meier & Partners, http://www.richardmeier.com).

used for the first time in 1998 for the construction of the church "Dio Padre Misericordioso" in Rome, designed by Richard Meier (see Figure 4).

The basic working principle of the PCO of TiO_2 is based on the optoelectronic properties of the crystalline form anatase. This crystalline form shows a band gap of 3.2 eV and a high oxidizing potential of the valence band that amounts to 3.1 eV (at pH = 0). The PCO is induced by the transfer of electrons from the valence band to the conduction band by photons in the UV-A range. The UV-A absorption creates electron holes that are responsible for the formation of radicals and charged species such as $OH^\bullet$, $O_2^{\bullet -}$, $HO_2^\bullet$.

The generation of hydroxyl radicals results from the presence of water at the surface of the photocatalyst. For this purpose, a certain amount of water molecules, supplied by the humidity of the atmosphere, and electromagnetic radiation are required to initiate the degradation process. The electromagnetic radiation E is expressed by the product of Planck's constant h and the frequency f /5/:

$$TiO_2 \xrightarrow{hf} TiO_2 + e^- + h^+ \quad (1)$$

$$H_2O \leftrightarrow OH^- + h^+ \quad (2)$$

$$OH^- + h^+ \rightarrow OH^\bullet \quad (3)$$

The formed hydroxyl radicals act as a strong oxidant for organic and inorganic compounds in further reactions. According to Herrmann /5/, the most reactive species are hydroxyl radicals after fluorine ones. Further reactions follow the heterogeneous photocatalysis and are characterized by the adsorption of the precursor and the desorption of the reaction products. A test setup including a suitable measuring procedure was developed allowing the evaluation of photocatalytic concrete products under equal test conditions (ISO standard ISO 22197-1:2007). The methodology is described in detail in /6/.

3.3 Air-purification of cementitious mortars containing TiO_2

Air quality in inner-city areas remains a major problem for the future. Promising solutions are given by the use of air-purifying concrete products since available filters to reduce the emission of NO_x are not effective. According to the literature (e.g. /7/ and /8/) the degradation of nitric oxide (NO), or more generally of nitrogen oxides (NO_x), also referred to as the DeNOx-process (denitrogenization), is as such necessary to purify the air in inner-city areas. This denitrogenization process can roughly be described as a two-stage reaction on the surface of the photocatalyst:

$$NO + OH^{\bullet} \rightarrow NO_2 + H^{+} \tag{4}$$

$$NO_2 + OH^{\bullet} \rightarrow NO_3^{-} \tag{5}$$

The formed nitrogen dioxide (NO_2) is a key precursor for the further reaction and is oxidized to nitrate ions (NO_3^-) that can either be bound by alkalis dissolved in the pore solution or will, most probably, be washed from the concrete surface as weak nitric acid.
A comparative study on selected concrete products of the European market was carried out in 2007 to show the efficiency of air-purifying concrete products under laboratory conditions /9/. This study was followed by the development of specific cementitious mortars containing TiO_2 dioxide. The composition of the mortars differed with respect to the amount and the type of TiO_2 powders and the addition of pigments. The properties of the tested TiO_2 are given in Table 2. The composition of the designed mortars is given in Table 3.

Table 2: Properties of the tested TiO_2.

	TiO_2 A	**TiO_2 B**	**TiO_2 C**	**TiO_2 D**	**TiO_2 E‡**
Specific density [g/cm^3]	3.9*	3.94	3.9	3.9*	3.9*
Characteristic particle sizes [m]					
$d_{0.1}$	0.65$^{\#}$	1.193	0.641$^{\#}$	0.593$^{\#}$	0.574$^{\#}$
$d_{0.5}$	1.245$^{\#}$	2.72	2.104$^{\#}$	2.014$^{\#}$	2.075$^{\#}$
$d_{0.9}$	2.487$^{\#}$	6.535	7.123$^{\#}$	4.349$^{\#}$	4.92$^{\#}$
Surface area (computed)					
Specific surface [cm^2/g]	15 847$^{\#}$	7 916	11 910$^{\#}$	13 139$^{\#}$	13 113$^{\#}$
Specific surface [m^2/cm^3]	6 181$^{\#}$	3 115	4 645$^{\#}$	5 195$^{\#}$	5 114$^{\#}$

‡ carbon-doped TiO_2
* taken from data sheet
# based on measured agglomerates

Table 3: Mortar composition.

	Reference mortar		3% TiO_2	5% TiO_2	10% TiO_2
	dm³/m³	**kg/m³**	**kg/m³**	**kg/m³**	**kg/m³**
CEM I 52.5N	195.8	600.0	600.0	600.0	600.0
Sand 0-2	490.6	1 300.0	1 300.0	1 300.0	1 300.0
TiO_2	-	-	18.0	30.0	60.0
Water	250.0	250.0	250.0	250.0	250.0

Slabs of 100 x 200 x 20 mm were produced and tested with respect to their degradation properties according to the procedure described in /9/.
In Figure 5 the results obtained for different types of TiO_2 are shown. The experimental data show a clear dependence of the fineness of the powder on the degradation properties (see Figure 5 and Table 2).

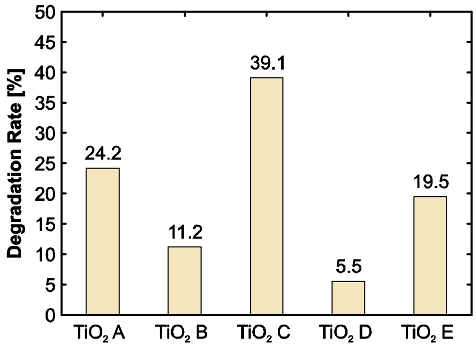

Figure 5: Degradation rate of tested TiO_2-powders.

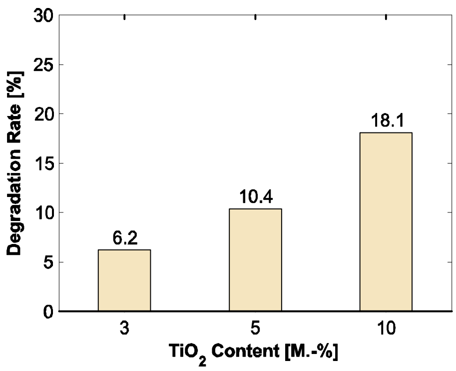

Figure 6: Influence of the TiO_2 content on the degradation rate.

This is in accordance to the expectations based on the higher specific surface area of e. g. TiO_2 C, which is about 30% higher than the surface area of TiO_2 B. Furthermore, the effectiveness of the degradation of NOx could be increased for the doped TiO_2 E as this modified powder uses UV-A radiation as well as bigger parts of the visible light.

In Figure 6 the degradation rate of TiO_2 B for varying powder contents is shown. The test results show clearly that the degradation rate increases for increasing powder content.

The influence of a red pigment on the degradation of NO_x is shown in Figure 7. The results shows that the degradation rate of the mix containing 3% TiO_2 is not influenced by the addition of pigments 1 (P1) or 2 (P2) for contents up to 2%. The values of the degradation rates are deviating in the same order of magnitude as expected for the scattering of the measuring data. Higher contents of TiO_2 (5% and 10%) associated with higher pigment contents (5% P1) are not reducing the degradation rates verifiably and the obtained degradation values are increasing, as expected from Figure 6, with increasing TiO_2 content. Solely the workability of the fresh mortar was reduced significantly as the content of fine particles (TiO2 and red pigment) increased.

3.4 Prevention of soiling processes by means of TiO_2

The staining of building materials due to black soot precipitation and by the growth of green algae poses a problem in case of conditioning in a shady and permanently humid environment. This biological staining is typical for roof tiles and façades facing north especially in a rural environment. Paved areas without direct sunlight are also affected by this phenomenon.

Besides the oxidative degradation of a wide range of organic and inorganic compounds, biological species (bacteria, algae and molds) can also be decomposed by means of UV-A in the presence of TiO_2. The decomposition of green algae

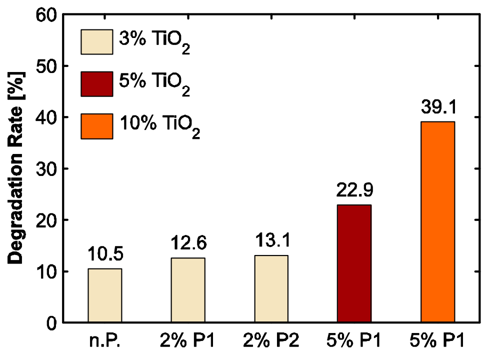

Figure 7: Influence of red pigments on the NO_x degradation rate: no pigment (n.P.); 2% pigment type 1 (2% P1); 2% pigment type 2 (2% P2); 5% pigment type 1 (5% P1).

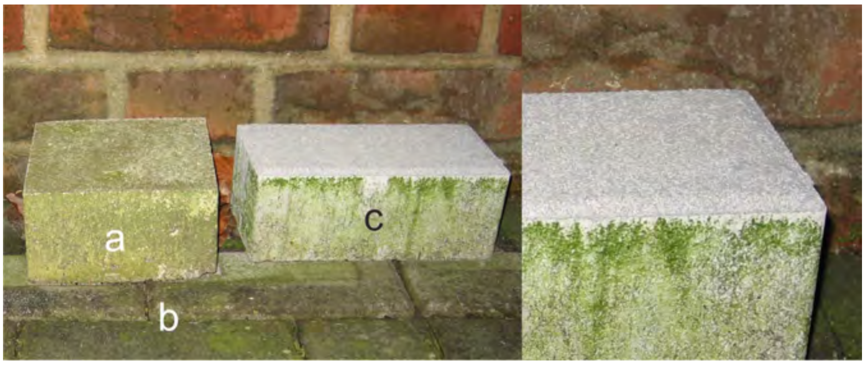

Figure 8: Staining of concrete paving blocks due to algae growth: untreated sample (a); paving of untreated paving blocks (b); paving block containing TiO2 in the functional top layer (c).

(Cladophora) was successfully shown on TiO_2 coated glass beads /10/. Therefore, the decomposing mechanism of TiO_2 in its anatase form is also expected for cementitious mortars. To investigate the inhibitive effect of TiO_2 on the growth of green algae, a concrete paving block with a cementitious mortar containing TiO_2 in its functional top-layer (sample c) and a blank sample (sample a) were placed in humid conditions and exposed to low direct sunlight where the staining of an already existing paving (sample b) by algae is a typical problem (see Figure 8). After a short period of time, the reference sample (sample a) of Figure 8 was covered with algae on its lateral side as well as on its top side. This process also occurred on the lateral side of the concrete paving block containing TiO_2, (sample c) but here only up to the level of the core mix which did not contain photocatalytic active TiO_2. The remaining lateral side of the functional top-layer as well as the top side of the paving block are not covered by any algae as here the photocatalytic material prevents soiling by algae. This exposition of concrete paving blocks at a location that is not suitable for the degradation of NO caused by high humidity and low natural light showed another potential of photocatalytic products regarding the prevention of undesirable staining due to algae growth.

4 Conclusions

This paper presents innovative developments in the field of cementitious mortars. These mortars are characterized by their multifunctional properties such as low cement contents and photocatalytic activity. Low cement contents are obtained by a denser granular structure of the designed mortars due to optimized particle packing. The lowered cement contents cause an economical and environmental benefit in comparison to classical systems.

Furthermore, the application of photocatalytic materials, such as titanium dioxide, gives the designed mortars multifunctional properties. Here, the degradation of air pollutants as well as the prevention of soiling is possible. The air-purifying abilities of these mortar systems are a valuable contribution to improve the inner-city climate. Moreover, the original appearance of buildings is preserved.

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WTA-Colloquium, March 11-12, 2010, Eindhoven, The Netherlands,
WTA-Schriftenreihe, Heft 34, 59–76 (2010)

Impact of Climate Change on Medieval Stained Glass[1]

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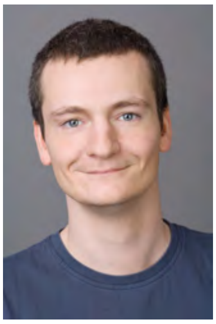
Abstract

Medieval stained glasses are characterized by a low chemical durability due to a high content of potassium and calcium oxides and a low amount of silica. Such glasses were exposed to polluted atmospheres under natural conditions within an EU-supported international exposure programme (MULTI-ASSESS), in order to investigate their weathering mechanism. After exposure times of 6 or 12 months (field exposures) the sample surfaces and their cross-sections were investigated in the scanning electron microscope in combination with energy-dispersive microanalysis (SEM/EDX). The dominant chemical species identified on the weathered samples were sulphates such as syngenite ($CaSO_4 \cdot K_2SO_4 \cdot H_2O$) and gypsum ($CaSO_4 \cdot 2H_2O$) and to a much lower extent also arcanite (K_2SO_4), chlorides (KCl and NaCl) and carbon-rich weathering products. Statistical evaluations of the leaching data for the network modifiers K^+, Ca^{2+}, Na^+ and Mg^{2+} indicate selective leaching of the main network modifier (K^+) compared to all other ions. Dose-response functions (DRFs) relating the measured leaching depths and the environmental and climatic conditions reveal statistically significant influences of the concentrations of SO_2 and NO_2, the temperature (T) and the relative humidity (RH) on the weathering process.

1. Parts of this paper were also presented at the European Master-Doctorate Course "Vulnerability of Cultural Heritage to Climate Change" of the European University Centre for Cultural Heritage. Council of Europe, Strasbourg, 7-11 September 2009.



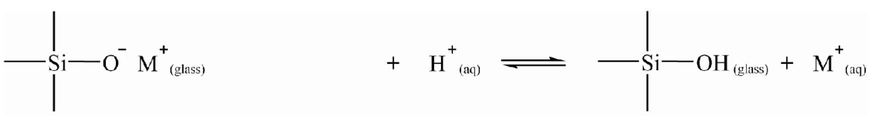
Michael Melcher
Michael Melcher is a trained chemist and received his engineering degree as well as his PhD at the Vienna University of Technology. His diploma and PhD thesis were devoted to energy dispersive x-ray analysis in scanning electron microscopy of archaeological silver objects. He is also studying mathematics and statistics at the Vienna University of Technology and has therefore the knowledge for non-destructive material as well as data analysis and data processing.

Manfred Schreiner
Manfred Schreiner is professor and head of the Institute of Science and Technology in Art at the Academy of Fine Arts in Vienna/Austria. He has vast experiences in non-destructive material analysis of art objects and has developed transportable instruments for non-invasive material analysis based on XRF. He holds also a lectureship (Univ. Doz.) for analytical chemistry at the Vienna University of Technology, where he could supervise several PhD students in the past, working on non-destructive analysis of artifacts as well as the weathering mechanism of potash-lime silica glass and the corrosion of Cu and Ag alloys. Manfred Schreiner is author and coauthor of more than 150 publications dealing with the application of scientific methods and techniques in the fields of art and archaeology.

1 Introduction

Glasses are known to be attacked by various liquid and gaseous substances. In one of the first publications on the “Corrosion of Glass Surfaces” by Morey in 1925 /1/ a discussionof the dependence of the durability of glasses on their chemical compositions can be found. Although the author states that the initial stages of the corrosion process are still unknown, it seemed to be clear that “*the power of a glass to resist corrosion is inversely proportional to the alkali content* “. In the early 1930s Zachariasen /2/ set up the first useful model for the chemical structure of silicate glasses. According to him glasses can be described as a three-dimensional network of [SiO_4]-tetrahedra, which are linked to each other sharing oxygen atoms. In the voids of these silicate structures mono- and bivalent cations such as Na^+, K^+, Ca^{2+} or Mg^{2+}, which are mostly added in the form of oxides, carbonates or nitrates to the batch of glass raw materials in order to decrease its melting temperature, are incorporated /3/. On that basis the glass corrosion process could be explained as a combination of two fundamental processes: (i) the diffusion of alkali and also alkaline earth ions out of the glass and the inward-diffusion of hydrogen-bearing species (H^+, H_3O^+ or even larger aggregates, Equs. 1a and 1b) originating from the aqueous solution (also known as “leaching”) and (ii) the so-called network dissolution caused by the attack of hydroxyl ions OH^- (Equ. 2). These silanol (Si-OH) groups may condensate reforming bridging siloxan (Si-O-Si) bonds again (Equ. 3). Hence the characteristics of the so-formed leached layer on top of the glass are a reduced alkali and alkaline earth and an increased hydrogen concentration.

The aqueous corrosion of glasses under various conditions (temperature, glass compositions, concentration of corrosion medium, ratio of glass surface area : solution volume etc.) has been discussed in the literature extensively. For example, Douglas and co-workers /4, 5/ investigated the action of aqueous solutions (pH from 1 to 13) on binary and ternary silicate glasses. They found a linear relation between the quantity of alkali extracted and the square root of time in the very early stages of the reaction, whereas at later stages the process became linearly dependent on time. Hence, they proposed an equation (Equ. 4) containing a square-root term as well as a linear term to account for these two mechanisms. While the diffusion process leads to an increase of the thickness of the leached layer, the dissolution of the silica network reduces it. A complete deduction of the mathematical background of the underlying physical processes is given by Doremus /6/.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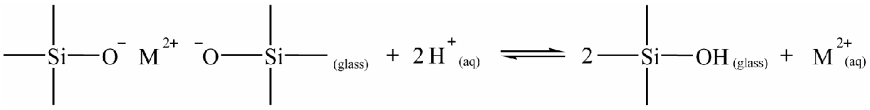
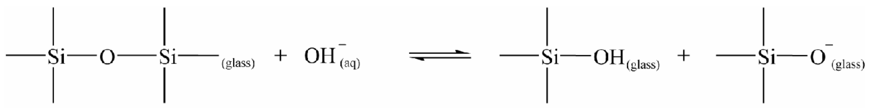


(1b)



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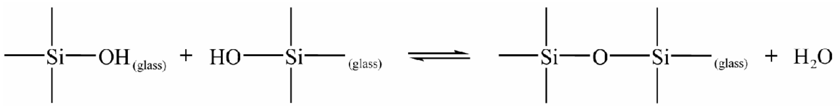

(3)

$$Q = a \cdot \sqrt{t} + b \cdot t \qquad (4)$$

Q … total amount of leached alkali ions
a, b … model parameters
t … time

In another work El-Shamy /7/ investigated the chemical durability of glasses in the system K_2O-CaO-MgO-SiO_2. The leaching experiments on glass grains in water and 0.5N HCl showed that the quantities of leached K_2O, CaO and MgO were much higher in acidic solution than in pure water. If SiO_2 was replaced by CaO (or MgO), not only the amount of leached Ca (Mg) increased, but also that of K. He also observed a sudden drop in the chemical resistance of the glasses when the silica content was reduced below 66.67 mol-%. Above this threshold the SiO^--sites are isolated by Si-O-Si groups and no interconnected path of neighbouring non-bridging oxygen (NBO)-sites exists for an easy movement of alkali ions during ion exchange. The author concludes that the silica content of the glass plays a dominant role for glass durability.

Salem et al. /8/ studied the corrosion of four types of low-durability potash-lime-silica glasses and its dependence from pH. The authors found a selective alkali and alkaline earth leaching in the pH-range from 2 to 7. Solution analyses revealed negligible silica concentrations although the typical change of the kinetics from $t^{1/2}$ to *t* occurred after about 180 minutes. Therefore, the change of corrosion kinetics is not necessarily accompanied by silicate dissolution. Furthermore, a more rapid alkali leaching is observed in acidic solutions than under neutral or basic conditions. Additionally, surface analytical investigations carried out by secondary ion mass spectrometry (SIMS) on potash-lime-silica glass treated in HCl and H_2SO_4 revealed a preferential leaching of the monovalent ions compared to Ca and a remarkable influence also of the nature of the acidic solution on the leaching process /9/.

Further fields of research with respect to the aqueous corrosion of glasses are for instance the computational simulation of the stability and durability of glasses /10, 11/ and studies concerning the immobilization of high-level waste (HLW) /12-16/. Review articles on the durability of glasses are given by Newton /17/ or Clark et al. /18/.

Similar to the corrosion of glass in aqueous media, the weathering of glass can be described as the attack of the environment (including air moisture, ambient gases or airborneparticulate matter) on the glass surface and its resulting degradation. Due to the complexity of this multiphase system bulk glass/glass surface/water-film/air there are only relative few works dealing with this type of degradation of glass. A stronger interest in the mechanisms of glass weathering came up in the second half of the 20th century, when a severe degradation of medieval glass windows in European churches and cathedrals was observed. Generally, glasses produced in medieval periods north of the Alps often consisted of comparably high amounts of network modifiers (mainly K and Ca) and low concentrations of silica /19/. These so-called potash-lime-silica or “wood-ash” glasses turned out to be much more susceptible to corrosion and weathering than ancient or modern glasses, which are of the soda-lime type.

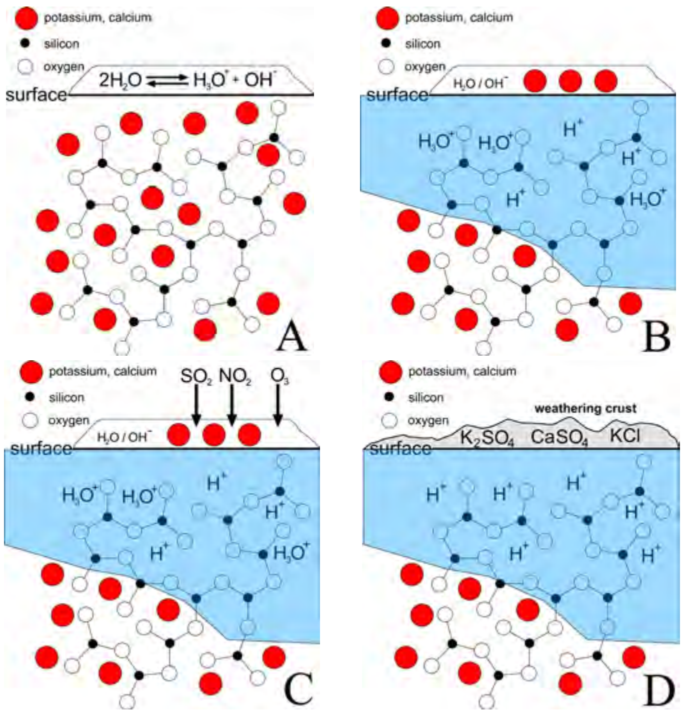

Figure 1: Scheme of the stages involved in the weathering of glass showing the formation of a water film on the glass surface (A), the extraction of cations (B), the dissolving of acidifying gases (C) and the formation of a weathering crust (D).

The principles of weathering are summarized in the scheme in Figure 1. On the glass surface a thin water layer may be formed (Figure 1A), which can reach a thickness of up to 50 microns /20/. The subsequent step is an ion exchange between the network modifiers (K^+, Ca^{2+} etc.) and the H^+/H_3O^+ ions or other hydrogen bearing species originating from the moisture layer. The consequence is a local increase in the pH value and the formation of an alkali and alkaline earth depleted layer (Figure 1B). Acidifying gases such as SO_2, O_3, CO_2 or NO_2 present in the ambient atmosphere can be absorbed in the water film (Figure 1C), leading to a decrease of the pH and a formation of various chemical compounds (such as sulphates, chlorides and to a smaller extent also carbonates, nitrates and organic compounds). Finally, these chemical compounds can precipitate and form crystalline weathering products on the surface after the evaporation of the water film (Figure 1D).

Schreiner et al. /21, 22/ investigated the concentration profiles of the glass constituents in the leached layers of glass specimens with low silica and high K_2O and CaO contents by SIMS and NRA. The authors found leached layers with H-enrichments up to 30 at-% and decreased K- and Ca-intensities within a region of a few micrometers in these naturally weathered medieval glasses exposed to the ambient atmosphere for nearly 600 years. In order to study the weathering mechanism of this type of glass extensively, in-situ investigations were carried out in an atomic force microscope (AFM), where the climatic conditions could be controlled /23-25/. While no weathering products were observed on freshly cleaved glass samples after 1h of exposure to dry N_2-gas, round features with diameters between 10 and 100 nm appeared already after 4 min if humid N_2 was used. After 90 min the surface was covered completely and a surface layer was formed. If the exposure was carried out with humid N_2 + 1 ppm SO_2, crystalline weathering products with flower-like shapes were observed immediately after the experiment started.

Results of SEM-investigations on naturally weathered glass samples of the potash-lime-silica type were also reported by Woisetschläger et al. /26, 27/. The glasses were exposed within the UN/ECE ICP-Materials project /28/ under sheltered and unsheltered conditions for 6, 12 and 24 months. The most frequently observed weathering products were sulphates in different morphologies indicating the importance of SO_2 for glass weathering.

The effects of polluted atmospheres on medieval glass paintings have been investigated by Fitz et al. /29/. It turned out that especially Gothic glass windows exhibit the severest damages compared to Romanesque or Renaissance objects. Again, the most important weathering products were sulphates, but also quartz (crystalline SiO_2) and calcite ($CaCO_3$). A correlation between the presence or absence of certain weathering products and environmental parameters such as SO_2 or O_3 could not be determined.

Munier et al /30/ studied the chemical compositions of the neocrystallisations developed on low durability model glasses of the soda-lime and potash-lime type after sheltered exposure for various months in the urban atmosphere of Paris. They found that the formation of weathering products strongly depends on the environmental parameters. Sulphate formation was only observed at relative humidities beyond 65%. While no correlation between the atmospheric NO_2 concentration and the amount of nitrates on the glass was found, nitrate production might have been favoured by the presence of deliquescent salts originating from deposited particulate matter.

Lefèvre et al. /31/ investigated the weathering crusts, which have formed on the 13th century stained glass windows of Saint-Gatien Cathedral in Tours in the Loire-valley, which have a typical medieval composition (51 to 55 wt.% SiO_2, 14 to 19% K_2O, 12 to 14% CaO and others). Besides sulphates (mainly gypsum, only traces of syngenite) also calcite, quartz and amorphous silica were detected besides numerous microparticles of different morphologies and compositions. Because of the large thickness of the weatheringcrust the authors assume a transfer of material from stone to glass. It also was concluded that airborne particulate matter is involved in the glass weathering process.

The influence of airborne particulate matter (APM) on the weathering behaviour of potash-lime-silica glasses has been previously investigated by Melcher et al. /32/. According to these studies, the level of the relative humidity (RH) plays a decisive role in the weathering of glasses. Below 70% RH a significant reduction of the weathering rate was observed. If atmospheric particles, which often consist of hygroscopic material, are present on the glass surface, no deceleration could be determined. Therefore, APM seems to be able to compensate low levels of RH in the ambient atmosphere.

In the present work results obtained from field exposures of potash-lime-silica glass under sheltered conditions (i.e. protected from rain and sun radiation and partly also from wind) for periods of 6 and 12 months are discussed. The main aim was a quantification of the influence of various environmental (SO_2, NO_2, O_3) and climatic (T, RH) parameters measured on site on the degree of glass weathering in the form of dose-response functions (DRFs). Therefore, a measure for this “degree of weathering” was developed and previously reported /33-34/. Linescan measurements in the SEM allow for the determinationof diffusion profiles of leached elements. These spectra can then be used to calculate characteristic leaching depths for the network modifier ions. Previous results of exposures performed within the UN/ECE ICP-Materials project were presented in /35-38/.

2 Experimental

The characteristics of the glass exposed (Table 1) are high K and Ca and comparably low silica concentrations, which makes the glass typical for medieval stained glass windows. The model glasses were prepared at the Fraunhofer-Institut fuer Silicatforschung in Wuerzburg/Germany by mixing oxides and carbonates of specific elements in certain stoichiometric quantities and melting in a Pt crucible at approximately 1720 K. From the glass ingots small plates of approximately $10 \times 10 \times 2$ mm^3 were cut with a low-speed diamond saw (Buehler Isomet II-1180), embedded in epoxy resin, polished (SiC-paper of 500 to 4000 mesh) and mounted

Table 1: Chemical composition in wt.% and mol-% (in brackets) of the model glass M1 exposed within the MULTI-ASSESS project.

Glass	SiO_2	K_2O	CaO	P_2O_5	Na_2O	MgO	Al_2O_3
M1	48.00 (53.16)	25.50 (18.01)	15.00 (17.80	4.00 (1.88)	3.00 (3.22)	3.00 (4.95)	1.50 (0.98)

on glass fibre reinforced plastic plates (Figure 2). After the exposure the samples were stored in plastic boxes together with drying mats in order to guarantee a low relative humidity (approximately 10-15%) in the box in order to avoid further corrosion prior to the investigations.

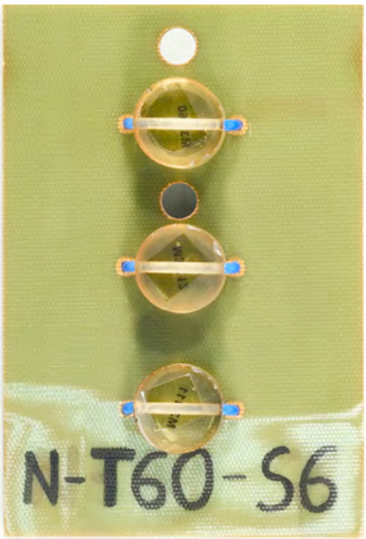

Figure 2: Glass samples embedded in epoxy resin and mounted on glass fibre reinforced plastic plates for the exposure under natural conditions.

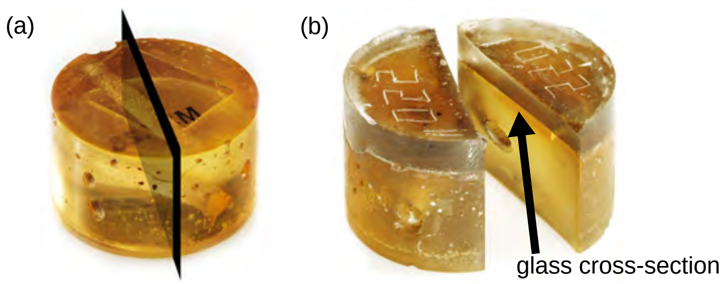

Figure 3: Original glass sample in an epoxy resin matrix with a schematic drawing of the cutting plane (a) and the cut specimen with an additional layer of resin (b).

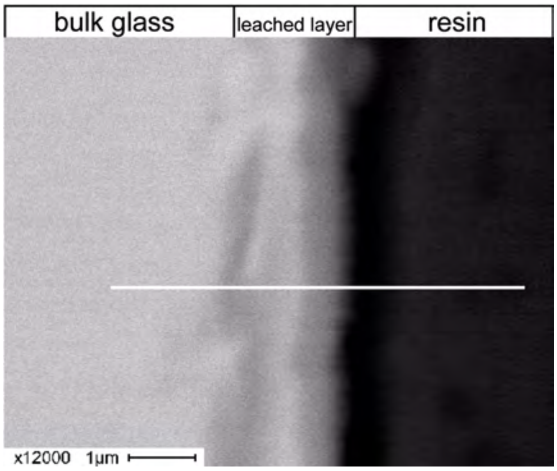

Figure 4: BE-image showing the bulk glass (bright grey, left), the leached layer (dark grey, middle) and the resin (black, right). Furthermore, the white line indicates the position of the linescan measurement.

For the SEM-investigations of the weathering products formed on the glass surfaces the samples were coated with a thin carbon layer in order to avoid any charging during the measurements. For the determination of the leaching depths, the specimens were covered with a thin layer of epoxy resin and cut perpendicular to their surface in order to produce cross-sections of the weathered glass surface (Figure 3). The depths of the leached layers were calculated from the distribution of K and Si determined from linescan measurements (Figure 4) /33/.

The field exposure was carried out in six European cities (Athens, Krakow, London, Rome, Prague and Riga) within the framework of the MULTI-ASSESS project /39/ for exposure periods of 6 and 12 months starting in November 2002. In each city up to seven exposure racks were available in order to investigate the weathering of the glasses under various environmental and climatic conditions. In total, more than 150 samples were exposed. Descriptions of the exact locations of the exposure sites and the measured environmental and climatic data are given in the literature /40/.

3 Results and Discussion

Figure 5 depicts typical examples for weathered glass surfaces. In many cases the whole surface is covered with weathering products (WPs), mostly consisting of syngenite ($CaSO_4 \cdot K_2SO_4 \cdot H_2O$) and gypsum ($CaSO_4 \cdot 2H_2O$). Often a second layer of WPs can be found on top of this crust (Figures 5a and b). The typical length/diameter of these crystals is between 5 and some ten microns, only carbon rich K- and Ca-compounds as well as chlorides (NaCl and KCl) are significantly smaller (typically 1-2 µm, Figure 5c). Mostly the glass surface, which is now depleted in the network modifiers, seems to be still intact, while on a few specimens deep cracks and loose glass blocks can be found in the superficialglass layers (Figure 5d). These detached silica-rich particles might mix with regular WPs suggesting the presence of deposited atmospheric particulates. Unfortunately, no correlation between the appearance of a certain WP and the environmental conditions at the corresponding sites can be determined, as often the same WP appears in different morphologies even on the same sample. On all exposure sites the dominant chemical species were syngenite and gypsum, the latter being identified predominantly on the 12-months samples. Arcanite (K_2SO_4) appeared on less than 20% of all samples. Chlorides as well as C-rich K- and Ca-compounds could be identified on approximately half of all specimens. Si-rich WPs could be detected mainly on the surfaces of samples, which were exposed for 12 months. A possible explanation for this phenomenon could be an increasing importance of the network dissolution (Equ. 2) with longer exposure times and a resulting dissolution of the silicate glass network. Generally, higher amounts of WPs and a stronger tendency to form weathering crusts were observed for those samples, which were exposed in more polluted areas (e.g. Krakow or London, with a strong influenceof the local traffic) than in background sites such as Rome (the site was located in a park) or Riga. In this context it must be mentioned that the location of the exposure sites is by no means representative for the whole city!

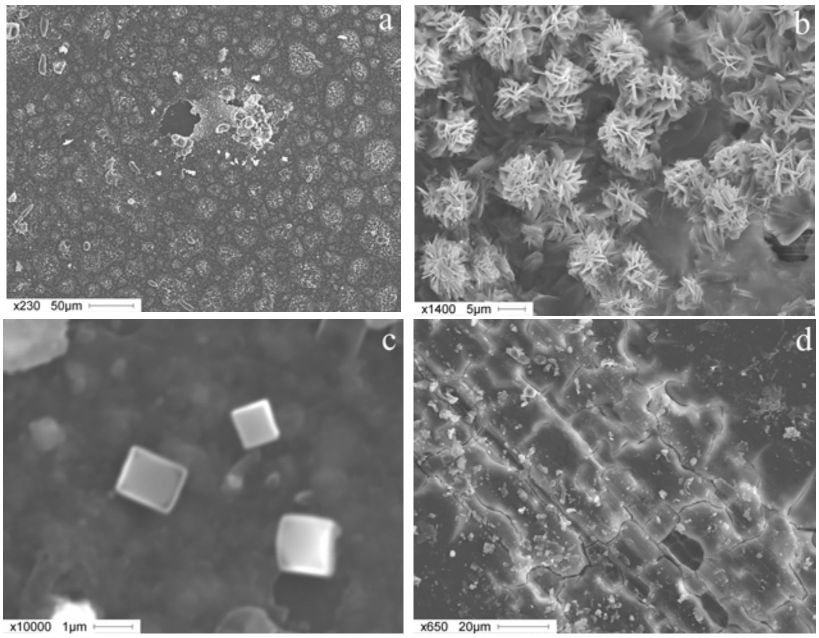

Figure 5: Weathered glass surfaces after six months of field exposure: thick weathering crusts mainly consisting of syngenite (images a and b), NaCl crystals (edge length approx. 1 µm, c) and a cracked and pitted glass surface (d)..

This observation is also reflected in the data of the leaching depths d(X) for X=K, Ca, Na and Mg /34/. The most important results are:

a) The leaching depths are different for different types of cations. Generally, the leaching depth d(K) is approximately 35% higher than d(Ca), which can be explained with the higher mobility of the potassium ion. In contrast to K, Ca is bond to two oxygen atoms in the glass and is stronger retained in the network, which results in a lower diffusion coefficient. A high correlation (R^2 = 0.9) between the leaching depths for different cations suggests reliable data.
b) In the observed time-frame (up to 12 months) the leaching depths increase with time indicating the dominance of the diffusion (Equ. 1) over the network dissolution process (Equ. 2).
c) The leaching depths seem to depend on the average pollution or "general pollution GP", which was calculated using the data for the SO_2, O_3 and NO_2-concentrations according to Equ. 5, where $\bar{c}(X)$ stands for the average gas concentration and $\sigma(X)$ for the standard deviation of the corresponding distribution. Figure 6 shows a scatter plot of the leaching depths d(K) measured for the 12-month specimens versus GP. It becomes obvious that for low pollution values (GP < -0.5) d(K) and hence the degree of weathering is roughly independent from the pollutant concentrations. Therefore, it seems justified to call this level the "background level" $d(K)_{background}$ of glass weathering (marked in grey in Figure 6), which specifies some kind of "inevitable" loss of glass material due to weathering. A reasonable determination of the corresponding "critical" pollutant concentration is not possible because of the special scaling procedure in Equ. 5. Also for comparably high pollution levels (GP>+0.5) no dependence of d(K) on GP can be determined.

$$GP = \frac{c(SO_2)-\bar{c}(SO_2)}{\sigma(SO_2)} + \frac{c(NO_2)-\bar{c}(NO_2)}{\sigma(NO_2)} + \frac{c(O_3)-\bar{c}(O_3)}{\sigma(O_3)} \qquad (5)$$

Especially the latter two points raise the question, if the factors "time" and "pollution" can be combined into one equation allowing the prediction of the leaching depth (and thereforeof the severity of the environmental attack on the glass) given solely the exposure time and certain pollution and climatic data. The dose-response functions (DRFs) listed in the Equs. 6a and b were calculated by multiple linear regression based on Equ. 4, in which the parameters a and b (representing the coefficients of the diffusion and network dissolution term) were modelled as functions of the environmental and climatic data. The leaching depths d(K) and d(Ca) were used as dependent variables. In order to assure the "best" regression model, the "all-possible-subset" method was chosen, which calculates all regression models with 1, 2, … n independent variables. The resulting 2^n equations are

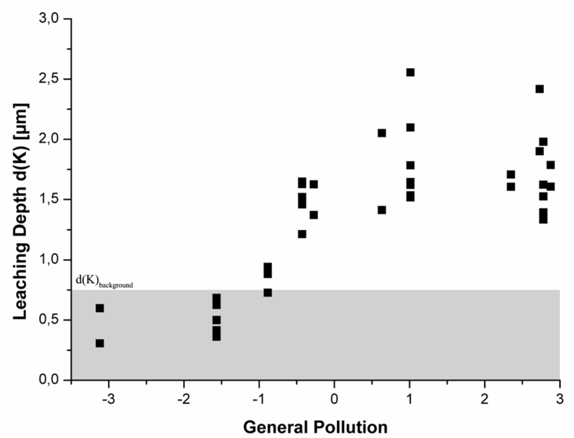

Figure 6: Scatter plot of the leaching depth d(K) after 12 months of weathering versus the "general pollution" parameter (GP). The grey band indicates the level of "background weathering".

sorted according to their prediction power expressed by R^2 and the significance of the regression coefficients. The latter restriction guarantees that only those variables (i.e. the environmental data) are considered in the final equations, which show a statistically significant (P>95%) influence on the weathering process.

For both dependent variables (d(K) and d(Ca)), the regression model with RH and $c(SO_2)$ in the diffusion term and T and $1/c(NO_2)$ in the network dissolution term showed the best results, the values for R^2 being around 0.70. A definitely poorer quality of fit (R^2 between 0.4 and 0.5) was obtained for the Na- and Mg-datasets, which is due to their lower X-ray count rate during the linescan measurements because of their much lower concentration in the glass (around 2 wt.-%). All offsets in the regression equations were significantly different from zero, which cannot be interpreted reasonably (leaching depths < 0 at t=0), but nevertheless the intercept-models were preferred, as no-intercept models generally tend to yield biased results.

$$d(K) = -0.642 + \left(0.0281 \cdot RH + 0.0388 \cdot c\left(SO_2\right)\right) \cdot \sqrt{t} - \left(0.0548 \cdot T + 2.025 \cdot \frac{1}{c\left(NO_2\right)}\right) \cdot t \qquad (6a)$$

$$R^2 = 0.709$$

$$d(Ca) = -0.794 + \left(0.0257 \cdot RH + 0.0347 \cdot c\left(SO_2\right)\right) \cdot \sqrt{t} - \left(0.0434 \cdot T + 1.912 \cdot \frac{1}{c\left(NO_2\right)}\right) \cdot t \qquad (6b)$$

$$R^2 = 0.713$$

Figure 7 depicts the scatter plots of the calculated versus the observed values for the leaching depths of the two main network modifier ions K^+ and Ca^{2+}. The graphs show that only very high d-values (i.e. higher than 2.0 µm) are systematically underpredicted, as in the case of d(K) = 2.42 and 2.55 µm, which occurred on samples exposed at the highly polluted sites in Krakow for 12 months. The over- or underprediction of extreme values is an often observed phenomenon in regression analysis and can be explained with the few amount of data, which are generally available in that region of the regression line, and the resulting higher error in estimation. In short, the quality of prediction given by the Equs. 6a and 6b is more than satisfying.

In a next step, these DRFs can be used to determine threshold levels for the concentrationsof pollutants. As leached layers were observed on all samples, the leaching mechanism is dominant over the network dissolution, which can be neglected in a rough approximation. Furthermore, only the d(K)-equation has to be considered, as K exhibits the highest leaching depth. The Equs. 6a and 6b can then be reduced to the form in Equ. 7 containing only the relative humidity RH and the concentration of SO_2 as independent variables.

$$d(K) = -0.642 + \left(0.0281 \cdot RH + 0.0388 \cdot c\left(SO_2\right)\right) \cdot \sqrt{t} \tag{7}$$

The calculated leaching depths for the element potassium and an assumed 1-year exposureat different levels of RH and $c(SO_2)$ in Tab. 2 give an estimate for the thickness of the affected surface zone (or: for the loss of glass material) under these conditions. It must be kept in mind that reasonable estimates are only possible for values of RH and SO_2 lying in the range of those data points, which were used for the calculation of the DRFs. As the data for the highly polluted regions are about d(K)=2.0-3.5 µm, the loss of approximately the half or two thirds of the glass

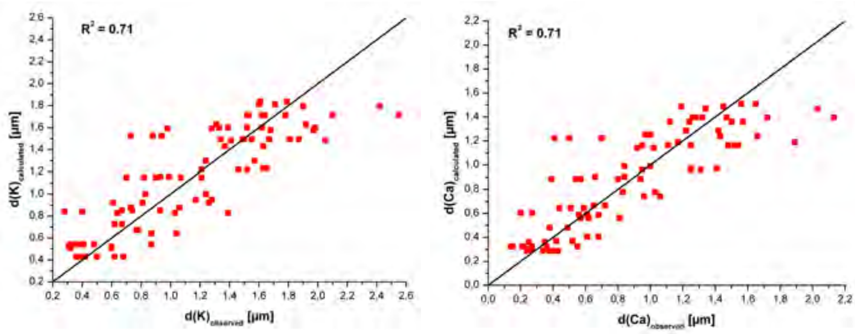

Figure 7: Scatter plots of the calculated (predicted) versus the observed (measured) values for the leaching depths d(K) and d(Ca).

Table 2: Estimates for the leaching depth d(K) for a 1-year exposure under different humidity and pollution conditions.

d(K) [µm]		$c(SO_2)$ [µg/m³]								
		5	**10**	**15**	**20**	**25**	**30**	**35**	**40**	**45**
RH [%]	**50**	0.96	1.15	1.35	1.54	1.73	1.93	2.12	2.32	2.51
	55	1.10	1.29	1.49	1.68	1.87	2.07	2.26	2.46	2.65
	60	1.24	1.43	1.63	1.82	2.01	2.21	2.40	2.60	2.79
	65	1.38	1.57	1.77	1.96	2.15	2.35	2.54	2.74	2.93
	70	1.52	1.71	1.91	2.10	2.30	2.49	2.68	2.88	3.07
	75	1.66	1.85	2.05	2.24	2.44	2.63	2.82	3.02	3.21
	80	1.80	1.99	2.19	2.38	2.58	2.77	2.96	3.16	3.35
	85	1.94	2.13	2.33	2.52	2.72	2.91	3.10	3.30	3.49

material can be avoided by reducing the pollution level to 0-10 µg/m³ SO_2, where only leaching depths between 1.0 and 1.5 microns can be expected. Nevertheless, it must be noted that these values are only estimates based on the available data and simplifying assumptions such as the disregarding of the network-dissolution term. Especially for longer exposure times the simplification of Equ. 7 might produce large deviations.

4 Summary and Conclusion

As already mentioned at the beginning, potash-lime-silica glass is very sensitive towards atmospheric corrosion. Laboratory experiments have shown that even after a few hours of exposure the first weathering products appear. Unfortunately, many objects of our cultural heritage, namely a large number of medieval stained glass windows in northern or central Europe, are made of that type of glass and are at high risk when exposed to polluted urban atmospheres.

The exposure of glasses within the framework of the MULTI-ASSESS project is an attempt to quantify this risk. Therefore, more than 150 glass specimens were systematically exposed under different environmental conditions and investigated using SEM/EDX. One-dimensional elemental distribution spectra (“linescans”) enabled the determination of leaching depths, which can be used as a measure for the corrosive attack of the environment on the glass surface. Multiple regression analysis was used as a tool to relate these leaching depths to the environmental data measured on-site. The results indicate that $c(SO_2)$, $c(NO_2)$, T and RH do have a significant influence on the degree of weathering. To the authors’ knowledge, no similar data or equations exist in the glass literature. These DRFs can now be used to predict the risk for potash-lime-silica glasses exposed to various environmental conditions or for the assessment of threshold-levels for certain parameters, which only produce a minor risk for the glass objects. Of course it must be kept in mind that long-term predictions on the basis of these DRFs might be affected with significant errors.

While sulphur dioxide has been the dominant pollutant for the last decades, the pollution situation in many European cities has changed. Nitrogen oxides as well as airborne particulate matter gain importance in this multi-pollutant situation due to the increasing car traffic. Therefore, one of the main aims in the near future in the field of glass durability assessment must be the consideration of these "new" pollutants and a quantification of their contribution to the weathering of glass.

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The Effects of Climate Change on Structural Loads

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Abstract

In this paper, the possible impact of climate change on structural safety is discussed. Our work concentrates on possible changes in the structural loads. The work presented is based on the situation for the Netherlands, but conclusions are valid for at least the north west of Europe. The fundamental choices for structural safety are discussed and the effects of climate change are discussed with respect to our current design rules. Research questions are formulated, which need to be solved to come to a general approach to incorporate climate change in design of new and evaluation of existing building structures. These research questions include the scales on which climate change scenarios are presented, both in space and in time, and also the treatment of this information with respect to design and evaluations guidelines.

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Chris Geurts works at TNO Built Environment and Geosciences and has a part time position as Professor 'Technology of the Building Envelope' at Eindhoven University of Technology, Faculty of Architecture Building and Planning. He graduated in 1992, and got his PhD at the same University. The title of his PhD thesis was ' Wind induced pressure fluctuations on building envelopes'.

Since 1997, he is working at TNO in different positions. After a period as project engineer in the subjects ' dynamics and reliability studies of structures' he works now in the field of development of new building systems. He was a member of the working group for the development of the strategic plan for TNO in the period 2011-2014.

Chris is a member of various code committees, both on national and EU level, in subjects related to the building envelope. He was member of the project team of EN 1991-1-4, the Eurocode Wind Loads, and technical secretary of CUR Recommendation 103, for the applicability of wind tunnel research for wind loads on buildings.

He is chairman of KIVI-Niria Steering Committee on Wind Technology, and is chairman of the organization of the international conference on wind engineering, to be held in 2011 in Amsterdam.

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Projects included dynamics of several high-rise buildings, reliability and dynamics of the largest Ferris Wheels in the world, the probabilistic assessment of existing concrete and steel bridges, safety analysis of large roofs of railway stations. Currently he started a project concerning the determination of the design load for traffic on bridges based on measurements in practice.

He is instructor in several courses for engineers in the field of the finite element method, probabilistic design of structures and wind-induced vibrations.

He is editor of the international journal Heron on structural engineering and a reviewer for several international journals. He publishes on a regular basis in the field of wind-induced vibrations and probabilistic design.

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Carine van Bentum works at TNO Built Environment and Geosciences. She graduated in 2002 at Delft University of Technology, Faculty of Civil Engineering. For TNO she works as a consultant and project manager in the specialties of wind, sound and vibration at the department of Civil Infrastructure.

Recent projects in which she was involved as consultant, are: wind tunnel studies of intended high-rise buildings in Rotterdam and The Hague, expert advice with reference to wind loads in urban areas, storm damages, the development of sunblind systems for facades and the determination of wind loads for solar energy systems.

As project manager she participated in the development of a calculation model for sound and vibration transmission through lightweight junctions. She contributed to two major railway projects. The projects concerned changes in rail layout and train speed and TNO made predictions of the vibration levels in adjacent residences. Both projects also contained research to measurements for vibration reduction.

Carine is instructor of several courses regarding the backgrounds of the wind loads in the Dutch builiding code and the Eurocode. She is secretary of KIVI-Niria Steering Committee on Wind Technology, and one of the organisers of the international conference on wind engineering, to be held in 2011 in Amsterdam.

1 Introduction

Buildings are designed to have at least a minimum resistance to the loads that act on the structure and on building parts such as roofs and cladding. Existing buildings, and in particularly historical buildings, may have not been designed according to standards, still these buildings should have a minimum of resistance to withstand the loads. These loads are for an important part determined by climate effects. Changes in climate therefore will have consequences for the structural loads, thus affecting the overall safety. This is relevant in the design of new buildings, but is also relevant when assessing the safety of existing structures. Design standards, e.g. the Eurocodes /1, 2/, include rules to take climatic loads by extreme winds, temperatures, rain and snow into account, both for new and exisiting structures. However, these standards do not include effects of trends caused by climate change, as given by IPCC /3/.

In this paper, the possible impact of climate change on structural safety is discussed. Our work concentrates on possible changes in the structural loads. The work presented is based on the situation for the Netherlands, using the four climate change scenarios of the Royal Dutch Meteorological Institute (KNMI) /4, 5/. The authors however believe the information in this paper is valid for a wider region in (at least) north-western Europe. Similar studies are done in other countries, and extended reports are available from the UK /6/.

First, background information on the fundamental choices for structural safety is given on which current design rules are based. Secondly, the effects of climate change for the Netherlands are discussed with respect to our current design rules. A rough estimate is made of the relevance of climate change in these rules. Finally, research questions are formulated, which need to be solved to come to a general approach to incorporate climate change in design of new and evaluation of existing building structures.

2 Structural Safety and Building Codes

The calculation of building structures in building codes is based on a reliability analysis. This analysis is based on probabilistic models for the loads on, and the resistance of the structure. All relevant aspects, both for the loads and for the resistance, are considered to be stochastic in nature, and are treated stochastically. In such an analysis, the probability densities of the resistance R of a structure and of the load effect E are predicted. A structure is safe when the probability P_f that R is larger than E is acceptably small ($P_{acceptable}$). This can be expressed as follows:

$$P_f = P\ (E > R) < P_{acceptable} \qquad (1)$$

Using statistical methods and adequate models it is possible to calculate the probability of failure P_f. Given the abovementioned variability of the loads in time, P_f is always relative to a defined lifetime of the structure.

The acceptable probability $P_{acceptable}$ depends on the importance of the building, the type of loss of performance taken into account, and the level of risk which is accepted. Risk is defined as the probability P that failure will occur multiplied by the consequences given that failure occurs, i.e: Risk=P*C. The level of risk which is accepted is determined more or less by our society, based on economic considerations and safety and welfare of human beings. Given a certain risk, the larger the consequences, the smaller the accepted probability of failure $P_{acceptable}$ will be.

For newly designed buildings, this acceptable probability of exceedance is given in building codes, e.g. EN 1990 /1/. For existing buildings, requirements are made in several international publications, such as Vrouwenvelder and Scholten /7/, Arnjberg-Nielsen and Diamantidis /8/ and Schueremans /9/. Also the building standards ISO 13822 /10/, ISO2394 /11/ and the Dutch NEN 8700 /12/ provide special guidelines for the acceptable probability of exceedance for existing buildings. These values are higher than the $P_{acceptable}$ used to design new buildings, thus accepting a higher risk for existing buildings.

For in particular monuments, no explicit rules are available in many countries. As an example, the Dutch National Annex of EN 1990 /1/ prescribes the use of design life class 4 for monuments; this means an increased reference period of 100 years in which the accepted safety level must be realised; this leads to higher design loads.

In these codes, methods to determine a design load are given. The design load and design resistance must have values which are chosen so to obtain a structure that is safe enough during its lifetime. This implies that the design load has a very small probability of exceedance in the order of about 10^{-3} or 10^{-4}. Values for cultural heritage may be smaller, but have not been given explicitly in current standards.

To establish these design loads, statistical distributions are needed of the extreme loads. Traditionally, design codes have used extrapolations of past climatic load data to help forecast future loads on buildings. The possible existence of long term trends with a period of some decades or so is not taken into account.

When climate change influences structural risks, the distribution E of the load, used to determine the design load, will change. On the other hand, changes in climate may influence the resistance R of a structure as well. An overview of possible effects, with special attention to cultural heritage is given in /13/.

A new distribution of the load effect should be based on a combined statistical analysis of past observations and the possible trends. In the following sections this is worked out for the four climatic impacts wind, temperature, rain and snow in the Netherlands. The current procedure to determine the load is described, the relevant properties in the four KNMI scenarios are discussed, and consequences, including adaptation strategies are proposed.

The KNMI defines four possible scenarios for the climate change: G, G+, W and W+ (from moderate to more extreme). For the four scenarios the effects are summarized in Table 1. The criteria for discriminating the four scenarios are the global temperature increase in 2050 and the change of atmospheric circulation over The

Table 1: Summary of effects of four possible scenarios for the Netherlands in 2050, relative to 1990 /4/.

Scenario		**1990**	**G**	**G+**	**W**	**W+**
			Summer			
Mean temperature	°C		+ 0.9	+ 1.4	+ 1.7	+ 2.8
Yearly warmest day	°C		+ 1.0	+ 1.9	+ 2.1	+ 3.1
Summer days 25 °C						
NW Netherlands		8	11	14	16	22
NE Netherlands		20	27	30	34	41
Central Netherlands		24	30	34	39	47
SE Netherlands		28	36	41	44	53
Mean precipitation	%		+ 2.8	- 9.5	+ 5.5	- 19.0
Wet day frequency	%		- 1.6	- 9.6	- 3.3	- 19.3
Precipitation on wet day	%		+ 4.6	+ 0.1	+ 9.1	+ 0.3
Potential evaporation	%		+ 3.4	+ 7.6	+ 6.8	+ 15.2
			Winter			
Mean temperature	°C		+ 0.9	+ 1.1	+ 1.8	+ 2.3
Yearly coldest day	°C		+ 1.0	+ 1.5	+ 2.1	+ 2.9
Mean precipitation	%		+ 3.6	+ 7.0	+ 7.3	+ 14.2
Wet day frequency	%		+ 0.1	+ 0.9	+ 0.2	+ 1.9
			Yearly			
Yearly maximum daily mean wind velocity	%		0	+ 2	- 1	+ 4

Netherlands in the GCM model: For scenario G, a temperature increase of +1 °C is expected and a weak change of atmospheric circulation; for scenario G+, the same increase of +1°C is expected and a strong change of atmospheric circulation; for scenario W, a temperature increase of +2 °C and a weak change of atmospheric circulation and for scenario W+, +2°C and a strong change of atmospheric circulation.

3 Wind Loads

The wind gives loads on practically all types of building structures. In the Netherlands, it is the only horizontal load on buildings, thus being relevant for the stability of structures. Additionally it leads to design loads for roofing and cladding and their fixings. Worldwide, storms have the largest contribution to the total loss figures caused by natural disasters, both insured and non-insured.

The relevant parameters which determine the wind loads can be described by the so called wind loading chain. The total wind load effect depends on the characteristics of the wind statistics (first link in the chain), terrain (second link), shape and dimensions of the building (third link), and the structural properties (fourth link). The structural response should be checked against criteria for safety and serviceability (final link).

The first link in the wind loading chain is the statistical analysis of the wind climate. In building codes, this first link leads to the definition of a basic wind velocity. The wind load is proportional to the square of this basic wind velocity. This implies that relatively small changes in the wind velocity may have a relatively large effect on the wind loading.

All other parameters in the calculation, represented in the second to fifth link, such as gust factors, aerodynamic coefficients and models for dynamic resonance of structures, are assumed independent of the mean wind velocity, and will therefore not be affected by changes in climate.

Values for the basic wind velocity in wind loading standards are based on statistical analysis of the extremes in the mean wind velocity, measured at meteorological stations. In EN 1991-1-4, the basic wind velocity is defined as a 10-minute mean wind velocity with a return period of 50 years, measured under standard conditions (10 meters height, above terrain with roughness length of 0.05 m).

Since all other parameters in the wind loading chain are not influenced by climate change, we are interested in the effect that climate change may have on the extreme wind velocity. An overview of information available from scenario studies, and based on recent observations is presented in /15/. The scatter in this information is quite large, and possible trends are much smaller than the observed scatter. Both negative and positive trends have been observed, even for meteorological stations not far away from each other. An aspect which should not be forgotten, and may partially be responsible for the scatter, is that surface observations are easily disturbed by local effects. For the Netherlands, terrain effects are routinely removed from the data, and the analysis is done based on potential wind velocities. This is however not standard practice in all countries, and trends in observed wind velocities might well be caused by these effects.

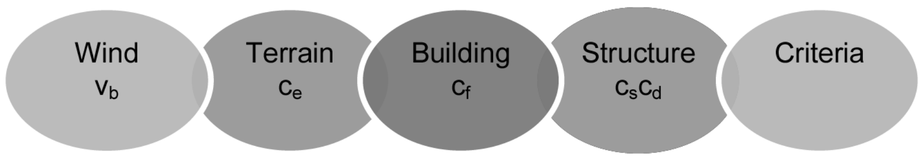

Figure 1: Wind Loading Chain, after Davenport /14/

In the Netherlands, the basis for the design wind speeds is the detailed description of the wind climate based on potential wind speeds by the KNMI in the period 1962 to 1976, which is a well documented basis for such analysis /16,17/. Based on extrapolations of these time series, the so-called Rijkoort-Weibull model, the basic wind velocity for Schiphol has a value of 27 m/s. Additionally, a design value for the wind speed is derived for structures. Based on an accepted probability of exceedance of 10-4, an average return period of about 1000 years is found. The corresponding extreme wind speed has a value of 32.3 m/s.

Focusing on climate change trends for the Netherlands, the KNMI scenarios provide an increase in the yearly maximum daily mean wind velocity of 0% (G), +2%(G+), -1%(W) and +4%(W+). No results have been found for possible trends in gust wind velocities, or for hourly or 10 minute mean wind speeds. Under stormy conditions, gusts are induced by mechanical turbulence (by terrain roughness) mainly, so therefore it is assumed that the maximum gust wind velocity changes proportional to the (hourly) mean wind velocity.

When we want to include this information in our building standards and guidelines we need answers to the following questions:

1. What is the likelihood that either one of the scenarios will be seen in future?
2. How can we translate the wind properties in the scenarios, now given as daily mean values, into extreme value with a typical averaging time of seconds?
3. Is the trend described best by a linear development of the wind velocity?
4. How do trends in wind velocity relate to other trends, e.g. in the exposed value, or terrain developments?

Up to now, no detailed study has been performed to link the scenarios of IPCC and KNMI to the way we treat the wind loading on buildings. Some work related to this theme has been done by Kasperski /18/, but this has not yet lead to inclusion of possible climate change effects in our codes.

To translate these values to new design values for the wind velocity, extreme values with return values of typically 1000 years are needed. A possible approach on how to derive such values is extensively described in /15/. This may lead to increasing design wind speeds, however a number of choices are made which are based on guesses. In this study, it is assumed that the extreme 10-minute mean wind velocity follows the trends for the daily mean wind, and that all scenario’s have the same likelihood of occurrence. This introduces new uncertainties, which need to be identified, and where possible quantified.

The consequences for the existing building stock have not yet been considered in such a way. There are scenario’s available from the insurance industry, but these focus on trends in losses, rather then in direct translation into guidelines and measures.

Besides the KNMI scenarios, it might be of use to see how the extreme wind velocities have developed over the past decades. Measurements at Schiphol Airport show a decreasing trend in storminess over the past 20 years, compared to the period of 30 years before. The timeframe studied is probably too short to conclude in general about possible climate change effects, and a single station might not be representative for the effects on a larger spatial scale. This is also true for the observations, presented in /18/ for the airport of Düsseldorf.

In a recent study /19/ the hourly mean potential wind speeds with a return period of 1000 year were investigated. These return periods are similar to the design values for the structural analysis of buildings. A Gumbel fit was applied to the yearly maxima of hourly mean wind speed and these were extrapolated to a 1000 year return period. In this study two different time series were used:

The yearly maxima from the period 1962-1976, where the actual parameters in the code originate from.

The yearly maxima from the period 1993-2007. The choice of this period was motivated by the fact that is constitutes the same observation length as the original study by Rijkoort. For further details on this information, see /18/.

The calculations where carried out for several observation stations in The Netherlands. It turns out that the extremes based on the 1993-2007 series are 10-30% lower than similar estimates for the period 1962-1976. These findings together with the observation that the number of storms decreases over the last decades may be a signal that the extreme wind speeds are decreasing with the actual climate change. However, for the design of future buildings more insight is needed in the future predictions of extreme wind speeds. Knowing however that with respect to the period 1962-1976 the actual extremes of the wind velocities are lower than the values used in the building code, provides some hidden reserve and we can have more confidence for the future where perhaps some increase can occur in the extreme wind speeds due to climate change effects that do not exist nowadays.

4 Temperature Loads

Differences in temperature cause structures to expand and become smaller. These movements should be taken into account by proper design of tolerances in the structures. This is relevant for design of all types of structures, especially where different materials meet each other, or for long or tall buildings. Historical buildings have had a large amount of temperature differences, and the question arises whether this effect is relevant for such structures as well.

Thermal actions on buildings due to climatic and operational temperature changes shall be considered in the design of buildings where there is a possibility of the ultimate or serviceability limit states being exceeded due to thermal movement and/or stresses. In EN 1991-1-5, rules are specified and in the National Annex of this standard, temperature values are provided for the specific country under consideration. Climatic and operational thermal actions on a structural element are specified using the following basic quantities:

1. A uniform temperature component ΔT_U given by the difference between the average temperature T of an element and its initial temperature T_0.
2. A linearly varying temperature component given by the difference ΔT_M between the temperatures on the outer and inner surfaces of a cross section, or on the surfaces of individual layers.
3. A temperature difference ΔT_P of different parts of a structure given by the difference of average temperatures of these parts.

The temperature of the inner environment, T_{IN}, and the temperature of the outer environment, T_{OUT} for structural calculations are specified in EN 1991-1-5.

The possible changes in temperature, collected in Table 1, are the outside temperatures. Indoor temperatures are assumed not to change, when we have to deal with the extreme loads on structures. The surface temperatures in summertime are related to the outside temperature and the amount of solar radiation. Although the scenarios do not specify any values for radiation, it is likely that this will increase as well. To what extent this will lead to an additional increase in surface temperature, should be further examined.

Winter time extremes may also be higher. The difference between summer and winter extremes however remain roughly the same in all scenarios. For structures which are only exposed to the outdoor climate (e.g. facades, masts, bridges), this difference in temperature extremes is the relevant loading. In those cases, climate change does not have an effect.

For those elements where both indoor and outdoor temperatures play a role, this may give rise to higher loads. The outside temperatures are increasing; in summer it can be until 3.1 ºC warmer outside. This means that structures have to be able to withstand larger temperature differences between inside and outside, so structural systems may need to be adapted. This is propable a minor problem when considering historical buildings, and assumed to be a possible effect only to smaller elements, such as windows.

Additionally the difference between the extreme temperature and the temperature at the moment of construction will be larger. For new buildings and possible additions to existing buildings, this means that more care should be given to dilations to take up larger expansions. For existing historical buildings this is of minor relevance.

5 Precipitation

Precipitation, in the form of rain, hail or snow, may cause damage on structures and structural parts. Apart from problems caused by rain ingress, heavy rainfall has lead to various collapses of flat roofs, caused by ponding. Snowfall may lead to heavy loads and is of concern not only for flat roofs, but also for pitched roofs when snow accumulation is likely to occur. These two loading mechanisms will be discussed here. Values for hail loads can not be derived, and are not present in any building code up till now.

Table 2: KNMI'06 scenarios for precipitation

	G +1°C	G+ +1°C	W +2°C	W+ +2°C
Winter				
average precipitation amount	+4%	+7%	+7%	+14%
1-day precipitation sum exceed once in 10 years	+4%	+6%	+8%	+12%
Summer				
average precipitation amount	+3%	-10%	+6%	-19%
1-day precipitation sum exceed once in 10 years	+13%	+5%	+27%	+10%

Table 2 shows a summary of precipitation trends in the four KNMI scenarios. The values present climatological mean values. The scenario value quantifies the change of the 30 year mean around 2050 relative to 1990. The 30-year means do not allow an interpretation of the typical interannual variability /4/. Figure 2 plots the observed precipitation with interannual variability compared to the four scenarios.

In all scenarios the precipitation amount in the winter increases. In the W+ and G+ scenarios this is partly due to an increase in the wet day frequency. The main effect is however the thermodynamic increase of precipitation with increasing temperature. In the summer the wet day frequency decreases in all scenarios. The decrease is most pronounced in the G+ and W+ scenarios. The increase of precipitation intensity within the showers leads to an increase in precipitation in the W and G scenarios. An extensive review of possible effects is presented in /15/. The most recent update of the KNMI scenarios /5/ gives more detailed information on the geographical distribution of precipitation patterns. It is concluded that for the extreme daily precipitation amounts that are exceeded with a probability of once in 10 years, the differences between the most wet and dry parts of the country are currently almost as large as the changes in the scenarios for 2050.

6 Ponding

Ponding is the phenomenon that a roof deflects under rainwater loading, which means that additional rainwater runs to the deflected spot, giving more loading and more deflection, etc., this effect is in particular relevant for relatively light weight, steel structure flat roofs. In the Netherlands, ponding leads to approximately 20 collapses per year. Historical buildings may usually not fall in the category of buildings under risk. A brief description of the possible impacts is given here to give a complete picture of the way climate change may influence relevant loading conditions for buildings in general.

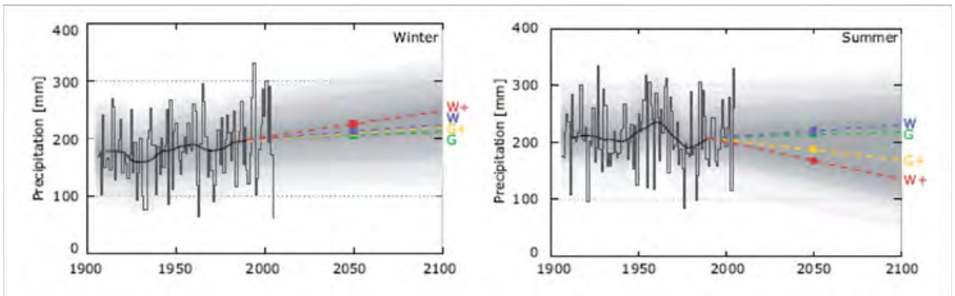

Figure 2: Time series of observed precipitation (mm/3 months in period 1901-2005). The black line is the running 30-year mean of the observations. The dotted lines are the scenarios. The shaded area represents the boundaries of the highest and lowest scenario. Left: precipitation in wintertime (December, January, February); right: precipitation in summertime (June, July, August).

The basis for the calculation is the extreme rainfall averaged over a time interval of 5 minutes with a return period of 50 years. Usually, this loading is smaller than the design snow load, which is described in the next section. For well-designed and constructed roofs equilibrium is reached and the roof is able to carry the loading. Problems occur when the rainwater discharge capacity is insufficient or the roof structure is not stiff enough.

The extreme amounts of precipitation due to climate change will probably increase. The change in 5-minutes precipitation with a return period of 50 years has not been given in the scenarios. For 1-day precipitation in summer with a return period of 10 years a maximum increase of 27% in precipitation is foreseen. Assuming this is also the increase for the 5-minute extremes, the precipitation intensity will increase to $0.592.10^{-3}$ $m^3/s/m^2$. It should be considered that the 5 minutes extremes might change more or less than the daily mean.

For the design of flat roofs it may be necessary to add more rainwater discharge capacity and a higher roof pitch. Additional stiffness of the structure and its components is another solution. Existing flat roofs may be considered and checked for this possible increase. Further research should focus on the translation of the KNMI scenarios to the 5-minutes precipitation with a return period of 50 years and on the impact on light-weight roofs and its economic consequences (for example material use).

7 Snow load

Extreme snowfall gives vertical loads on roofs, which have to be carried by the roof structure itself, and this load has to be transported to the foundation by the main structure. It is relevant in all designs, in particular for buildings. Recent damages in the Netherlands, about 100 collapses in November 2005, have renewed attention for this loading and the possible relation with climate change. Collapses occurred both on flat as well as pitched roofs.

Snow loading is determined by the number of days with snow cover and the period with continuous snow cover (called run length), the distribution of the annual maximum snow depths and distribution of snow depths /20/. The annual maximum snow depths of observations in the period 1955/1956-1982/1983 is the basis of the current building code in The Netherlands and in the National Annex of the Eurocode /1/. The annual maximum snow depths of 13 synoptic stations in The Netherlands are fitted by a Gumbel distribution and extrapolated to the 50-year snow depth (see Figure 3). A maximum 50-year snow depth is found of 35 cm.

The study from Buishand /20/ also shows that the mean annual number of days with snow cover ranges from 12 in the south-west to 31 in the north-east. The mean annual numbers of days with snow cover decreases with increasing mean winter temperature by about 10 per 1°C. The mean run length is slightly over 4 days and the distribution of the run lengths is similar over the country.

The bulk weight density of snow varies. In general it increases with the duration of the snow cover and depends on the site location, climate and altitude. For fresh snow a bulk weight density of 1.0 kN/m^3 is normally used and for wet snow 4.0 kN/m^3. Settled snow of a couple days old, the typical run length of 4 days, has a bulk weight density of 2.0 kN/m^3. Combining the snow depth and its weight a snow loading on the ground of 0.7 kN/m^2 is used in the building codes.

In all climate change scenarios, the precipitation amount in the winter increases. In the W+ and G+ scenarios this is partly due to an increase in the wet day frequency. The main effect is however the thermodynamic increase of precipitation with increasing temperature. The mean precipitation increase is mainly due to the precipitation on wet days, and this is strongly dependent on circulation. Extreme precipitation changes in winter are close to changes in the mean precipitation

No distinction is made in rain, hail and snow in the precipitation values of the KNMI’06 scenarios. Whether the expected increase in precipitation will lead to more frequent or an increase in snowfall is therefore unclear. The effects of changes in snow cover has not been analysed systematically in the whole scenario definition chain including regional climate models and observations /4/. The higher average temperatures probably lead to less snowfall. On the other hand, the expectation of larger amounts of rainfall in the winter may lead to an increasing amount of snowfall. However, the frequency of front passages also affects the snowfall and its influence is still subject of further research /21/.

All mentioned parameters: the number of days with snow cover, the distribution of the annual maximum snow depths and the run lengths and distribution of snow depths, can change due to climate change. The snow cover should be incorporated in the definition of the four KNMI scenarios before the current models can be checked and the impact on roofs, main structure and foundations of buildings can be investigated.

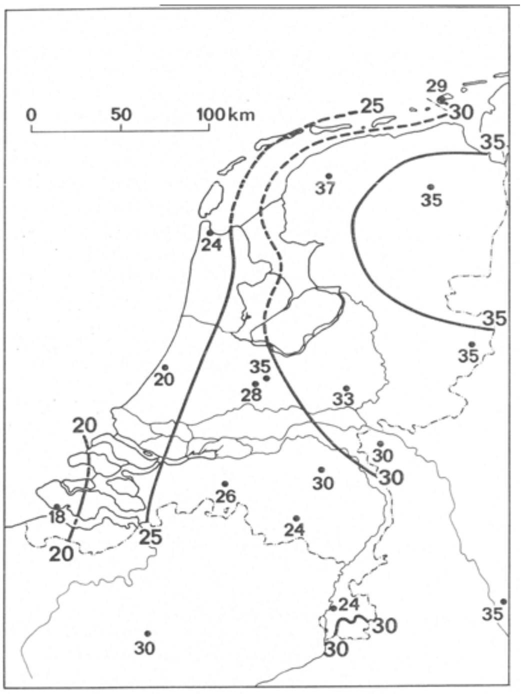

Figure 3: Estimates of 50-year snow depths (cm) based on past observations /20/.

8 Discussion

This paper focuses on the effects of changing extreme climate events to structural loads on structures, and the possible needs to adjust building standards. Building standards are used for new design of buildings or building elements. The existing building stock is usually not included. There are, on a European scale, several codes available for checking the structural safety of existing structures. If we consider existing buildings, designed and built according to the current loading standards, the overall level of safety will decrease with possibly increasing climatic loads. However, still quite a lot of research has to be performed in order to predict these future loads.

In the Netherlands a lower level of safety is prescribed when checking existing buildings. This is included in a national standard. This lower level is motivated by the fact that existing buildings have already proven to be able to withstand recent loads, so this decreases the uncertainties which are present in new designs. Now we have to deal with uncertainties in the climatic loads, we also need to include this in the way we treat our existing buildings. The effect of climate to the existing building stock may also be of special interest for the insurance industry.

Adapting building standard for design of new buildings is relatively easy, and legislation will force new designs to be engineered on these effects. Adaptation of existing buildings is more difficult to organise. It is the responsibility of building owners, and can hardly be forced. It could be stimulated to take climate change effects into account when maintenance is carried out or additions to buildings are planned. Instruments for building owners are required to make proper decisions on this matter, and to design and carry out measures to cope with these effects.

Changes in climate do not occur from one day to another. The current safety philosophy is based on an accepted risk during the lifetime of the structure. If e.g. the wind loading is the leading effect, an increase of 8% in 100 years is found as the maximum increase possible /4/, and there is time to adapt to these changes. The uncertainties involved however are large. Structural safety deals with extreme effects which may last only seconds (e.g for wind loads) or minutes (e.g. precipitation). The climate effects in the scenarios are described in terms of days or longer. In this paper we have based our conclusions on an assumption that the trends for the short terms are similar to the trends in the longer time scales; however we do not know whether this is right. Besides, we are sometimes interested in combinations of climate effects. Extreme snowfall is related to precipitation extremes and temperature. These combinations require combined statistics. We need more, and more reliable, information on the climate effects, before we can definitively change building standards or guidelines.

Since national standards are now being replaced by European codes, research on the need to include climate change in building codes should not be limited to individual countries. At least a European approach is needed here. Collaboration between meteorological offices, research institutes and building sector is strongly recommended in this work.

Regarding possible consequences for the cultural heritage sector, we should start at the definition of accepted risk, which probably differs from new buildings and also from all-day existing buildings. When this level is determined, calculations of design, or rather evaluation-, loads could be defined and determined. Simultaneously, the effects of climate change on the resistance should be assessed.

9 Conclusion

There are still large uncertainties in possible effects of climate change on the structural loads. The design rules for wind and temperature loads are probably valid for the coming years and climate change will play a small role. However precipitation values may increase considerably, affecting loads to take into account for snow loads and ponding. This is especially of concern for flat roofs with relatively light structures.

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Calcium Sulfoaluminate Cement: an Example of a Low CO_2-Alternative to Portland Cement

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Abstract

Calcium sulfoaluminate cements (CSA) are a promising low CO_2 alternative to ordinary Portland cements. They are produced by burning CSA clinker from limestone, bauxite and calcium sulfate at about 1250°C and blending the clinker with 15-25% gypsum and/or anhydrite. In this study, the hydration of CSA cement has been investigated experimentally and by thermodynamic modelling at hydration times between 1 hour and 28 days. The main hydration product of CSA is ettringite, which precipitates with amorphous $Al(OH)_3$ until the calcium sulfate is consumed after around 1-2 days of hydration. Afterwards, monosulfate is formed. In the presence of belite as minor clinker phase, strätlingite occurs as an additional hydration product. CSA cements exhibit a very dense microstructure. The pore solution, of which the pH is around 10-11, is dominated during the first hours of hydration by potassium, sodium, calcium, aluminium and sulfate. When the calcium sulfate is depleted, the sulfate concentration drops by a factor of 10. This causes an increase of the pH to around 12.5-12.8. A thermodynamic hydration model for CSA cements based on cement composition, hydration kinetics of clinker phase and calculations of thermodynamic equilibria by geochemical speciation has been established. The modelled phase development with ongoing hydration agrees well with the experimental findings.

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WTA member and board member of WTA Switzerland since 2003.

1 Introduction

Concrete, mainly based on Portland cement, is the most used material worldwide with a production of about $1.7 \cdot 10^9$ tons per year /1/. The production of Portland cement clinker accounts for about 5% of the total man-made CO_2-emissions, as the manufacturing of 1 t cement clinker generates about 800 kg of CO_2 /1,2/. Thus, there is an increasing driving force for research and development in the field of more environmental friendly binders like blended Portland cements and non Portland cements.

There are several ways to produce ecological friendly cement. One of them is based on the reduction of the clinker factor in the cements by blending Portland cement clinker with supplementary cementitious materials such as blast furnace slag or fly ash from coal power plants. The partial replacement of fossil fuels by the use of alternative fuels in the cement kiln is also beneficial concerning the CO_2 balance.

The binder chemistry can be changed to a non-Portland cement based system. There are several suitable materials described in the literature, like alkali activated slags, fly ashes or calcinated clays, sulfate activated slags (supersulfated cement) or pozzolanic cements /1,2/. A promising low-CO_2 alternative is the production of clinkers based on calcium sulfoaluminate (ye'elimite, C_4A_3s*) /1-5/. Unlike Portland cements, where the main properties such as strength are due to the presence of calcium silicate hydrates, calcium sulfoaluminate cements are systems based on calcium aluminate sulfate hydrates.

*Cement notation is used throughout the document:
A = Al_2O_3, C = CaO, F = Fe_2O_3, H = H_2O, S = SiO_2, s = SO_3.

2 CO_2 balance of Portland cement clinker

The CO_2 balance of Portland cement clinker with respect to the main clinker phase tricalcium silicate (alite, C_3S) is displayed in Figure 1. One t of alite is produced by firing 1.32 t of calcium carbonate and 0.26 t of silicon dioxide in a rotary kiln at about 1450°C. This process needs 0.15 t of fuel. The total CO_2 output is 1.02 t, of which 0.44 t originates from the combustion of the fuel (fuel-derived CO_2) and 0.58 t are released by the calcination of the calcium carbonate (raw materials CO_2). While one can reduce the fuel-derived CO_2 by the use of alternative fuels like used oil, waste tyres, sewage sludge or animal meal. Concerning the last, 46.5% substitution of primary fuel by CO_2 neutral alternative fuels was achieved in Switzerland for example in 2008 /6/. The reduction of the raw materials CO_2 is hardly possible when producing a Portland cement clinker.

During the service life of a Portland cement based concrete structure and even beyond, the concrete will take up CO_2 (carbonation), which improves the CO_2 balance in a long term perspective. However, carbonation is in general an unwan-

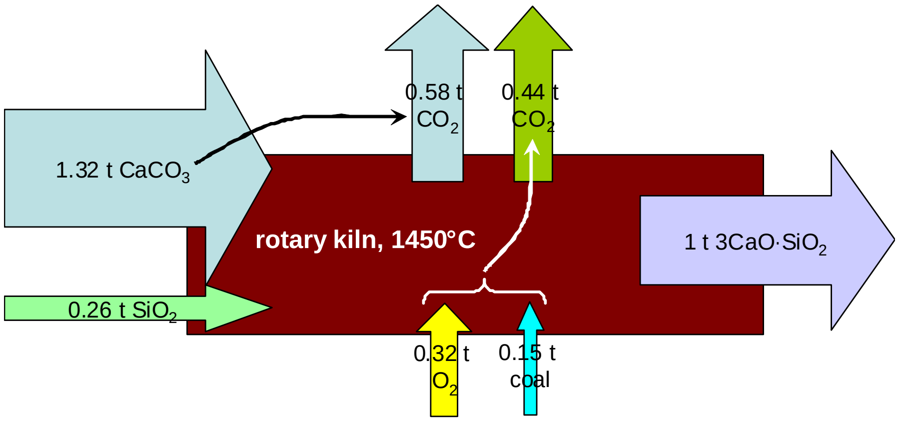

Figure 1: CO_2 emission during the formation of tricalcium silicate in the cement kiln. data taken from /1/.

ted process in concrete technology, as it leads to a decrease of the pH of the concrete's pore solution which is unfavourable for corrosion of the steel reinforcement. In order to examine the impact of CO_2 re-absorption, a study on the CO_2 balance of Scandinavian cement production was carried out in Denmark /7/. A period of 100 years was considered in the calculation and a service life of concrete structures of 70 years was assumed. It was assumed further that the building is dismantled afterwards and the crushed concrete is deposited on a landfill for 30 years. The outcome of the study is that after 100 years between 58% and 86% of the concrete should be carbonated. Thus, re-absorption of CO_2 by concrete structures may play a role in the mid- and long-term perspective. However in the current situation of strongly increasing worldwide cement production, changes in cement composition with respect to lower CO_2 emissions are needed.

3 History, properties and application of CSA cements

Calcium sulfoaluminate cements (CSA), which contain the ye'elimite phase (C_4A_3s) as major constituent, are regarded as a promising low CO_2 alternative to Portland cements due to several reasons /1/, see also Table 1:

- Compared to alite (1.80 g CO_2 per ml of the cementing phase when made from calcite and silica), ye'elimite releases only 0.56 g CO_2 per ml of the cementing phase when made from limestone, alumina and anhydrite.
- They can be made from calcium sulfate, limestone and bauxite at a temperature of about 1250°C. Thus, the firing temperature is about 200°C lower than for ordinary Portland cement clinker. The heat of formation of ye'elimite (800 kJ/kg) is remarkably lower than the one of C_3S (1848 kJ/kg) /5/.

Table 1: Comparison between ordinary Portland cement and calcium sulfoaluminate cement

	Ordinary Portland cement (OPC)	**Calcium sulfoaluminate (CSA) cement**
main phases	C_3S, C_2S, C_3A, C_4AF	C_4A_3s (ye'elimite)
raw materials	limestone & clay	limestone, bauxite & anhydrite
burning temperature	1450 °C	1250 °C
CO_2 release from raw materials	C_3S: 1.80 g/ml	C_4A_3s: 0.56 g/ml
grindability	medium	easy
gypsum addition	4-8 wt.-%	15-25 wt.-%
w/c total hydration	0.4	0.6
main hydration products	C-S-H phases, portlandite, ettringite, AFm-phases*	ettringite, AFm-phases*, amorphous $Al(OH)_3$

* monosulfate = $C_3A{\cdot}Cs{\cdot}12H$ or related phases

- Various industrial by-products or waste materials like fly ash, blast furnace slag or phosphogypsum can be applied for the production of calcium sulfoaluminate based clinkers /8/.
- CSA clinker is easier to grind than ordinary Portland cement clinker or supplementary cementitious materials like ground granulated blast furnace slag or fly ash.

CSA clinker, which mostly contains around 30-70% C_4A_3s, is usually interground with 15-25% of calcium sulfate to obtain the CSA cement. The main hydration phase of CSA cements is ettringite (tricalcium aluminate trisulfate hydrate, $C_3A{\cdot}3Cs{\cdot}32H$).

Since the Sixties calcium sulfoaluminate has been used as cementitious material, after it was patented by Alexander Klein as an expansive or shrinkage compensating addition to cementitious binders (“Klein-compound”) /9/. Such CSA based expansive agents contain besides calcium sulfoaluminate free lime and calcium sulfate /10/. In contrary, CSA cements themselves generally do not contain large quantities of free lime. While the application of CSA cements in Europe is not widespread yet, they have been produced, used and standardised in China for more than 30 years, where they are known as the third cement series /3,5,11-14/.

Setting times (typical between 30 min and 4 h) and strength development (generally a higher early and late strength compared to Portland cement) of CSA cements depend on their ye’elimite content, on the kind and content of minor phases as well as on the amount and reactivity of the added calcium sulfate /

4,5,11,13-17/. Heat of hydration is quite high (e. g. close to 400 J/g cement after 72 h /18-20/) and mostly develops during the first 24 hours.
In the absence of calcium oxide or calcium hydroxide, which accelerates ettringite formation /15,17/, CSA cements are often dimensionally stable /15/. They exhibit a chemical shrinkage about twice as high as Portland cements /19,20/. This is related to the fact that the apparent density of the water bound in the hydrate phases, like ettringite, is higher than the density of free water. However, expansion may occur if ettringite forms in reasonable amounts after setting /21/, which can be triggered by the amount of added calcium sulfate /14/. Due to the high water/cement ratio needed for complete hydration, typically around 0.60, CSA cements usually applied at lower water/cement ratios of around 0.30-0.45 tend to undergo self desiccation due to a lack of water needed for hydration /5/.
Building materials based on CSA cements show a dense pore structure, which exhibits a good impermeability towards water or air /11/, explaining the favourable durability properties of these cements. Durability with respect to freezing/thawing, chemical attack (e. g. by sulfates, chlorides), carbonation, steel reinforcement corrosion or alkali-aggregate reaction seems to be comparable to conventional Portland cement based materials /3-5,11-14,16,21/.

CSA cements are used mainly in the following cases:

- Since the Seventies, CSA cements have been used mainly in China as binder for concrete in a wide range of concrete applications. Among them are precast concrete (e. g. beams, columns), leakage and seepage prevention projects, concrete pipes, pre-stressed concrete elements and shotcrete /3-5,12-14/.
- They are applied as expansive compound in shrinkage compensating or expansive cementitious mortars /9,10,14/. These expansive compounds contain generally a reasonable amount of free lime.
- In special rapid setting and rapid hardening mortars they can be used in blends with ordinary Portland cement and calcium sulfate /22,23/. These ternary systems usually exhibit a very quick setting and thus require the use of a retarding admixture.
- Due to their low pH value, their low porosity and the ability of ettringite and AFm phases to bind heavy metals, CSA cements and their blends with Portland cement are used in the field of hazardous waste encapsulation /24,25/.

4 Hydration of CSA cements

4.1 Overview

About 15-25 wt.-% of gypsum is usually interground with the clinker for optimum setting time, strength development and volume stability /5/. The hydration of the CSA cements mainly depends on the amount and reactivity of the added calcium sulfate as well as on the kind and amount of minor phases present /3-5,14,15,17-19,26,27/. The amount of water necessary for complete hydration is determined by the amount of calcium sulfate added (maximum around 30%) /5/. The required water/cement ratio for complete hydration is higher compared to an OPC, e. g. 0.78 for pure ye'elimite reacting with 2 moles of anhydrite or around 0.60 for technical cements /5,14/.

With water, pure C_4A_3s reacts according to equation (1) to monosulfate and aluminium hydroxide. With gypsum or anhydrite, C_4A_3s forms ettringite and aluminium hydroxide, see equation (2), until the calcium sulfate is consumed. Afterwards, monosulfate is generated according to equation (1). Aluminium hydroxide does not occur as a crystalline phase, but as an amorphous (gel-like) form.

Technical cements contain accessory phases, like dicalcium silicate (belite, C_2S), calcium aluminate (CA) or tetracalcium aluminate ferrate (C_4AF) /28/. These phases participate in the hydration reactions and lead to the formation of additional hydration products like strätlingite (C_2ASH_8, see equation (3)), calcium aluminate hydrates (e. g. CAH_{10}) or calcium silicate hydrates (C-S-H).

$$C_4A_3s + 18\,H \quad C_3A{\cdot}Cs{\cdot}12H + 2\,AH_3 \text{ (monosulfate formation)} \tag{1}$$

$$C_4A_3s + 2\,CsH_2 + 34\,H \quad C_3A{\cdot}3Cs{\cdot}32H + 2\,AH_3 \text{ (ettringite formation)} \tag{2}$$

$$C_2S + AH_3 + 5\,H \quad C_2ASH_8 \text{ (strätlingite formation)} \tag{3}$$

4.2 Hydration of a technical CSA cement

A technical CSA cement was examined at different hydration times by solid phase and pore solution analysis as well as by thermodynamic modelling. For experimental details see /18,19/. The results of chemical analyses of the tested CSA cement are given in Table 2. Its main constituents derived from X-ray diffraction (XRD) analysis and stoichiometric calculations based on the X-ray fluorescence analysis are ye'elimite (54%), belite (19%) and anhydrite (21%). Minor phases are mainly iron and titanium containing phases, which can be regarded as hydraulically inactive.

Table 2: Chemical analysis results of the tested CSA cement (density 2.84 g/cm^3, Blaine surface area 4630 cm^2/g)

	CaO	SiO_2	Al_2O_3	Fe_2O_3	MgO	Na_2O	K_2O	TiO_2	SO_3	L.O.I.*
mass-%	41.2	6.9	26.8	0.88	0.75	0.13	0.40	1.2	19.5	1.84

* L.O.I. = loss on ignition

The changes of the solid phase composition with ongoing hydration were determined by XRD and thermogravimetry (TGA). XRD analyses (Figure 2) of the CSA reveal that even after 1 h of hydration part of the C_4A_3s and anhydrite are consumed, and ettringite is formed as a new crystalline phase. Secondary gypsum is never detected by XRD, as sulfate originating from the dissolution of anhydrite is rapidly consumed by the formation of ettringite. Between 1 and 4 h a moderate progress of hydration is visible. After 2 d of hydration, when the formation of ettringite is terminated, traces of monosulfate are detectable, while anhydrite is almost depleted. After 28 d, strätlingite (C_2ASH_8), is formed from belite and aluminium hydroxide according to equation (3). At 28 d the crystalline phase assemblage consists of the hydrate phases ettringite, strätlingite and traces of monosulfate, as well as some non reacted traces of C_4A_3s, anhydrite and inert phases. It can be assumed that $Al(OH)_3$ (gibbsite) occurs as an amorphous form since it is not detected by XRD.
The XRD results are confirmed by the TGA analyses (Figure 3). Contrary to the XRD measurement, $Al(OH)_3$ is detectable due to its water loss around 300°C. After 1 h of hydration, ettringite (weight loss at 50°C-120°C) has formed together with some $Al(OH)_3$. Hydration continues until 2 d exhibiting an ongoing formation of ettringite and $Al(OH)_3$. After 2 days of hydration, monosulfate starts to form (weight loss at about 190°C), and ettringite content stays constant. There is no significant increase of $Al(OH)_3$ between 2 d and 28 d. This can be explained by a consumption of $Al(OH)_3$ to strätlingite, as the belite takes part in the hydration process after several days. The strätlingite formed can be identified in the sample hydrated for 28 d (weight loss at 160°C) besides ettringite, $Al(OH)_3$ and traces of monosulfate.

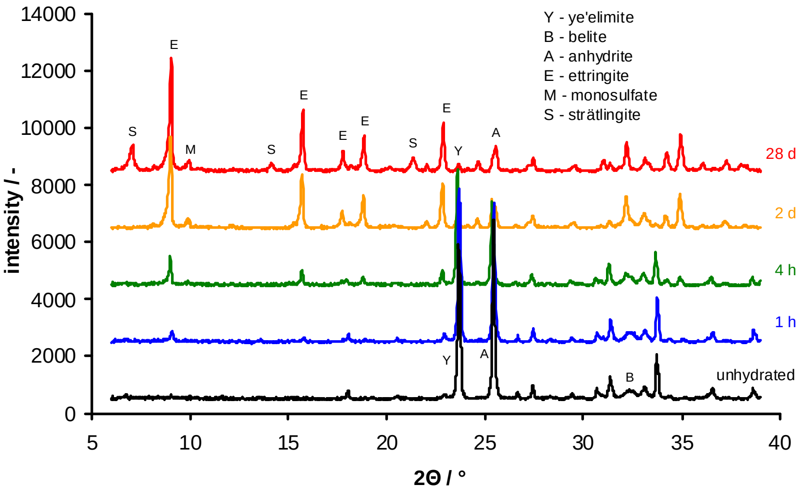

Figure 2: Solid phase development of CSA cement (water/cement = 0.80) with increasing hydration time measured by X-ray diffraction /18,19/.

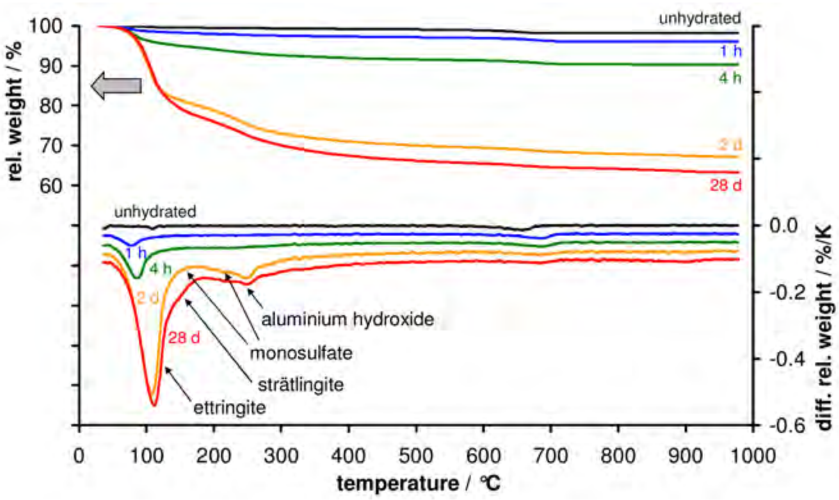

Figure 3: Solid phase development of CSA pastes (water/cement = 0.80) with increasing hydration time measured by thermogravimetric analysis /18,19/. Note, that 0.05 %/K is added for each time step to the differential curve.

Figure 4 displays the microstructure of hydrated CSA cement. After 2 d of hydration, it already shows a dense microstructure. Besides unhydrated clinker grains, ettringite needles of about 10 µm length and gel-like areas mainly consisting of aluminium hydroxide can be identified with the help of energy dispersive X-ray microanalysis (EDX). After 28 d of hydration, some clinker relicts are still present. Plate-like crystals of strätlingite can be recognized.

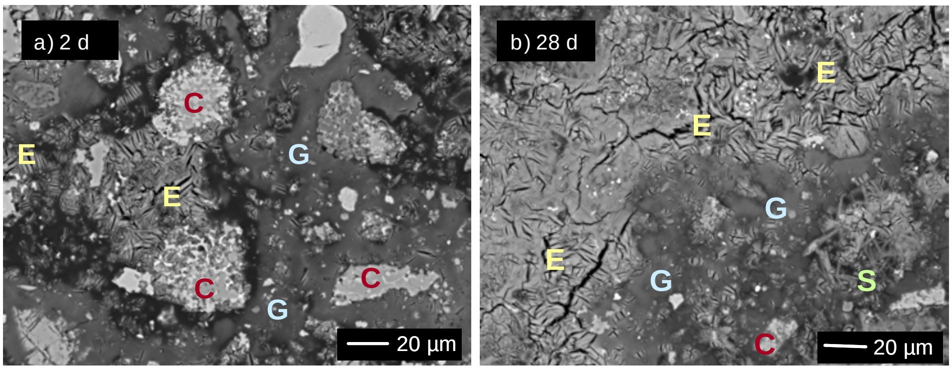

Figure 4: Scanning electron micrographs (polished sections) of CSA pastes after a) 2 days and b) 28 days of hydration (water/cement = 0.80) /18,19/.
C = clinker, E = ettringite, G = gel-like Al(OH)3, S = strätlingite

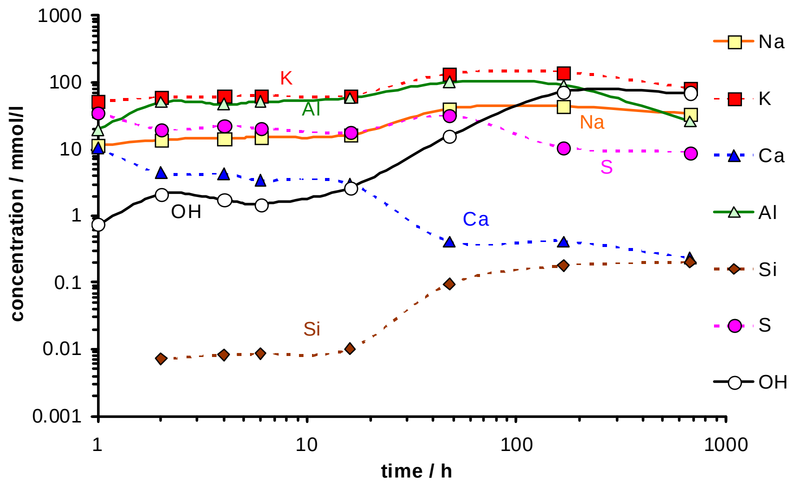

Figure 5: Composition of the pore solution as a function of hydration time of CSA pastes (water/cement = 0.80) measured by ICP-OES /18,19/.

The composition of the pore solution is shown in Figure 5. During the first hours of hydration the pore solution is dominated by alkali, calcium, aluminium and sulfate ions. The pH values are quite low (pH 10.9-11.7) compared to a Portland cement (pH 13-14). As hydration proceeds, the alkali ion concentration in the pore solution increases due to the continuous release of Na and K by dissolution of the reactive anhydrous phases. Between 2 d and 7 d of hydration a remarkable change in the pore solution chemistry occurs. Due to the depletion of anhydrite, sulfate and calcium concentrations decrease and hydroxide concentration increases, leading to a pH value of 12.8 after 28 d. The silicon concentrations are generally in the range of 0.01-0.05 mmol/l and increase with increasing pH of the pore solution.

Thermodynamic modelling was carried out using the geochemical GEMS-PSI software /29/, coupled with a cement-specific CEMDATA database /30/. A thermodynamic model of the hydration of CSA cements was set up, based on the empirical dissolution kinetics of their relevant phases, in this case C_4A_3s, C_2S and anhydrite /19/.

Figure 6 shows the thermodynamic modelling of the phase development (volume % of the phase content with respect to the sum of the initial amount of dry cement and mixing water) with ongoing hydration. Ye'elimite, belite and anhydrite are dissolving over time. Dissolution of the phases mentioned above leads to the formation of ettringite, amorphous $Al(OH)_3$ and strätlingite, while the quantity of pore solution decreases. Monosulfate forms after about two days of hydration, when the main part of ye'elimite and anhydrite has already dissolved. At this time, the formation of $Al(OH)_3$ stops and its amount decreases slightly while strätlingite is formed. After 28 d, ettringite and strätlingite are the main hydration products, $Al(OH)_3$ and

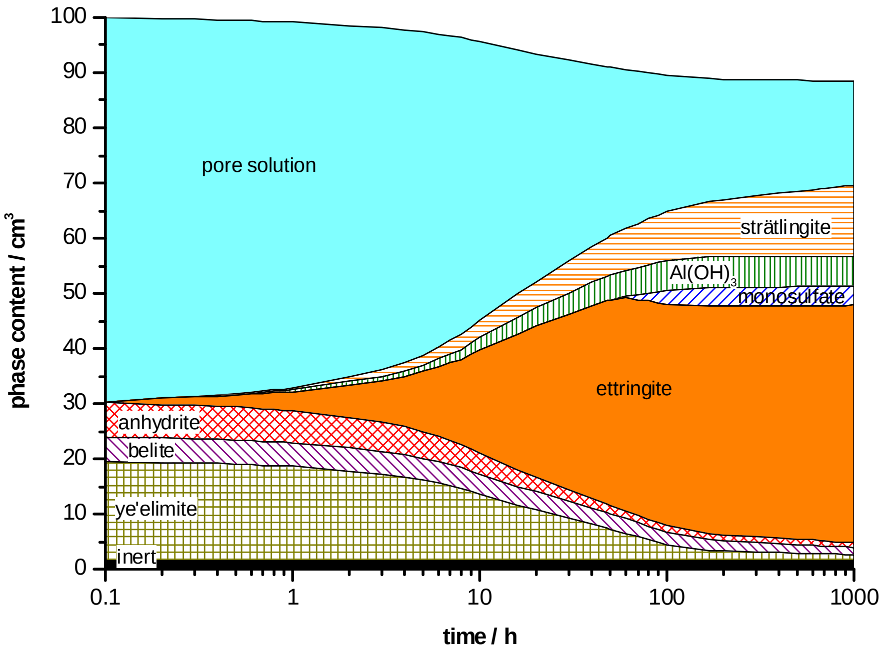

Figure 6: Thermodynamic modelling of the phase development of CSA pastes (water/ cement = 0.80) as a function of hydration time /19/. The volumes refer to the initial volume of cement plus water, which is set to 100 cm^3.

monosulfate are minor products. The results of the thermodynamic modelling are in agreement with the experimental results.As expected, hydration leads to an increase of the volume of solids and to a decrease of the volume of the liquid phase. The total volume decreases with time, giving a calculated chemical shrinkage of 11.5 cm^3/100 g dry cement after 28 days, which fits well to experimental data on a similar system /21/.

5 Conclusion

The hydration mechanism of a calcium sulfoaluminate cement has been investigated by experimental means as well as by thermodynamic modelling. During the first hours of hydration, ettringite and gel-like $Al(OH)_3$ form from the hydration of ye'elimite with anhydrite. After the depletion of the calcium sulfate, monosulfate starts to form, and a strong decrease of calcium and sulfate concentration in the pore solution, as well as an increase of pH from about 10-11 to 12.5-12.8, are observed. From the belite present as minor phase, strätlingite forms as further hydration product, consuming a part of the $Al(OH)_3$. The formation of C-S-H phases is not observed experimentally. The microstructure appears quite dense after 2 d and after 28 days it contains reasonable amounts of large strätlingite crystals.

The thermodynamic model developed in this study can be used to predict the hydration of CSA cements, allowing an easy and fast parameter variation like clinker composition, amount of calcium sulfate or water/cement ratio.

Currently, the use of CSA cements is reinvestigated mainly due to the climate debate, but also to their special properties like rapid strength development and low porosity. New products are coming to the market but are currently more expensive than Portland cement. At present state, it is not yet evident if CSA cements could significantly contribute to lowering the CO_2 emissions due to the production of cementitious building materials. Moreover the current lack of standardisation (except in China) might be an obstacle against a more widespread use of CSA cements.

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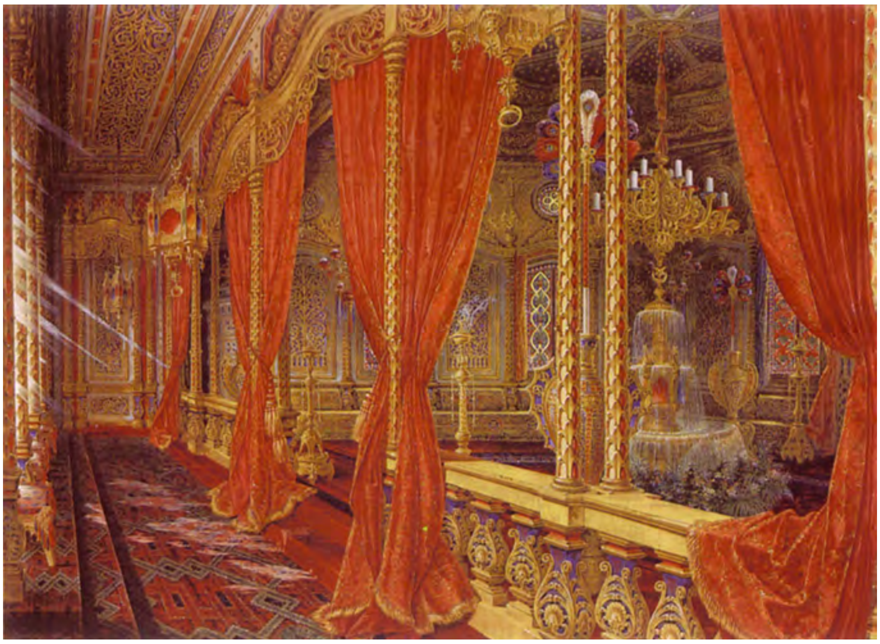

Chapter 3: Impact of Climate Change on the Indoor Environment

"Effect of Climate Change on Built Heritage",
WTA-Colloquium, March 11-12, 2010, Eindhoven, The Netherlands,
WTA-Schriftenreihe, Heft 34, 111–130 (2010)

Climate Change Consequences for the Indoor Environment in The Netherlands

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Abstract

Scientists warn us about climate change and its effects on the outdoor environment. These effects can have significant consequences for the indoor environment, also in the Netherlands. Climate changes will affect different aspects of the indoor environment as well as the stakeholders of that indoor environment. Buildings will require less heating in the winter and more cooling in the summer, resulting in an increase use of air conditioning systems. Increasing relative humidity indoors and rising moisture from the ground will cause significantly more mould problems resulting in further health risks. Additionally, effects on lighting and acoustical quality, but also several psycho-social effects seem likely to occur. It is concluded that possible adaptations, whether performed at the **source** of climate change effects, the **building** or by **involving people**, can only be executed properly when the possible effects of climate changes on occupant wishes and needs as well as the interactions of these occupants with their environment are well understood.

Myriam Aries

Myriam Aries holds a MSc in Building Technology (TU Delft, NL) and a PhD in Building Physics/Lighting (TU Eindhoven, NL). Following the completion of her PhD she has worked as a post-doctoral fellow of Lighting (NRC Canada) for two years, and as an Indoor Environment and Health researcher (TNO Built Environment and Geosciences, NL). After a M.Sc. project with regard to visual comfort, she has expanded her knowledge of human lighting demands and health requirements in office buildings during her PhD-research. During the two-year post-doctoral fellowship she continued her work with light and health with the lighting group of NRC Canada. She worked on (statistical) models explaining the relationship between the physical aspects of the (work) environment, environmental satisfaction, health, and job satisfaction. At TNO, her work had focused predominantly on practical and socially relevant (health) assessment research and tools. Currently, she is working as a assistant professor lighting at the technical university in Eindhoven.

Philomena M. Bluyssen

Mrs Dr. Philomena M. Bluyssen performed her PhD at the Technical University of Denmark on the topic Air Quality under supervision of Prof. Fanger. In 1998 she received her MBA degree at the University of Rotterdam. From 1991 she has worked with TNO mainly on European projects related to health and comfort of people in indoor environments. Some of the projects she coordinated are:

1992-1995: the European audit project to optimize indoor air quality and energy consumption in office buildings

1998-2000: the European project AIRLESS: a project focussed on HVAC systems as pollution sources

2002-2004: the European project HOPE (Health Optimisation protocol for Energy-Efficient buildings)

2007-2010: the European project HealthyAIR.

She is member of ASHRAE, ISIAQ and CIB. She has written more than 145 publications on national and international conferences and journals. Recently she wrote a book titled: The Indoor Environment Handbook: How to make buildings healthy and comfortable (published by Earthscan in the UK). This book is an attempt to capture the essence of the challenge faced in managing buildings: understanding the ways people perceive and react to the space they live and work in.

1 Introduction

Despite the fact that the Earth always had a changing climate throughout its 4.5 billion years of history, today's climate changes seem different than before e.g., /1/. Preceding evidence shows that humanity plays an important role with respect to climate change, as concluded by the Intergovernmental Panel on Climate Change [IPCC] /2/ in the Fourth IPCC Assessment Report ‘Climate Change 2007’. Since the first measurements of CO_2 in 1958 by Revelle /3/, scientists have warned us about climate change and possible consequences. The problem is named ‘radiative forcing’, which is defined as the change in average net radiation at the top of the troposphere (lower atmosphere). Positive radiative forcing warms up the Earth’ surface to keep the heat balance. Negative radiative forcing would cool down the surface of the earth /4/. In scientific literature, a debate and controversy exists about the actual cause of radiative forcing; in particular about the relative importance of anthropogenic or human induced sources versus natural influences such as the variability of the solar activity and radiation. Although it seems that something is happening with our climate, what exactly will happen in the next centuries is difficult to predict.

From the observed trends, altered frequencies and intensities of extreme weather, together with sea level rise, are expected to have mostly adverse effects on natural and human systems. The American National Research Council /5/ concluded that climate change has the potential to influence the frequency and transmission of infectious disease, alter heat- and cold-related mortality and morbidity, and influence air and water quality. Depending on the scenarios occurring from now on, some health consequences related to climate change can be identified:

- Direct temperature effects: Particular segments of the population such as those with heart problems, asthma, the elderly, the very young, and the homeless can be especially vulnerable to extreme heat.
- Extreme events: Extreme weather events can be destructive to human health and well-being. An increase in the frequency of extreme events may result in more event-related deaths, injuries, infectious diseases, and stress-related disorders.
- Climate-sensitive diseases: Climate change may increase the risk of some infectious diseases, particularly those diseases that appear in warm areas and are spread by mosquitoes and other insects. Though average global temperatures are expected to continue to rise, the potential for an increase in the spread of diseases will depend not only on climatic but also on non-climatic factors, primarily the effectiveness of the public health system /6/.
- Air quality: Respiratory disorders may be exacerbated by warming-induced increases in the frequency of smog (ground-level ozone) events and particulate air pollution. Ground-level ozone can damage lung tissue, and is especially harmful for those with asthma and other chronic lung

> diseases. Sunlight and high temperatures, combined with other pollutants such as nitrogen oxides and volatile organic compounds, can cause ground-level ozone to increase. Climate change may increase the concentration of ground-level ozone, but the magnitude of the effect is uncertain. Climate change may indirectly affect the concentration of particulate matter [PM] pollution in the air by affecting natural or "biogenic" sources of PM such as wildfires and dust from dry soils.

2 Climate change scenarios

Generally, Global Climate Models [GCMs], driven by greenhouse gas emission scenarios, are used to construct regional climate scenarios. Global models are downscaled and completed by e.g., statistic data to give information on a regional scale. The climate change scenarios for the Netherlands are constructed differently from this general approach /7/. For the Dutch situation, four scenarios of climate change have been developed by the Royal Netherlands Meteorological Institute [KNMI] /8/. In all of the four possible New Climate Change Scenarios for the Netherlands (G, G+, W, and W+), similar effects of climate change will be experienced by the Netherlands and its surrounding regions /8/. The majority of these effects will have significant consequences for the indoor environment of Dutch buildings. General tendencies, relevant for the indoor environment, in all four scenarios are:

- (Outdoor) temperatures will increase (see Figure 1), resulting in a higher frequency of more temperate winters and warmer summers;
- Winters will, on average, become wetter, and intensity of extreme rain will increase;
- Intensity of extreme rain in the summer will increase, however, in contrast, the number of rain days in summers will decrease (in two out of the four scenarios);
- Changes in wind regime are small compared to current natural variation. It is likely that wind speeds and frequency of storms will increase, however this scenario is uncertain.

The temperature increase over the previous decades was not globally equal. Temperature in the Netherlands has increased more rapidly than the global average temperature /9/ (PCCC, 2007), and most recent sources report the temperature to be increased even faster than forecasted previously /10/. One of the causes is changes in atmospheric circulation, like e.g. the predominating wind direction. Southern and western winds have contributed strongly to the warmth record in autumn and winter. The atmospheric circulation naturally shows large changes. Global warming will most likely influence atmospheric circulation; however, the extent is not yet determined unambiguously.

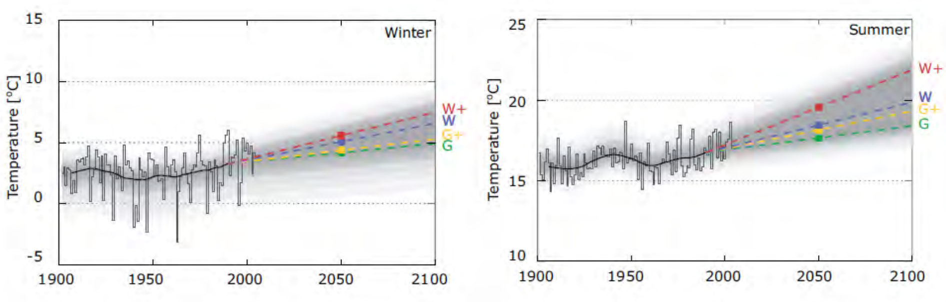

Figure 1: Temperature in De Bilt between 1900 and 2005: the four climate scenarios for 2050 (coloured points) for winter (left) and summer (right) (after /8/)

Intensity of extreme rain in the summer will increase, although, in contrast, the number of rain days in summers will decrease. The relative humidity in summer remains high, which is ideal for different types of insects (anopheles and tiger mosquitoes). Related to temperature and humidity, it seems that eventually the Dutch climate may change into a type of climate that is currently seen in countries close to the equator. There is first evidence to suggest that part of the recent changes in the lichen flora of the Netherlands is attributable to an increase in temperature /11/. (Sub)tropical types start to invade whereas the number of northern types decreases, clearly shown from the shifts in the composition of the Dutch lichens (see also Figure 2).

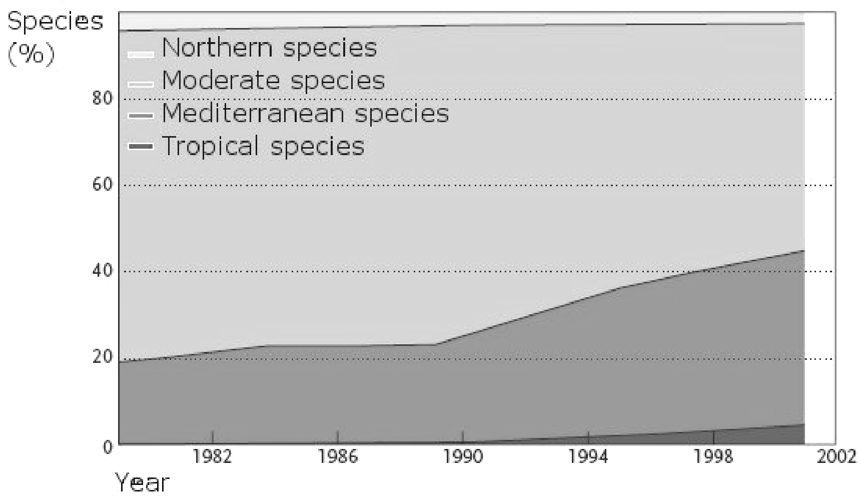

Figure 2: Recent shift in Dutch lichens species (after /11/)

3 Possible climate change consequences for the indoor environment

3.1 Introduction

Changes in the outdoor environment have impact on the indoor environment. Cities are probably the worst case scenario. It has long been recognized that the built environment can have so called 'Urban Heat Islands' [UHI]. An UHI refers to the tendency for a city to remain warmer (up to 5–6°C) than its surrounding countryside /12/,/13/. Vegetation and soil moisture normally use much of the absorbed sunlight to evaporate water as part of photosynthesis. Due to a lack of vegetation and soil in most present-day cities, sunlight is absorbed by manmade structures like roads, parking lots, and buildings instead.
Before describing the possible effects of climate change on the indoor environment, we will first describe 'indoor environment'; keeping in mind this worst case scenario in cities.

3.2 Indoor environment

The indoor environment can be described by the so-called indoor environmental factors or (external) stressors:

- Indoor air quality: comprising odour, indoor air pollution, fresh air supply, etc.
- Thermal comfort: moisture, air velocity, temperature, etc.
- Acoustical quality: noise from outside, indoors, vibrations, etc.
- Visual or lighting quality: view, illuminance, luminance ratios, reflection, etc.

All together, these factors outline the indoor environmental quality. They provide the environmental stimuli that form the input for our physical sensations, which are the data of perception upon which we react in the form of behaviour and/or evaluations /14/. They can influence our sensations via the three major regulation and control systems of the human body (nervous system, immune system and endocrine system), resulting in both mental (e.g., memories, anxiety) and physical effects (e.g., escape, fight, protect). Stimuli can cause changes in our psychological state, of which we do not know the cause (no conscious experience), and can also be harmful to our physical state of well-being (for example, invisible radiation, gases, chemical compounds, etc.). Besides these direct stimuli, a number of interactions take place that eventually determine how well you will feel, how healthy you will be and how comfortable you will be at a certain moment in time, and determine your interaction with your environment over time (see Figure 3):

- Interactions at human level: physical, psychological and interhuman.
- Interactions at indoor environmental parameter level: between and in.
- Interactions at building level: between elements of the building and between the building and the environment.

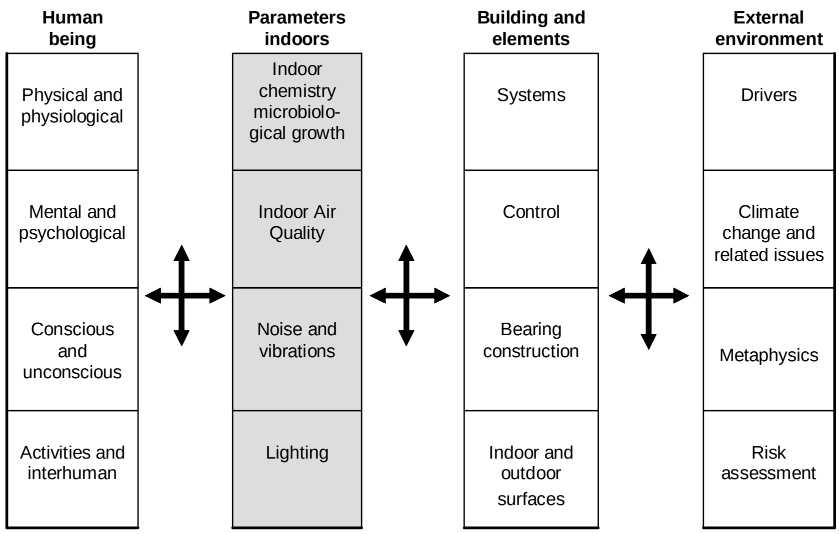

Figure 3: Interactions at different levels with examples of factors in each column (after /15/)

3.3 Direct consequences

3.3.1 Introductory remarks

Despite the scenario occurring from now on, some indoor environmental aspects will change (or have to change) in order to be able to cope with the climate change consequences. Not all variables contained in the KNMI scenarios correspond directly to those needed for indoor environment design, but relevant parameters may be derived. Largely consistent with the implications in the UK /16/, the main implications of the climate change scenarios on Dutch buildings may be on thermal comfort and air quality through:

- changes in the need for space heating;
- the risk of summertime overheating;
- the occurrence of the need for comfort cooling;
- performance of mechanical air conditioning systems.

3.3.2 Effects on thermal comfort

Due to the consistent increase of the average global air temperature near the Earth' surface, - causing mild winters and hot summers -, buildings will require less heating. Depending on the scenario, the number of heating degree-days around 2050 will decrease between 9 and 20% /8/. Van Dongen and Vos /17/ found in their study of 1240 Dutch homes that the average indoor temperature is likely to be higher as houses are of a more recent date, mainly caused by less temperature decrease at night. Relatively warm night temperature can cause problems for the night's rest. A small (short term) skin temperature change of less than 1°C has already a large impact on sleep quality, especially for the elderly /18/. Long term changes in environmental temperature can result in an adjustment of the basal metabolic rate and heat production by altering hormone secretion /19/.

The fact that temperature in winter will go up, combined with increased insulation of Dutch buildings due to energy saving policies, will reduce the demand for space heating. Therefore, not only energy consumption will slightly decrease, also indoor comfort will increase during milder outdoor temperatures during winter. Conversely, the increasing average temperature will make cooling a more crucial and energy consuming issue. The potential increase in winter comfort is to some extent in contrast with the situation in summer. Well-insulated and reasonably air-tight buildings slowly warm up due to entering solar energy and indoor heat sources. The heat remains trapped in the construction, causing an uncomfortable warm indoor climate after a couple of hot days. Therefore, air conditioner use will increase during hot summers. This will affect the power use significantly. The effects of electricity shortfall during hot days in (rich) countries with warmer climates like the US and Canada are already noticeable. However, electricity shortfalls not only happen during the cooling season. Meier /20/ found that a shortfall in Arizona was mostly driven by air conditioning, but an electricity shortage in Norway was caused by drought and a Swedish utility required electricity conservation for very cold days in the winter. The causes of the shortages include many severe weather events, such as droughts, heat or cold waves. Intentional cut-backs in electricity consumption without fully understand all consequences, will not automatically lead to less problems and more energy efficiency. For example, allowing the temperature to float somewhat upwards during warm periods means that certain zones of buildings will raise in temperature faster than other zones. These procedures can seriously disturb the balance of a building's Heating Ventilation and Air Conditioning [HVAC] system and result in uneven delivery of services, reduced efficiency, and of course discomfort. In winter, temperature set-backs may lead to cold spots and localized thermal discomfort for the occupants. Condensation may appear on unexpected surfaces and water pipes are more likely to freeze if a cold wave arrives /20/.

3.3.3 Effects on air quality

As a result of possible increased storms and wind speed (scenario G+ and W+), air pollution comprising of dust particles (from fine to the more heavy) are most likely to be transported more easily from one area to the other. For example, the orange dust coming from the Sahara covering cars after a rain fall will be a more frequent sight. This increase in outdoor air pollution can require buildings to be more airtight than usual, relying more on air conditioning systems which clean the air before it enters the building. In that case, attention should be paid even more to the cleaning and maintenance of air conditioning systems, as these have proven to be a major source of health and comfort problems indoors /21/.

Ozone is another pollutant of concern. Increased ozone outdoor concentrations (smog) can lead to an increase in secondary pollution indoors. An increase in temperature and primary emissions combined with solar radiation will lead to secondary air pollutants. In two of the four scenarios, the smog situation in winter may improve due to mainly westerly winds with relatively clean air. High temperatures and UV-radiation stimulate the production of photochemical smog as well as ozone precursor biogenic Volatile Organic Compounds [VOCs] /22/. Organic compounds that react with ozone on the surface of a used filter are transformed to more highly oxidized species. If thus oxidized chemicals are released fast enough compared with the airflow through the filter (organic compounds diffuse through the filter to the surface), they can influence the air quality downstream of the filter. In one study formaldehyde was found /23/.

Many esters are used in indoor products/materials, such as plasticizers (phthalate esters, phosphates, sebacates, etc.) and flame retardants (halogenated phosphate esters, aryl phosphates, etc.), and therefore become part of the indoor environment /24/. These esters are susceptible to hydrolysis, especially under basic (high pH) conditions, a reaction which is slower than oxidation reactions and therefore insignificant in the gas phase (too little time for the reaction to occur before the molecules are ventilated from the space). But, on the surface these reactions can occur and occur more likely when the surfaces are moist. Moisture also facilitates the disproportionation of NO_2 in aqueous surface films, leading to increased levels of nitrous acid (HONO) in indoor air.

The primary pollution of building products indoors can be influenced by an increase in indoor air temperature, but this effect will be small. For most pollutants, temperature increases of only a few degrees do not influence the emission rate significantly.

The KNMI climate scenarios forecast humidity and ferocity of precipitation to increase during winter months. Higher precipitation, both in summer and winter, combined with increased wind effects could result in wetter walls. Wet wall areas can become a pleasant living environment for fungi and moulds. In general, locations, with long or short term exposure to high amounts of water in combination with organic material, are ideal spots for growth of mould and bacteria /25/, /26/, /27/.

3.4 Indirect consequences

3.4.1 Effects on lighting quality

Since the introduction of electric lighting, a large part of the population is spending time inside buildings during daytime. The consequences of the move from a bright and dynamic outside to a relatively dark and static indoor environment are incalculable. Light controls the human biological clock and is therefore an important regulator of the human physiology and performance /28/. During the day, it is important for humans to receive enough light at the eye for entrainment of the biological clock. Insufficient light levels could cause lower concentration, reduced performance, decreased well-being, sleep disturbance, or trends of (winter) depression. One of the consequences of climate change effects might be that people stay inside even more than they already do. In an attempt to shut out the sun, blinds and curtains will be used, decreasing daylight exposure even more. Additionally, the effect of storms and cloud forming may influence the quality of daylight.

3.4.2 Effects on acoustical quality

Possible increased wind speeds and frequency of storms can influence the acoustical quality indoors through the noise and vibrations perceived. Vibration is in general experienced by fewer people than noise. However, where significant vibration occurs, it can be a cause of nuisance (or disturbance, or complaint); and/or a cause of health effects (e.g., sleep disturbance) /29/, /30/. The increase in use of air conditioning systems may cause more people to complain about noise originating from these systems. In a study performed by van Dongen and Steenbekkers /31/ with 4072 respondents, about 30% of occupants were disturbed by noise from a fan in their own house, when mechanical ventilation is applied. A smaller fraction was seriously annoyed. It was not clear how many were not annoyed because they turned the system down or off, thus preventing the disturbance /31/.

3.4.3 Effects on psycho-social aspects

The indoor environment can cause physical stress, such as too warm or too cold, and the indoor environment can limit a person in coping with this stress. For example, not able to control the temperature in their office, open the window to get outdoor (fresh) air or have the possibility of a view. Additional to that, psycho-social factors such as fear for storm, flooding, mental well-being, etc., can influence the perception of those physical and coping stressors (mostly negatively). And, the amount of time spent indoors might well be increased as a consequence of climate change effects, causing more stress and probably an increase in mental disorders and obesity, as this relation has been indicated by /32/.

4 Adaptation possibilities

Adaptation is ‘the action taken to cope with a changing climate and may need to tackle present problems or anticipate changes in the future, aiming to reduce risk and damage cost-effectively, and perhaps even exploiting potential benefits’ /33/. Actions include adapting building codes to future climate conditions and extreme weather events. The European Union /33/ emphasized that adaptation includes both national or regional strategies and practical steps taken at community level or by individuals (home or installation level). Adaptation planning will be more effective if it is systematic and strategic and even though it may require special focus, it also has to fit into existing practices, policies, and strategies.
In fact, the adaptation process can be engaged at three levels:

- Take away or adjust the **source** of climate change effects
- Adjust the **building** to the changing outdoor climatic conditions
- Involve **people** (occupants and other stakeholders)

At the first level, mitigation - taking actions to reduce greenhouse gas emissions – will be necessary to reduce the global temperature increase, assuming that human induced sources are the actual cause. Consequently, the impact in the long run will be less severe and adaptation possibilities improve. Efficient lighting and daylighting, more efficient electrical appliances and heating/cooling devices, improved insulation, passive and active solar design for heating/cooling, alternative refrigerant fluids are all examples of mitigation technologies and practices that are currently commercially available. Technologies and practices projected to be fully commercialised before 2030 /34/ are the integrated design of commercial buildings including technologies such as intelligent meters and controls including feedback options, and solar photo-voltaic [PV] cells integrated in buildings.

However, amongst others, experts of the British Royal Society fear that it is already too late to prevent climate change by reducing the emission of CO_2 /35/. Humanity must possibly take more extreme measures. Crutzen /36/ called for active scientific research of the kind of geo-engineering. Geo-engineering is any large scale intervention or manipulation of the environment to help modify the Earth's climate, such as blocking sunlight through mirrors, increase precipitation, or removing carbon dioxide from the environment by injecting iron in the oceans or spreading dust in the stratosphere /37/. Therefore, to reduce the greenhouse gas emissions, possible adaptation measures may range from the development and use of new, innovative materials, which consume CO_2 and other green house gases, and can be used both indoors and outdoors to the design of façade or roof systems that bounce back sunlight into space.

For the second and the third level, it is important to realise that the indoor environment comes into existence as a consequence of the building process. Therefore, solutions for adaptations for the indoor environment should not be found in the building adaptation only, but should be part of the whole life cycle of the building and the processes involved, including technical as well as social (communicative) aspects. The lifecycle of a building comprises of initiation, design, realisation, occupation and renovation/demolition and reuse. Already at the initiation of a building, requirements for the indoor environment should be included in the brief in order to be taken on board. For existing buildings, the renovation also starts with a brief, followed by the detailed design and realisation of the intended adjustments and alterations.

4.1 Adjust the building (technical aspects)

Temperature increase will most likely have the largest effect of climate change on the indoor environment in the Netherlands. It means that summer time overheating in buildings and urban areas next to moisture damage to buildings will be the main issues that have to be tackled and both issues have considerable health implications. Overheating is a slightly more serious problem in more modern buildings; moisture is often more applicable to older ones. Over the years, energy saving has been an important focus of the building world, meaning that Dutch homes lose less and less energy due to better insulation and energy recovery systems. However, with increasing temperatures outside, the inside temperature will increase accordingly, and mainly in summer periods when the sun remains heating homes, the temperature will rise to unacceptable levels.

Direct and indirect heat gains can be decreased by adopting a cooling strategy based on the 'switch off', 'absorb', 'blow away', and 'cool' principles /16/. With 'switch off', the reduction of heat gains due to needless use of electrical equipment of devices is meant, next to the use of sun shading as those can 'switch off the sun'. With regard to indoor lighting quality and climate changes consequences, adaptation measures may range from the use of foliage as an environmental friendly and effective way for sun shading to the development of lighting installations that are a combination of daylight, daylight dependent dimming installations, and energy efficient lighting technologies (e.g., CFL or LED), without losing the attention for lighting quality and visual comfort aspects. One step further will be climatically-sensitive buildings and façade systems that do not limit the adaption to building installations only, but mean wisely designed buildings and facades that react to the outdoor circumstances as required by the indoor user. The next step in the cooling strategy will be 'absorbing'. By increasing the thermal mass of a building, (undesirable) heat gains can be distributed to reduce the peak. If the thermal mass cannot easily be changed (e.g., if the only way is to replace the building structure), adaptation measures have to go further by means of innovative solutions like e.g. phase change materials. Besides, increasing the thermal mass cannot be achieved without due attention to all the principles of low-energy and sustainable design, including proper appeal to the present-day and likely future climatic context of the site /1/. In case excluding or absorbing gains are not reasonable adaptation options, solutions have to be found by means of installations. The strategy steps involving installations are 'blow away' and 'cool'. In case of installation use extra attention has to be paid to avoiding installation noise and vibrations. The 'blow away' strategy means the introduction of an intelligent and properly ventilation strategy, with night cooling for example. Possible adaptation measures may range from the development and use of new, innovative energy recovery systems that are outdoor temperature dependable to climate-sensitive façade systems. In winter time, heat recovery systems recycle as much energy as possible while in summer they either discontinue working completely or operate in reverse. Incoming fresh air can should not only be warmed during the winter by means of an (earth) heat exchanger, but also cooled down during periods of high temperatures in the summer /38/.

As a consequence of indoor temperature increase, many air conditioning systems (primarily meant for cooling) will be introduced in homes, following the trend in increased air conditioning in non-domestic buildings. As stated before, attention must be paid to cleaning and maintenance of air conditioning systems. Although the first possible solution for this problem may be to avoid the use of air conditioning systems, especially in homes, adaptation strategies for pollution air conditioning systems may be range from the development of self-cleaning systems to systems which transform air pollution material into harmless components. Besides, Holmes and Hacker /1/ stated that HVAC systems will be replaced several times during the life of the building and therefore, a building and associated systems may take a number of different forms throughout the life of that building. According to the researchers, it is probably impossible to predict the changes that that will be made to the HVAC systems /1/, but systems that can be easily changed and/or modified may contribute to effective climate adaption.

4.2 Involve people (social, communication aspects)

Either buildings, or occupants, but in many circumstances both, have to endure smaller or bigger changes to adapt to the changing situation outside. Management of the indoor environment is an issue for many stakeholders at different scales. It is a dynamic issue which has to take into account changes over time at those scales and of the stakeholders.

The real occupants of a building can comprise of several kinds: occupants of dwellings, employees in an office building, employers, labour workers, personnel in a shop, etcetera. What they have in common is that they all like to be in a state of well-being that they can accept. This state of well-being can influence their productivity in the tasks they are performing and their state of mind and body.

Besides the occupants, the direct stakeholders of the indoor environment are the parties that initiate, create, build and maintain the indoor environments, in which we all live, work and play. These parties all have their own stakes for taking part in the life-cycle of the indoor environmental spaces. The parties involved are:

- the party who pays: the investor
- the party who initiates: the project initiator (often also the investor)
- the party who designs: design team including an architect and several consultants (systems, construction, etc..)
- the party who builds: the contractor and sub-contractors
- the party who owns/buys the building: the building owner (can be different from end-user)
- the party who maintains: facility manager
- the party who regulates: the regulator provides regulation and rules to keep
- the party who produces the products: construction, furnishing and HVAC system components producers
- the end-user who has his/her basic needs

The parties mentioned can have double functions, such as the project developer can also be the investor and the builder, and even the facilitator. The party who owns the building can be the end-user. Etc.

In the traditional process the project developer initiates a new project. From the acquisition of a construction location until the deliverance the regulator, the contractor, the design team (normally only the architect) and the owner are involved. After the first phases also the investor is involved, who is normally approached by the developer.

The communication between the stakeholders involved is crucial to make technical adaptations feasible and to make certain that end-users needs in a changing environment are translated in the appropriate way. Unfortunately, in the traditional building process, the so-called ‘over the bench methodology’ is often used; a real team is not formed. Parties do not understand each other, stakes or products and occupants’ wishes and demands are only incorporated on an individual basis. Next to the communication process, understanding the needs and requirements of the occupants, before thinking about the solutions, is crucial for incorporating adaptations /15/.

Fortunately, some “innovative” methods are available that do focus on the occupants requirements and the communication process between stakeholders, to incorporate the occupant requirements in the total building life-cycle via technical requirements in all the phases of the life-cycle. Communication i.e. interaction between supply and demand, and knowledge and/or technology transfer between sectors and stakeholders, is hereby of utmost importance. Several forms have been made available through communication, design, and even cooperation forms to make this interaction possible and more clear. Examples are the ‘Open building approach’ (ww.habraken.com), the ‘value-domain model’ /39/, the ‘PPC [Public-Private-Cooperation]’ /40/, and the ‘BriefBuilding Tool’ /41/. But perhaps the most complete approach is the system engineering approach, a holistic top-down approach in which occupants’ requirements form the starting point /42/.

For each of those can be said that they make use of an underlying structure (organisational structure, model, or even a contract) to accommodate the communication process, making it more effective and efficient whilst reducing the risks that overall project goals are not achieved.

Additionally, Cassar et al. /34/ stated that occupants will have to change their behaviour in relation to how they use and interact with buildings as the future climate changes. The change of occupant behaviour is – in theory – the quickest and most flexible adaptation strategy. However, in practice occupants have very little understanding of their interaction with the built environment. For example, many occupants let the heat into buildings during the hottest part of the day by opening windows. Issues like overheating need better designed solutions to cope with occupant behaviour. Other researchers like Cole et al. /43/ advised to engage occupants or inhabitants in the adaptation process. Also Chappells and Shove /44/ proposed several opportunities for behavioural and technological changes that promote adaptive (comfort) standards:

- People may become used to greater seasonal variety due to climatic variation;
- New clothing and furniture technologies could be developed to provide for insulation and environmental control;
- Institutional flexibility that includes variable work hours.

5 Conclusions

When Global warming is indeed inescapable, adaptations are necessary to reduce the impact also on the indoor environment. Bluyssen /15/ reported in her literature review a limited overview of facts and figures on (un)healthy buildings (see below, /15/). In case the adaptation process is not implemented at all three levels (source, buildings, and humans), health consequences due to the indoor environment will be as mentioned below /15/ or even worse.

- Approximately 20% of the European population is allergic to mites and fungi and the prevalence of asthma and allergies in domestic buildings is increasing /45/. A meta-analysis of health effects of dampness, suggests that building dampness and moulds are associated with increases of 30-50% in a variety of asthma-related health outcomes /46/.
- Most countries suffer from 5-25% winter mortality. In the UK, this involves an estimated 20-40.000 death /47/. There are clear indications that excess winter mortality is connected to poor thermal insulation, and to fuel ‘poverty’. The same accounts for an increase in respiratory and cardio-vascular ailments. Similar effects of cold stress have been pointed out in a Harvard study /48/.
- Sleep disturbance, linked to a multitude of indoor physical parameters, increases the risk of household accidents by at least 46%. Some 350 million Europeans complain regularly about sleeping problems. /32/.
- In 1998, more than 10 million accidental injuries in and around the house occurred in the Europe-15 countries. This resulted in more than 1 million hospital admissions and more than 42.000 deaths. The most common interior causes appear to be inadequate lighting, insufficient working space in kitchens and staircases /32/.
- It is estimated that in general 25% of families has one member a least suffering from mental disorder, which is the leading cause of disability worldwide. Depression affects 19 % of adults, and increases strongly with age. Antidepressant prescriptions have more than tripled the past 10 years /32/. Rise in obesity is leading to increase in diabetes and risk for cardiovascular disease. Obesity reduces life expectancy /49/. Both obesity and mental disorder seem to have a relation with the conditions of homes and neighbourhood’s people are living together with the increasing time they spend indoors /32/.

- In 2000 about 350000 people died in the EU prematurely due to outdoor air pollution caused by fine particulate matter ($PM_{2.5}$) alone. 11.5 % of children suffer from asthmatic symptoms in Europe /49/.

Adaptation strategies focused on health and comfort of people in the indoor environment should involve all stakeholders responsible and involved in the realisation of an indoor environment, using the appropriate communication processes.
Even though several adaptation possibilities have been sketched above, it should be reminded that, adaptation strategies cannot be executed properly until we:

- Understand the possible effects of climate changes on occupant wishes and needs both present and in the future, making modelling or predicting human behaviour under different environmental conditions possible and thus defining actions easier and straight forward.
- Understand the interactions at all interfaces of human being, indoor environment, building (elements) and outdoor environment.

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Modeling Climate Change impact on Cultural Heritage – The European Project Climate for Culture

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Abstract

The CLIMATE FOR CULTURE project, funded by the European Commission since 2009, will assess the damage potential of climate change on European cultural heritage, its socio-economic impact and possible mitigation strategies. Collections in historic buildings in different parts of Europe will be included for in situ investigation of contemporary problems and for the projection of future demanding issues. For this purpose, high resolution climate evolution scenarios will be coupled with whole building simulation models to identify the most urgent risks for specific regions with the aim of developing mitigation strategies. The identified economic and substantial risks for the European cultural heritage will be communicated to policy makers together with possible mitigation strategies to be included in the future IPCC Reports.

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Dipl.-Restaurator Univ. Ralf Kilian studied restoration, technology of arts and conservation science at the Technische Universität München, Diploma degree in 2004. Since July 2008 he is head of a working group on "Cultural Heritage Preservation and Preventive Conservation" at the Department of Indoor Environment and Climatic Impacts. He is responsible for research on the preservation of monuments / historic buildings and preventive conservation. Ralf Kilian is an active Member of CEN TC 346 "Conservation of cultural property", WTA "Climatic stability of historic buildings". He is one of the scientific coordinators of the large-scale integration EU-Project "Climate for Culture".

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1 Introduction – Climate Change and Cultural Heritage

Climate change is one of the most critical global challenges of our time. This factor, coupled with the increasing demand our society has on energy and resources, has forced sustainable development to the top of the European political agenda. Scientific research shows that the preservation of the cultural heritage is particularly vulnerable in this regard. As a non-renewable resource of intrinsic importance to our identity, there is a need to develop more effective and efficient sustainable adaptation and mitigation strategies in order to preserve these invaluable cultural assets for the long-term future. More reliable assessments will lead to better prediction models, which in turn will enable preventive measures to be taken, thus reducing energy and the use of resources.

For this purpose the CLIMATE FOR CULTURE project will connect new high resolution climate change evolution scenarios with whole building simulation models to identify the most urgent risks for specific regions. The innovation lies in the elaboration of a more systematically and reliable damage/risk assessment which will be deduced by correlating the projected future climate data (with the spatial resolution of up to 10x10 km grid size) with whole building simulation models and new damage assessment functions. Thus not only the impact on historic buildings can be evaluated but also the possible effects on the indoor environment which surrounds the works of art we are keeping inside them. In situ measurements and investigations at cultural heritage sites throughout Europe (Fig. 1) and the Mediterranean will allow a much more precise and integrated assessment of the real damage impact of climate change on cultural heritage at regional scale. Sustainable (energy and resource efficient) and appropriate mitigation/adaptation strategies, also from previous EU projects, are further developed and applied on the basis of these findings simultaneously.

The CLIMATE FOR CULTURE project will estimate more systematically the damage potential of climate change on European cultural heritage under different climate change scenarios at regional scale. The team consists of 27 multidisciplinary partners from 16 countries all over Europe and Egypt including leading institutes and experts in conservation, climate modeling and whole building simulation. One team partner is a member of the International Panel on Climate Change (IPCC) and four partners are members of the standardization body CEN TC 346 (Conservation of Cultural Property). To raise the awareness of the decision makers about the costs to take actions and what it costs, if we do not take actions to protect cultural heritage the economic impacts and physical risks to European cultural heritage will be identified.

2 The Climate for Culture Project

2.1 Main Objectives and Scientific Methods

To assess the effects of climate change high resolution climate evolution scenarios (based on regional climate model simulations) are connected with whole building

Figure 1: Linderhof Castle, Bavaria, is one of the buildings to be examined using hygrothermal building simulation

simulation models to identify the most urgent risks for the whole of Europe and the Mediterranean. The correlation of the climate data and the whole building simulation models with close up surface monitoring will build the basis for setting up new damage functions. Collections in historic buildings from various European regions as well as UNESCO World Heritage Sites are included as case studies for in situ assessment of existing problems, retrospective investigations on the state of preservation and for the projection of future challenging issues. All results will be incorporated into the report on the assessment of the economic costs and impacts on cultural heritage under two different IPCC climate scenarios on regional scale.

Almost the entire research in the field of microclimate related preventive conservation so far has focused on the climate responses of singular artistic, historic materials which generally has led to a definition of very strict and rather limited climate ranges. However, historic buildings are living places which are frequently inhabited, visited or used for a wide variety of activities. The change in their use and function is often the condition of their survival as a monument. Maintaining these strict microclimate ranges for most historic buildings is not feasible, in particular with regard to the global warming trend and often unnecessary because many of the movable cultural assets can withstand a wider range of climatic conditions.

The project aims at assessing the influence of climate change and microclimatic functioning of historic buildings with regard to the dangers for the interior equipment or works of art, as well as at new strategies for the improvement of the microclimatic control and the optimization of the buildings. The project will also contribute directly to the standardization process of the CEN TC 346 ”Conservation of cultural property”.

2.2 Climate Change Modeling

A comprehensive description of the climate system components as well as their interaction under different climate change conditions can be achieved by using physically-based climate models /1/. An entirely new high resolution simulation (10x10 km) will be executed over entire Europe for time slices 1960-2000, 2020-2050 and 2070-2100. Two IPCC scenarios will be considered (B1 and A1B). While A1B is the manifestation of “business as usual” with high economic growth the B1 scenario gives a more optimistic vision of a world with lower emissions where resource efficient and sustainable technologies are fast developed and introduced. This allows covering a range of possible climate changes over the selected regions.These two different climate scenarios will deliver climate indicators for assessment of future changes, including estimation and evaluation of uncertainties in the models.

To assess and simulate the local climate changes according to the different emission scenarios in a high resolution of 10 x 10 km the regional climate model REMO has been developed at the Max-Planck Institute for Meteorology (MPG/MPI-MET) in Hamburg /2, 3/ and has already been applied for several different areas (e.g. within the European CLAVIER, ENSEMBLES and the German KLIWAS, GLOWA-DANUBE projects). The global fields from the coupled general circulation model ECHAM5-MPIOM will be used as driving forces. In addition, the regional coupled model REMO/MPIOM with 25 km resolution in the atmosphere and 11 km in the ocean will be used to estimate both changes in mean sea level as well as changes in positive sea level extremes. The results from the this model will also be used to assess the uncertainty in the high resolution atmosphere-only simulations arising from the use of the coarse resolution sea surface temperature as lower boundary condition.

2.3 Hygrothermal Building Simulation

Historic buildings usually show elevated indoor humidity levels and a high variation of the climatic conditions, which can be dangerous to cultural heritage materials. This requires the detailed consideration of all hygrothermal interactions between the indoor air, the usage, the furnishing and the building envelope. The hygrothermal behaviour of a building component exposed to weather is an important aspect of the overall performance of a building. The calculation of the hygrothermal performance of a part of the envelope is state-of-the-art and a realistic assessment of all relevant effects can be carried out, but until now the total behaviour of the actual whole building is not accounted for.

How much ventilation and additional heat energy is required to ensure safe indoor conditions for cultural heritage when a historic building is exposed to extreme climate conditions or up to 4000 visitor per day? What will happen to the hygrothermal behaviour of walls and ceiling when a historic cellar is changed in its use and is turned for example into a restaurant? How do the indoor air conditions and the envelope of buildings with temporary use react to different heating and ventilation strategies? Can sorptive finish materials improve and stabilise the microclimate in historic buildings?

For risk assessment in cultural heritage buildings the exact indoor humidity fluctuations and the moisture profiles in the building envelope are extremely relevant. Therefore models that combine thermal building simulation with the hygrothermal component simulation have to be applied.

Different thermal and hygrothermal building simulation tools will be evaluated for their applicability to simulate the indoor environment and hygrothermal transport mechanisms in historic building materials. These computational models are usually used for simulating water and temperature distributions in modern building components like insulated walls or roofs. Whole building simulations will also take into account the type of use (e.g. visitors, events) and HVAC climatisation components to assess the indoor environment. Their applicability to existent historic buildings with often unknown constructions and material properties is still limited.

The whole building model WUFI® PLUS /4/ is a combination of thermal building simulation with the hygrothermal envelope calculation model WUFI®. This holistic model takes into account the main hygrothermal effects, like moisture sources and sinks inside a room and the moisture input from the envelope due to capillary action and diffusion as well as vapour ad- and desorption as a response to the exterior and interior climate conditions. Also different heat sources and sinks inside the room, heat input from the envelope, the solar energy input through walls and windows as well as hygrothermal sources and sinks due to natural or mechanical ventilation are considered.

Also other simulation software like Hambase /5/, ESP-r /6/, Energy Plus /7/ or IDA-ICE /8/ will be compared in a Common Exercise between the several research institutes with the aim of testing their applicability for historic buildings. The different tools are expected to have strength and weaknesses for different topics of the assessment, e.g. some simulate the combined heat and moisture transport through porous materials, whereas others only use simplified models for these processes or just simulate the heat transport but have higher possibilities in accurately modelling different HVAC systems.

The most suitable models will then be used to model the predicted impact of the climate change. As probably some features for the appropriate climate change impact modelling on complex historic buildings are missing, missing modules will be assessed, developed and implemented into the software tools. This allows to use the high resolution climate data to predict the future indoor environment of the case study buildings. This indoor climate data will then be assessed with the new damage functions.

In a final step, the effects of active and passive mitigation measures will be evaluated with the building simulation models. The most promising mitigation measures will be implemented in the simulation models. This allows the assessment of the effect of different measures suggested.

3 Case Example – The King's House on the Schachen

3.1 Introduction

The CLIMATE FOR CULTURE project aims at providing a general overview on the difference of the indoor environment in historic buildings all over Europe. Selected and representative buildings will be used as Case Studies for simulation. The best documented and thoroughly known of these buildings will be used for the simulation common exercise. These cases must allow a validation of the software tools on the basis of measured interior climate conditions from the past connected with the documented boundary conditions.

3.2 Building and Works of art

The King's house on the Schachen is one of five historic buildings in Bavaria (besides Linderhof Palace and St. Renatus Chapel, Lustheim, and two further churches), which are examined in the Climate for Culture project. The King's house on the Schachen, located in the Wetterstein Mountains in the Alps was built by King Ludwig II of Bavaria from 1869 to 1872 in a wooden post-and-infill construction. On the first floor there is the richly decorated Turkish hall furnished with different materials such as wall paper, textiles, polychromed and gilded wood surfaces, and coloured windows. Due to the exposed location, the building is set out rough atmospheric conditions all year with fast weather changes and long periods of frost during the whole winter. Nevertheless the condition of the house, the interior and especially the Turkish hall is very good (Fig. 2). To find out more about

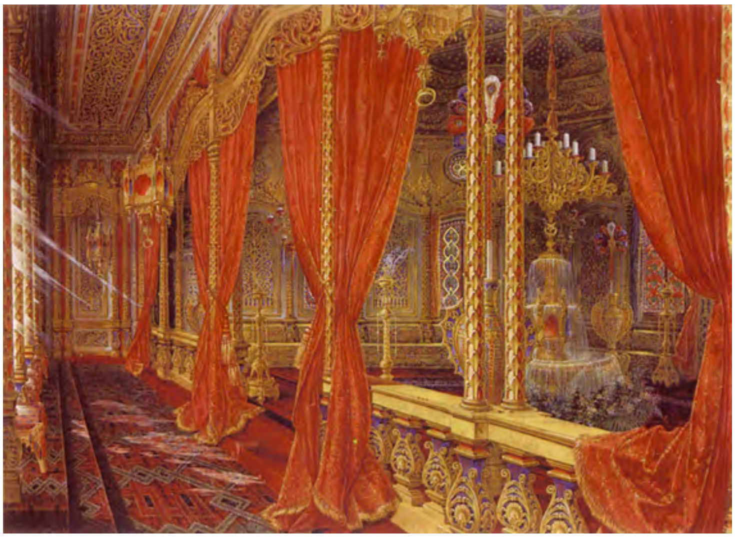

Figure 2: Interieur of the Turkish Hall on a watercolour painting from 1879 by Peter Herwegen. The decoration looks the same today as on the picture, so later changes to the decorative program can be excluded.

the circumstances for this state of preservation, the Fraunhofer-Institute for Building Physics has started climate measurements in 2006. The first step of examination was the simulation of the indoor climate of the king's house with the whole building simulation software WUFI®+ and the thorough analysis of the condition of the decoration of the Turkish hall by a trained conservator.

As first conclusions it has to be stated that many factors contribute to the good state of preservation: the house is open only in the summer months and due to the location the only access is by a three hour march. For this reason, compared to other Bavarian palaces for example Linderhof Palace, less visitors – who are one cause for indoor climate fluctuations – come to see the king's house on the Schachen. The indoor environment of the Turkish hall is buffered by a house-in-house-construction and stable without any heating or climatisation system. Also the indoor surface materials buffer moisture fluctuations. This helps to preserve the furnishing and works of art inside the building.

3.3 Simulation

The hygrothermal building simulation of the Kings House on the Schachen has been published earlier /9/. Here just exemplary results are shown (Fig. 3 and Fig. 4). The comparison of the simulations results with the measured data shows quite good fitting for the winter months. During summer in the simulation the temperature is too high in comparison with the measured data due to necessary simplifications in regard to the building construction and uncertainties in regard to the available weather data in the approximation of the model, especially solar radiation and shading from the mountains during winter months.

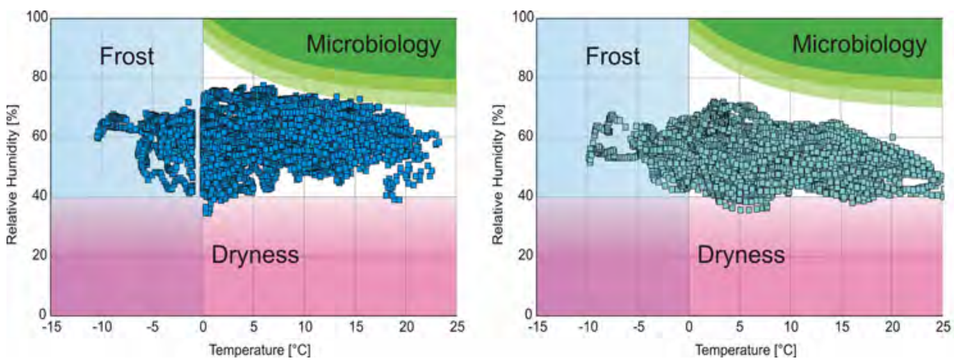

Figure 3: Scatterplots showing the comparison between measurement and simulation for 1 year of data (from October, 1st 2006 to September, 31st 2007). Risk assessment of the measured indoor climate (left) shows that most of the data is in a safe region for the one year monitoring period. The gap in the measured temperature at 0° C is due to a malfunction of the data logger. The simulation provides to high temperature and in turn lower RH for the summer months.

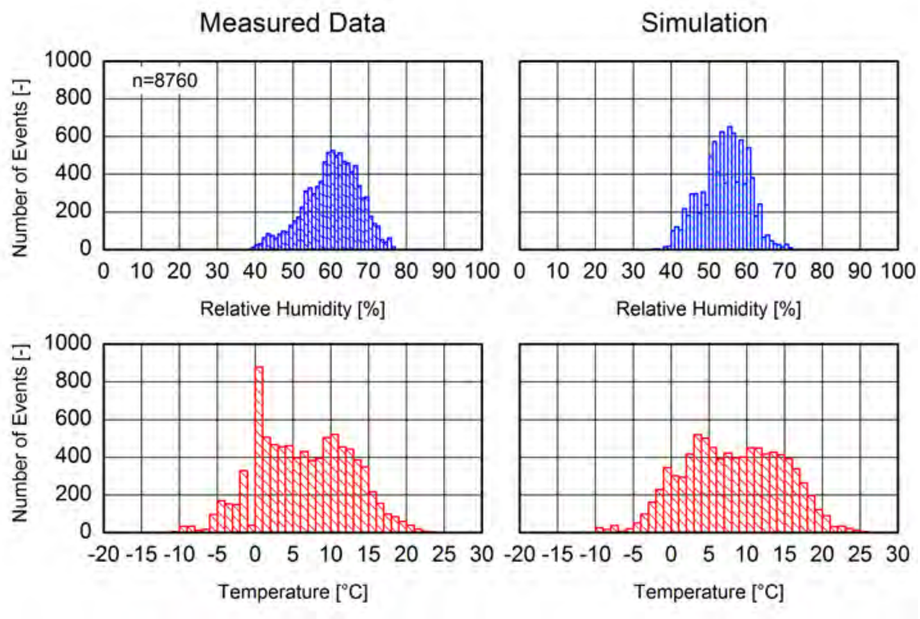

Figure 4: Histograms showing the comparison between measurement and simulation for 1 year of data (2006-2007). The gap in the measured temperature at 0° C is due to a malfunction of the data logger.

This will also pose difficulties for modelling local climate change, as also climate change modelling has limitations, e.g. when it comes to simulating mountain regions with very special local microclimates that cannot be modelled in sufficient high resolution up to now.

4 Summary

In general it is difficult to simulate historic buildings, due to multiple materials often unknown or with changed properties from aging and often unknown building constructions. Nevertheless it is possible to obtain approximations that are sufficiently close to reality.

With a good knowledge of the hygrothermal behavior of a historic building today coupled with high resolution climate change simulations it will be possible to assess future impacts of climate change on these buildings and on the works of art that are kept inside them, by looking at a large number of case studies all over Europe. Of course for this task all uncertainties of the climate change prediction models as well of building simulation will have to be taken into account. This will be our project for the next years to come.

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Impact of Climate Change on Historic Wooden Structures

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Abstract

The survival of open-air wooden constructions is limited by their susceptibility to organisms that degrade wood. If wood is wet for long periods at sufficiently elevated temperatures, wood-degrading fungi will attack it. Therefore, climate-based indices relating temperature and the time of wetness to the rate of fungal decay have been developed since 1970s to predict decay risk on one hand and to assess protective treatments and measures on the other. The investigations carried out within the recent European Commission Project Noah's Ark "Global climate change impact on built heritage and cultural landscapes", implemented between 2003-2006, have enhanced the understanding of the relationship between the precipitation pattern and dynamically changing moisture content profiles in the wood. A double permeability model, reflecting adequately the complex flow patterns, was used to describe the process. The modelling made possible to establish precisely the real moisture penetration depth and its temporal variation, resulting from a given precipitation pattern. By linking this information to the critical moisture conditions for fungal activity, such as critical moisture content and critical exposure time, the risk of decay could be predicted. The risk index obtained was used to map the effect of the climate change in the coming 100 years on the risk of decay in wood structures above ground across Europe.

Roman Kozłowski

Roman Kozłowski graduated in chemistry from the Jagiellonian University in Krakow, Poland in 1970. He received his PhD in 1974 and DSc in 1989, both from the same university. Since 1986, he has been head of the research related to conservation science and the protection of cultural heritage at the Institute of Catalysis and Surface Chemistry, Polish Academy of Sciences in Krakow, where he is an associate professor. His research focuses on microclimatic monitoring, composition and porous structures of historic materials, and their interaction with moisture. He has been principal investigator in several research projects within 4th, 5th and 6th Framework Programmes of the European Commission, including the NOAH's ARK project: Global climate change impact on built heritage and cultural landscapes. In the project, his research concerned damage of vulnerable materials like wood and clay-containing sandstones induced by temperature and humidity variations.

1 Introduction

The survival of open-air wooden constructions is limited by their susceptibility to organisms that degrade wood. If wood is wet for long periods at sufficiently elevated temperatures, wood-degrading fungi will attack it. Therefore, climate-based indices relating temperature and the time of wetness to the rate of fungal decay have been developed since 1970s to predict decay risk on one hand and to assess protective treatments and measures on the other.

Scheffer /1/ was first to introduce an index in which the rate of decay was assumed to be approximately proportional to the temperature above freezing point of water and to the mean number of days per month with precipitation exceeding certain minimal volume. Though still used to map the geographically dependent potential for decay in wood structures above ground /2/, Scheffer's climate index provides, according to several studies, an oversimplified approach which fails to establish a good correlation between climatic data and decay /3/. The macroclimatic data, especially their long-term averages, are factors only indirectly controlling the decay process in reality directly dependent on wood conditions: moisture content (MC) and temperature which change dynamically in response to the continually changing climate conditions. Therefore, direct measurements of average daily wood temperature and moisture content of exposed wood specimens - the latter by recording the electrical resistance of the wood – has been undertaken to estimate the temperature- and MC-induced daily doses which impact on wood in terms of biological decay /3-5/. Then, the dose-response functions were calculated by correlating the doses with the decay ratings for wood specimens exposed at the different exposure intervals and test sites.

2 European Commission Project Noah's Ark "Global climate change impact on built heritage and cultural landscapes"

The investigations carried out within the recent European Commission Project Noah's Ark "Global climate change impact on built heritage and cultural landscapes" /6/, implemented between 2003-2006, have enhanced the understanding of the relationship between the precipitation pattern and dynamically changing moisture content profiles in the wood. Water infiltration on wetting and release on drying were measured experimentally using Magnetic Resonance Imaging. A typical evolution of water infiltration in the longitudinal direction of wood is shown for fir in Fig. 1. The plots represent the moisture content along the wooden cylinder at different wetting times. As one can see, the moisture content increases at the wet end and water reaches gradually the opposite, dry end of the cylinder. The explanation discussed in the literature /7,8/ is that water is carried out rapidly in the vessels or ray-cells with a simultaneous, but much slower infiltration into the denser material surrounding the vessels.

A double permeability model was used to describe the infiltration of water into wood /7/ as such model reflects adequately complex flow patterns through hetero-

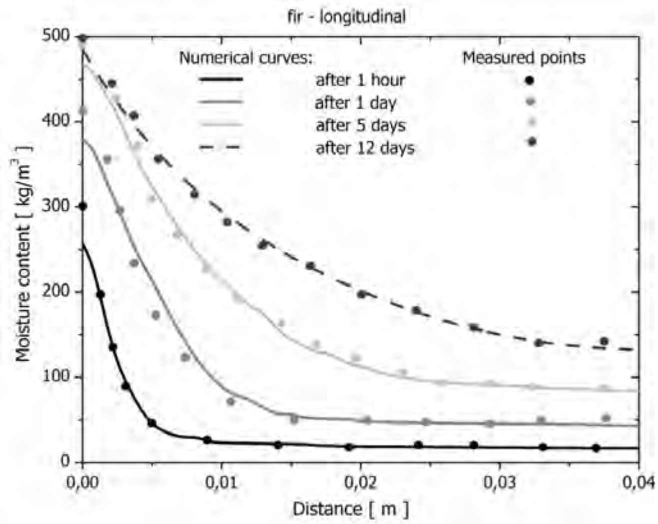

Figure 1: Water infiltration in the longitudinal direction of fir-wood.

geneous structure of wood. Figure 1 demonstrates good agreement between moisture profiles measured experimentally and predicted.

The presented approach allows for a numerical simulation of temporal variations of moisture profiles in wood for any sequence of wetting and drying events. By linking this information to the critical moisture conditions for fungal activity, such as critical moisture content and exposure time, the risk of decay can be predicted. By way of example, the index of wood decay risk was calculated basing on the assumption that moisture content of 20% is a threshold level above which the fungal growth occurs, 48 hours are the required "exposure time" to initiate fungal growth after a period of dry conditions and the growth rate is proportional to the number of degrees by which the temperature exceeds 2. The evolution of temperature and precipitation pattern in future was modelled by the Climate Research Unit, School of Environmental Sciences of the University of East Anglia, UK within the activities of the Noah's Ark project.

Fig. 2 shows the effect of the climate change in the coming 90 years on the risk of decay in wood structures exposed to the outdoor conditions above ground across Europe.

The risk will be especially high in Scandinavia and in the mountains mainly because of high precipitation. In contrast, the drier southern Europe will be not affected by the fungal growth significantly.

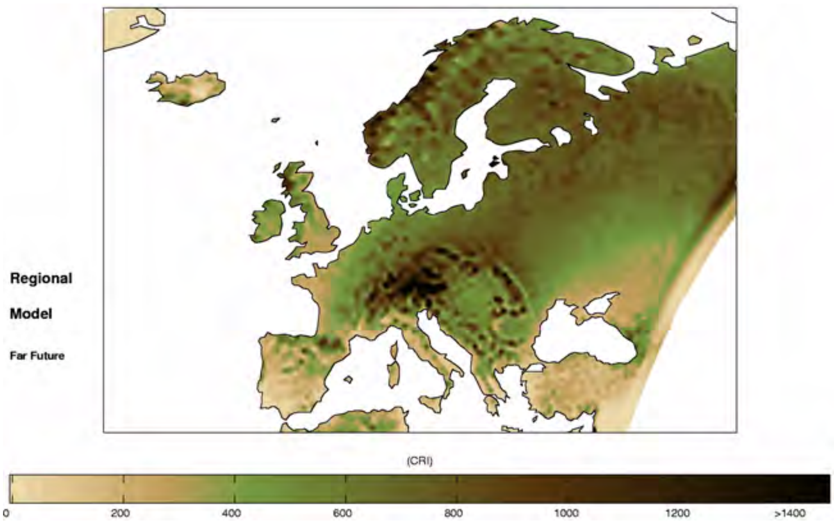

Figure 2: Climate risk index for wood decay due to the fungal growth (CRI) mapped over Europe, excluding seas, for years 2070-2099.

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Biodeterioration of Built Heritage and Climate Change. Can We Predict Changes in Biodeterioration?

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Abstract

The occurrence of organisms on stone surfaces can be regarded as biodeteriogenic. Biodeterioration start with the colonization of a substrate that usually involves succession of organisms settling over time in the same place, until a balance is established between the atmospheric/climatic factors, organisms and the substratum. A minimal stability of the substratum is required for colonization and settlement of organisms to make a bioderma constituted by bacteria, algae, fungi, bryophytes or lichens, among the most common. The colonization and development of bioderma on stony substratum is primary influenced by climatic parameters, such as light intensity, water availability, temperature and wind. Such climatic parameters can explain the composition and distribution of communities developing on monuments. Of all the communities, lichen communities are the most conspicuous ones. One of the aims of Noah's Ark project was to assess changes in the bioderma coating monument surfaces. In this context, changes in lichen species richness and biomass were investigated. Lichen species richness showed a significant and negative correlation with temperature, meaning that an increase in temperature would determine a decrease in species richness. On the contrary, precipitation did not show any significant correlation with species richness, although it had a positive effect. Bioderma biomass showed a significant correlation with temperature and precipitation. While temperature had a negative effect on biomass, like it had with species richness; precipitation had a positive effect.

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1 Introduction

The occurrence of organisms on stone surfaces does not automatically imply a destructive action /1, 2/. However, if we consider biodeterioration as 'any undesirable change in the properties of a material caused by the vital activities of organisms', then the presence of organisms on building stones can be regarded as biodeteriogenic, sometimes because of simply aesthetic damage they cause. This problem reaches further economic and social dimensions when the colonized substrates belong to cultural heritage (Figure 1).

Colonization and weathering of stone start as soon as a rock is extracted from a quarry or a mortar is placed in a building and exposed to the environment. Weathering is caused by climatic factors (sun, frost, wind, rain, pollutants, etc.), and contribute gradually to a process where materials break into smaller particles and ultimately disintegrate in mineral constituents, as part of the natural cycle of elements in the Earth. Concerning biological colonization, it is assumed that some omnipresent organisms, with fast growth, such as bacteria, settle in first; after which organisms with a slow growth settle in and develop, starting to compete with the bacteria and finally superseding them. Subsequently, other organisms with a slower growth will in turn supersede the latter, and so on, to build a bioderma composed by bacteria, algae, fungi, lichens or bryophytes, among the most common organisms. This process is referred to as a primary succession. However, a minimal stability of the substrata is required for colonization and settlement of organisms. When weathering exceeds the minimum of substratum stability that organisms need for the colonization and settlement, the rock surface remains bare (Figure 2).

Climate is the most important factor influencing the relationships between vegetation, soil, and substratum properties. The basic idea here is that climate, as a source of energy and moisture, acts as the primary control for the ecosystem. As this component changes, the other components change in response /3/. Hence, and likewise, the colonization and development of bioderma on stony substratum is primary influenced by climatic parameters, such as light intensity, water availability, temperature and wind. Such climatic parameters can explain the composition .

Figure 1: Vascular plants, algae and bryophytes, and bacteria, cyanobacteria and fungi, on different monuments. From the left to the right: Naples, Ravello (Italy) and Hagar Qim (Malta).

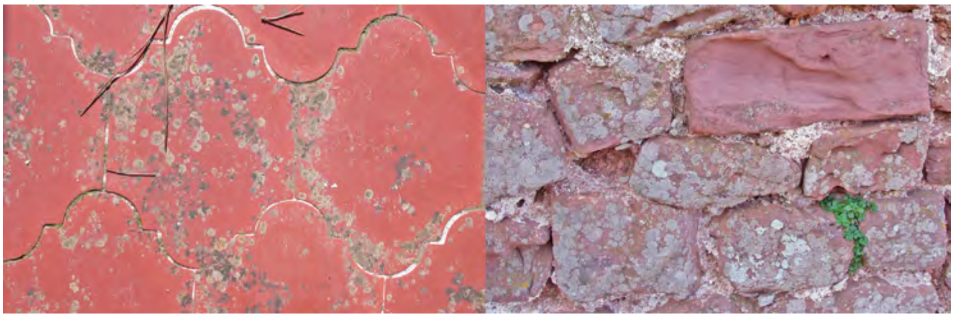

Figure 2: Recent colonization of brick (left) and old colonization of sandstone building (right). Weathering effect is evident in non colonized stones (right).

and distribution of communities developing on monuments. Among those communities, lichen communities are the most conspicuous ones. The most relevant features for understanding the main differences between communities from southern and northern Europe are related with water availability, understood as the degree of aridity, or balance between evaporation and water supplied by rain, fog or dew. In addition, there is the role played by air pollution, reducing the number of colonizing species mainly in industrialized areas; consequently, it modifies the composition of communities favouring those species resistant to pollution, which will expand more easily and replace previously settled species.

In monuments and buildings, particular microclimatic conditions are generated giving rise to special niches where different communities can be identified. As consequence, small alterations in microclimate, affecting irradiation, temperature, water availability, etc. can produce significant changes in the composition and structure of the community, even in macroscopic features as community colour. It is predicted that climate changes in Europe, mainly those affecting temperature and rainfall variation along the year, will exert a considerable effect on monument microclimate and subsequently will interfere in the colonization and settlement of phototrophic communities. In which extend these changes will affect biodeterioration of stones in cultural heritage is hard to evaluate. The role played by bioderma as biodeteriorating or bioprotecting agents depends on the composition of the community and the balance between weathering and biodeterioration. The composition of the communities has a main importance, because the biogeochemical mechanisms of deterioration depend on the specific organisms constituting the community.

One of the aims of Noah's Ark project was to assess changes in the bioderma coating monument surfaces. In this context, changes in lichen species richness and biomass were investigated based on predicted climate change, mainly precipitation and temperature (Figure 3).

Figure 3: Lichen species richness. Limestone column (Catalonia) with only one lichen species (left), and granite gravestone (North Ireland) colonized by a diversity of lichens (right).

2 Changes in lichen species richness

It is assumed that climate change will globally affect colonization and distribution of organisms. Consequently, a prediction of changes in lichen species richness on stone monuments in Europe could be possible if there is an acceptable correlation between lichen species richness and climatic parameters.

The study was based on a data base of more than one hundred European monuments, compiled from those where the biological cover of stones was available. From the data base, only 15 monuments fulfilled the following criteria:

1. reliability of bibliographic quotations;
2. being representative enough of the species richness;
3. including different and contrasted enough climatic areas;
4. with uniformity of substratum where studies have been performed.

Species richness showed a significant and negative correlation with temperature, meaning that an increase in temperature would determine a decrease in species richness. On the contrary, precipitation did not show any significant correlation with species richness, although it had a positive effect (Table 1).

Table 1: Correlation between species richness (D), temperature (T), and precipitation (P) based on Pearson's coefficient of correlation. Significant levels of correlation when $p < 0.05$ are noted as *.

	T	P
D	- 0.756(*)	0.452

Table 2: Correlation between biomass (B) and precipitation (P), and temperature (T) expressed as values of Pearson's coefficient of correlation Significant levels of correlation are noted as ** when $p < 0.01$, and * when $p < 0.05$.

	P	T
B	0.684**	-0.559*

3 Changes in biomass of the bioderma covering monuments

The establishment of relationships between climate parameters, namely precipitation and temperature, with changes in bioderma biomass coating monument surfaces in Europe was carried out on the basis of the following assumptions:

1. In a biological scale the primary succession, on the way to the climax community, attains persistent states of equilibrium represented by permanent communities.
2. In a permanent community, the biomass stabilizes and maintains a balance with microclimate.

In addition, it was considered that when some premises are accomplished, it is possible to establish a coincidence between microclimate and general climate. The study was focused on very particular conditions, in order to avoid variability due to other causes than climate parameters. Consequently, the study was based on hard acid stones (granites and schist), on exposed locations (horizontal surfaces), and in non urban environments.
The data evidenced that both climate parameters correlated significantly with biomass, although the effect was different from each other (Table 2). While temperature had a negative effect on biomass, like it had with species richness; precipitation had a positive effect.

4 Conclusions and comments

Changes in biodeterioration, as response to climate changes, can be expected in different ways. First, if environmental changes are sufficiently small, organisms may acclimatize to those conditions. Under this scenario, changes in biomass can be expected. Second, if environmental conditions exceed the ability of some individuals to cope with environmental change, then natural selection may favour some genotypes already present in the population. Third, if conditions are sufficiently severe, all organisms in the population will die or migrate from there /4/. Under this scenario, the distribution of species may be changed. Therefore, climate change can be the origin of changes in the bioderma that grow on the stone monuments.

Finally, we are in agreement with the conclusions of Morin and Lechowicz /5/, who suggested that using selected species at pilot sites (for us specific monuments) should yield better predictions of the species distribution subjected to climate changes.

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Chapter 4: Modelling of Climate Change Effects

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Modeling the Effect of Climate Change in Historic Buildings at Several Scale Levels

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Abstract

Within the new EU project ‘Climate for Culture’ researchers are investigating climate change impacts on UNESCO World Heritage Sites. Simulation results are expected to give information on the possible impact of climate change on the built cultural heritage and its indoor environment. This paper presents the current and new modeling approaches necessary for obtaining the required simulation results, by: Firstly, providing an overview of the current state of the art on the modeling of historic buildings at several scales using scientific computational software. Secondly, presenting an approach on how to incorporate the effect of climate change into the building models. Thirdly, providing a preliminary method for up-scaling building spatial level models onto a continental level. The latter provides maps that visualize the impact of external climate change on indoor climates of similar buildings spread over Europe.

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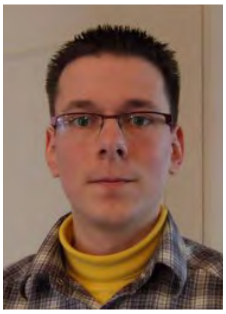

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1 Introduction

Effects of climate change on ecosystems and on the global economy have been researched intensively during the past decades but almost nothing is known about our cultural heritage. Within the new EU project ‘Climate for Culture’ researchers are investigating climate change impacts on UNESCO World Heritage Sites. Although these historical monuments are exposed to extensive loads caused by stampedes of visitors, there are many other factors deteriorating World Heritage Sites. The impacts of climate change are a long-term and substantial menace to the sites. For the first time completely new high resolution climate simulation modeling until 2100 will be coupled with building simulation software adapted for historic buildings. The simulation results are expected to give information on the possible impact of climate change on the built cultural heritage and its indoor environment.

The current scale levels incorporated in the research area Buildings as Dynamic Complex System (BuilDCoSy) succeeded from /1/, are shown in Figure 1.

Currently, the largest present scale is the urban level (~ km). However a continental scale is necessary for the new EU project ‘Climate for Culture’. This paper presents the current and new modeling approaches, necessary for obtaining the required scale level. The paper is organized as follows: Section 2 provides an overview of the current state of the art on the modeling of historic buildings at several scales using scientific computational software. Section 3 presents an approach on how to incorporate the effect of climate change into current models. Section 4 shows a preliminary method for up-scaling building spatial level models onto a continental level.

2 The modeling of historic buildings at several scales

2.1 Introduction

The modeling and simulation laboratory HAMLab (Heat, Air & Moisture Laboratory) is used /1, 2/. This in-house developed tool is implemented using state of the art scientific software packages MatLab, SimuLink & Comsol. Using HAMLab, the following general modeling facilities are available within the simulation environment SimuLink: (1) a whole building (global) modeling facility, for the simulation of the indoor climate and energy amounts; (2) a partial differential equation (PDE) solving facility, for the simulation of 2D/3D HAM responses of building constructions (i.e. materials) and 2D internal/external airflow; (3) an ordinary differential equation (ODE) solving facility, for the accurate simulation of building HVAC (Heating, Ventilating, and Air Conditioning) systems (see Figure 2).

2.2 The indoor climate modeling

Description - The whole building model originates from the thermal indoor climate model ELAN which was already published in 1987 /3/ (see Figure 3, top-left).

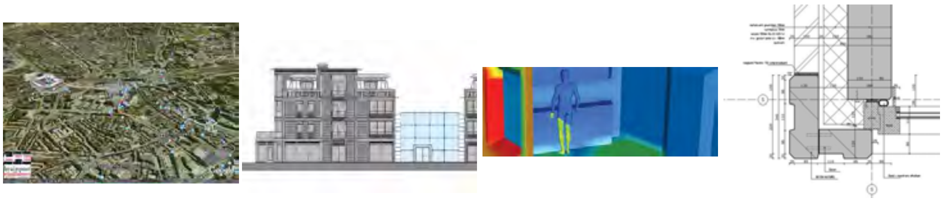

Figure 1: The current scale levels of the research area Buildings as Dynamic Complex Systems (BuilDCoSy): Urban, Building, Human, Material

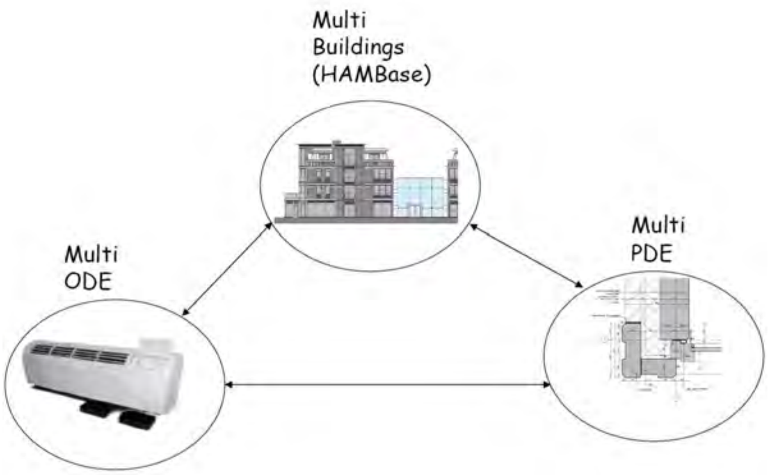

Figure 2: Schematic overview of the Heat, Air & Moisture Laboratory (HAMLab).

Separately a model for simulating the indoor air humidity was developed. In 1992 the two models were combined and programmed in the MATLAB environment. Since that time, the model has constantly been improved using the newest techniques provided by recent MATLAB versions. Currently, the hourly-based model named HAMBase, is capable of simulating the indoor temperature, the indoor air humidity and energy use for heating and cooling of a multi-zone building. The physics of this model is extensively described by de Wit /4/.

Validation – The HAMBase model has been validated using the latest state-of-art measurement from the International Energy Agency (IEA) Annex 41 /5/. Measured data are obtained from a test room which is located at the outdoor testing site of the Fraunhofer-Institute of building physics in Holzkirchen. The room was heated by electric heating and controlled on 20ºC air temperature. The measurements were carried out during a winter season. A comparison of the simulated heat supply and the measured one is shown in Figure 3 (top-right). The mean difference

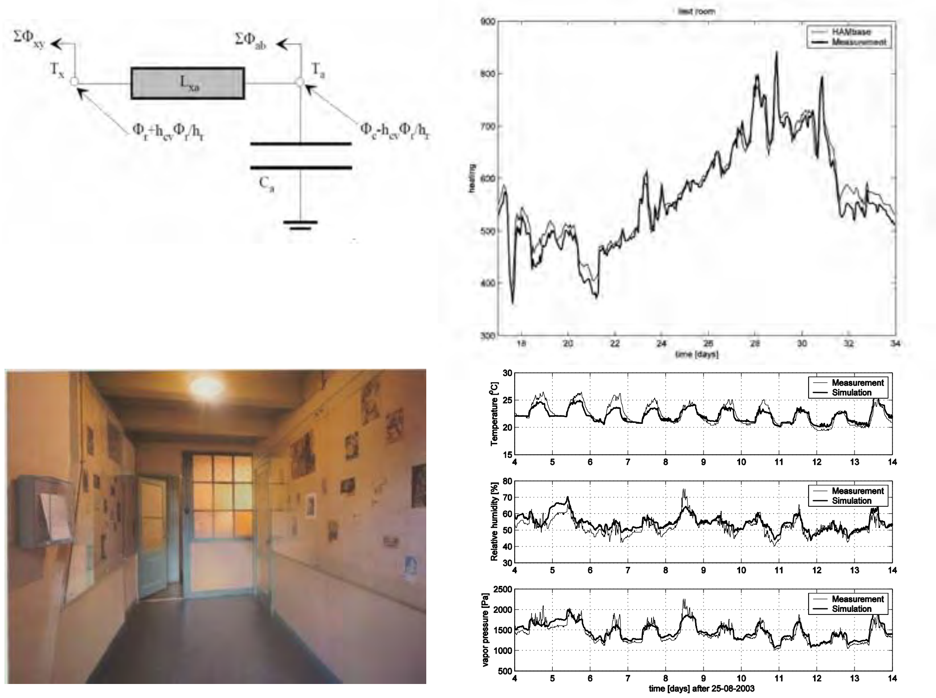

Figure 3: Overview of the indoor climate model HAMBase. Top Left: The two node thermal network of the ELAN model representing the air (Ta) and radiant (Tx) temperatures. Top Right: Validation of the heat balance. Bottom Left: Application at the Anne Frank House. Bottom Right: Comparison between model and measurements.

between simulation and experiment equals 10W and is less than 2% of the measured mean heating power. Also the results of the relative humidity (RH) simulation agree well with the measurements (mean error less than 4%).

Application – We successfully applied our indoor climate model for the Anne Frank House (see Figure 3 bottom left) /6/. This famous museum in the Netherlands reported possible damage to important preserved wallpaper fragments. An evaluation of the current indoor climate by measurements showed that the indoor climate performance did not satisfy the requirements for the preservation of old paper. To solve this problem we developed an integrated heat air & moisture (HAM) model consisting of models for respectively: the indoor climate, the HVAC system & controller and a showcase. The presented models were validated by a comparison of simulation and measurement results (see Figure 3 bottom-right). The model was used for the evaluation of a new HVAC controller design and the use of a showcase. It was concluded that it was not possible to satisfy the indoor climate within the recommended limits, exclusively by the use of a new control strategy. Furthermore in order to meet the recommendations, the wallpaper fragments should be placed in a showcase and a more robust control strategy had to be implemented in order to limit the room air temperature change.

2.3 The materials modeling

Description - Many scientific problems in building physics can be described by PDEs. The commercially available software Comsol is developed specifically for solving PDEs where the user in principle can simulate any system of coupled PDEs. The heat and moisture transport in materials can be described by two PDEs using temperature and LPc (logarithmic of capillary pressure) as potential for moisture transfer. An exemplary result of a 3D temperature distribution is shown in Figure 4 (top-left). Details on the modeling can be found in /7/.

Validation - Benchmarks are important tools to verify computational models. In the research area of building physics, the so-called HAMSTAD (Heat, Air and Moisture STAnDardization) project is a very well known reference for the (1D) testing of modeling tools on heat and moisture transport in materials /8/. The results of our HAMLab models are quite satisfactory. This shows that the modeling approach is valid for all kinds of materials. Furthermore, in Comsol, the mathematical modeling (i.e. PDE) part and geometry part are strictly separated. This means that (validated) models in 1D are extendable to 3D without the necessity of (re)validation.

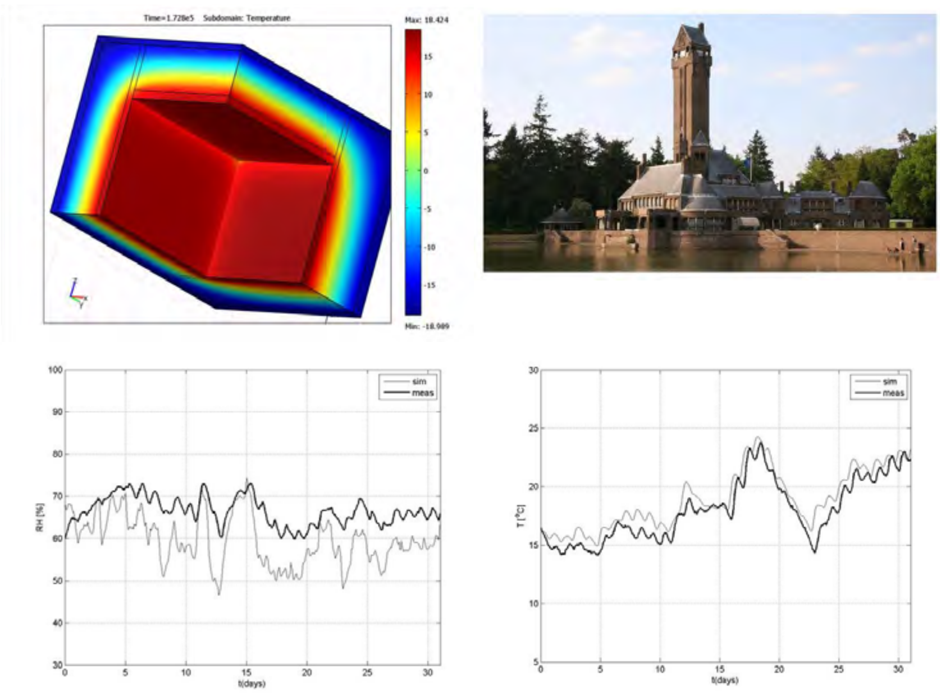

Figure 4: Overview of the heat and moisture transport modeling in materials. Top Left: Exemplary result of a 3D temperature distribution in a corner. Top Right: Application at the Hunting Lodge St. Hubertus (NL). Bottom: The simulated and measured internal surface conditions of an external wall, Left: Relative humidity, Right: Temperature

Application - The application is part of the measurement program at the Hunting Lodge St. Hubertus site, performed during 2006-2007 by Briggen et al. /9/. One of the problems was the high moisture content at the inside surface of the façade of the tower. The inside air temperature and relative humidity together with the inside surface conditions were measured using standard equipment. The construction is made of brick and concrete. We used these measurements to estimate the necessary materials properties. Figure 4 bottom shows the simulated and measured internal surface conditions for the relative humidity (left) and temperature (right). This so-called inverse modeling approach is currently under investigation (see section 3.3). Nevertheless, the model was successfully used to simulate the effect of possible measures to solve the high moisture contents at the inside surfaces.

2.4 The building systems modeling

Description - The main idea is to model the building systems as systems of ODEs and implement them into SimuLink /1/. In this case, each model has the following general characteristics: a vector of inputs, u, a vector of outputs, y, and a vector of states, x, as shown by Figure 5 top-left. As shown by /1/ a large range of buildings systems (and controllers) can be modeled and simulated using this approach.

Validation - For the preventive conservation of an important museum collection a controlled indoor climate is necessary. One of the most important factors is controlling relative humidity. So-called ‘conservational heating’ uses a hygrostatic device to control relative humidities by the heating system. High relative humidity is prevented by starting heating and reaching low relative humidity will stop heating. A comparison between simulated and measured indoor climate in case of a hygrostatic heating is shown in Figure 5 top-right.

Application - In the Walloon Church in Delft a monumental church organ is present which has been restored in the spring of 2000. The main task was to protect the wooden monumental church organ from drying induced stresses. The best solution to prevent high peak drying rates is not to heat the building. Due to thermal discomfort, this is not an acceptable solution. The worst solution to prevent high peak drying rates is full heating capacity. From Figure 5 bottom-right, it follows that the peak drying rate is of order ~100 times bigger than in case of no heating. This is seen as the main cause for the damage to the previous church organ of the Walloon church and is therefore not acceptable. Two possibilities to limit the peak drying rates are studied: Limitation of the changing rate of air temperature and relative humidity. Both are rather similar in case of the limitation of the peak drying rates. The disadvantages of a limitation of the relative humidity change rate compared to a limitation of the air temperature change rate are (1) The time to heat the church is not constant; (2) A more complex controller is needed. Therefore a limitation of the air temperature change rate is preferred. As a result of this research several adjustments have been made to the heating system. Afterwards measurements showed that the indoor climate did meet the requirements for preservation of the church organ.

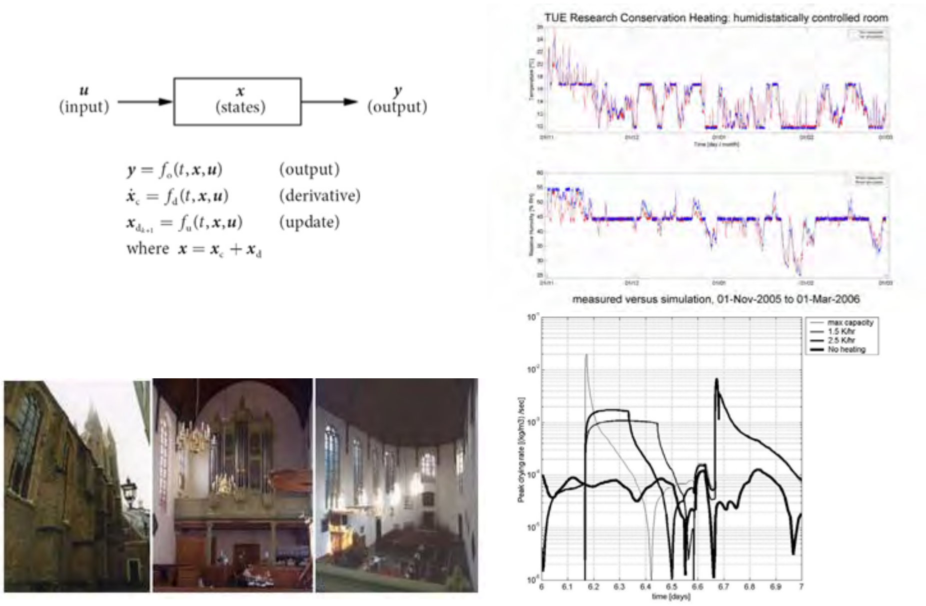

Figure 5: Overview of the (historic) building systems modeling. Top Left: ODEs modeling. Right: Validation. Bottom Left: Application at the Walloon Church. Right: Drying peak reduction

3 Incorporate the effect of climate change into the models

3.1 Using a commercial climate tool

At present artificial hourly based climate data for more than 8,000 locations on earth can be generated using the meteonorm software /10/. Meteonorm calculates hourly values of all parameters using a stochastic model. The resulting time series correspond to "typical years" used for system design. Additionally, the following parameters are derived: (1) Solar azimuth and elevation (2) Global, diffuse and beam radiation (horizontal and on inclined planes) (3) Long wave radiation (4) Luminance (5) Wind speed and direction (6) Precipitation, driving rain (7) Humidity parameters (dew point, relative humidity, mixing ratio, psychometric temperature).

It is very easy to import meteonorm data files into our building model HAMBase. This means that we have representative climate data (duration one year, resolution 1 hour) for almost any location on earth at our disposal. Furthermore, if for a building located in a certain region, the climate change can be expressed as a current climate on earth, then it is possible to simulate the impact on the indoor climate by just changing the climate data. For example for the Netherlands more hot and dry summers are expected during this century. The impact on the indoor climate in buildings in the Netherlands can be analyzed by comparison of the results using the current climate data (de Bilt) and climate data of a hot and dry region (for example some region of Spain).

3.2 Indoor climate performance evaluation

The main primary quantities related indoor (air) climates of uniform single zones are the time series of temperature T(t), relative humidity RH(t) and total power P(t) to the zone from the systems. The latter is the sum of heating, cooling and (de)humidification powers. In order to analyze these key time series we developed so-called Climate Evaluation Charts (CEC) /11/, shown in Figure 6:

The interpretation of the chart is explained (the data itself are not important at this moment): The background of the chart is a standard psychometric chart for air, with on the horizontal axis the specific humidity, on the vertical axis the temperature and curves for the relative humidity. Area 2 shows the performance demands on: (1) indoor climate boundaries: minimum and maximum temperature and relative humidity (min T, max T, min RH and max RH) and (2) indoor climate change rate boundaries: maximum allowed hourly and daily changes in temperatures and relative humidities (DeltaTh, DeltaT24, DeltaRHh, DeltaRH24). Area 1 shows the indoor climate boundaries and the simulated indoor climate of a building exposed to a Dutch standard test reference year. The simulated indoor climate is presented by seasonal (Spring from March 21 till June 21, etc.) colors representing the percentage of time of occurrence and seasonal weekly averages. The colors visualize the indoor climate distribution. For example, a very stable indoor climate produces

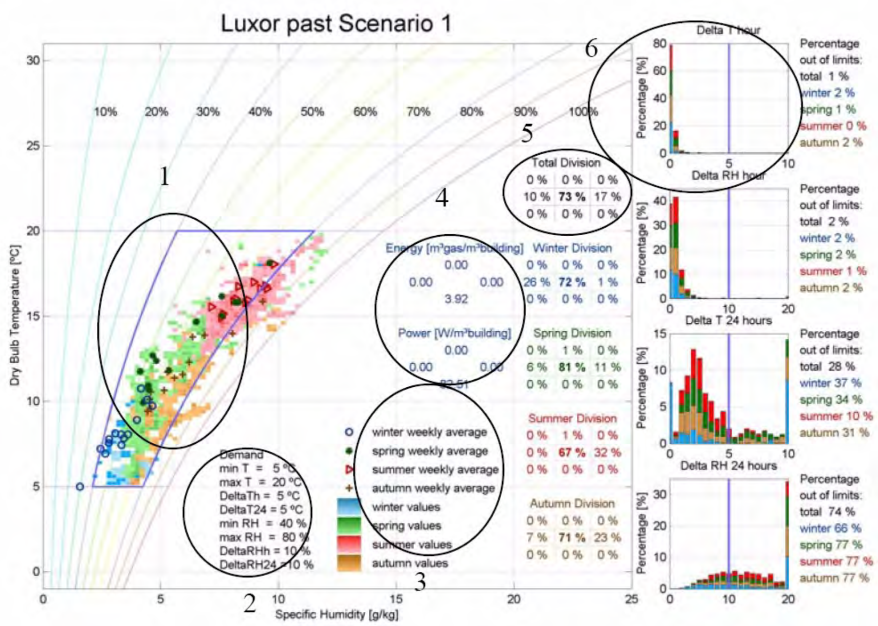

Figure 6: The Climate Evaluation Chart (CEC)

a narrow spot, in contradiction to a free floating climate which produces a large 'cloud' of data entries (see /11/). Area 3 provides the corresponding legend. Area 5 shows the total percentage of time of occurrence of areas in the psychometric chart (9 areas). In this example 73% of the time the indoor climate is within the climate boundaries; the area to the left (too dry) occurs 10% of the time, the area to the right (too humid) occurs 17% of the time. The climates in the other 6 regions do not occur. Below area 5 the same information can be found for each season separately. Area 4 shows the energy consumption (unit: m^3 gas / m^3 building volume) and required power (unit: W/m^3 building volume) used for heating (lower), cooling (upper), humidification (left) and dehumidification (right), assuming 100% efficiencies. In this example the energy amount is 3.92 m^3 (gas / m^3 building volume) and required power is 82.51 (W/m^3 building volume) used for heating. Cooling, humidification and dehumidification are zero in this example. Area 6 presents the occurrence (in percentage of time) outside the climate change rate boundaries. In the example the demand of maximum allowed hourly change of temperature of 5 (^oC/hour) is shown as a blue line. The distribution per season is provided together with the percentage of time of out of limits. In this example, area 6 shows that only 1% of the time, the hourly temperature rate of change is out of limits. This is also specified for each season. Below area 6 the same can be found for the other climate rate of change boundaries. Especially for comparing two indoor climates we developed also a so-called Multi Climate Evaluation Chart, shown in Figure 7.

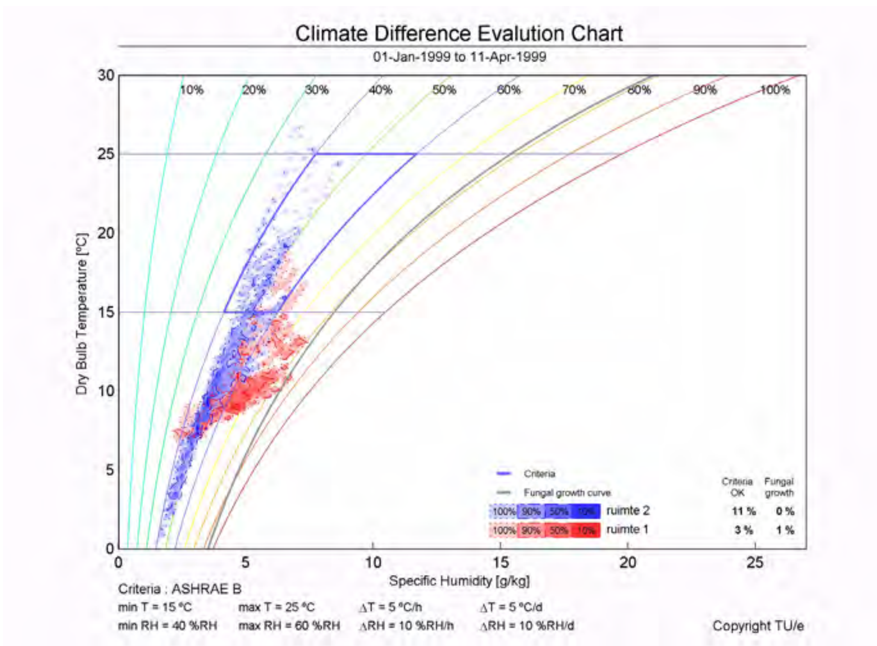

Figure 7: The Multi Climate Evaluation Chart (MCEC)

3.3 Current developments

Artificial weather data for (2010 – 2100) - Within the EU Climate for Culture project, future climate scenarios for Europe will be developed by researchers of the Max Plank institute /12/. These artificial data will contain the hourly values of the necessary climate parameters for several locations spread over Europe.

Inverse Modeling - Due to the monumental status of historic buildings, it is often not allowed to perform (destructive) measurements in order to get some information on the material properties of the façade. The main goal of this work is to investigate whether material properties can be obtained using an inverse problem technique. An inverse problem is the task that often occurs in many branches of science and mathematics where the values of some model parameter(s) must be obtained from the observed data. The inverse problem technique consists of three main parts: (1) A set of input data (time series and parameters) and the objective data (time series) to be reproduced; (2) A model capable of simulating the requested data; (3) Optimization of the modeling parameters by fitting simulated data with the objective data. For more details see /13/.

Risks of environmental changes for historical buildings using computational modeling for simulation studies back in time as well as for future scenario predictions - The main aim of the project is to develop a methodology for simulation-based prediction of risks related to indoor climate control and/or outdoor climate changes and their impact on historical buildings and their interior. Computational simulation will be used for future predictions as well as for analyzing what range of environmental changes a historical building and its interior can withstand. The latter will be achieved by simulating back in time, starting from a situation (point in time) where no damage had occurred to the building or its contents due to environmental changes. A pilot study will be done on climate related damage to panel paintings of Van Avercamp and wooden cabinets, fabricated by Van Meekeren, exposed to the historical indoor climate of Amerongen Castle and the Rijksmuseum. The historical indoor climate on both locations will be studied both from archives on the indoor use of heating systems and from simulation studies back in time. The damage to the panel paintings and cabinets and their restoration history will then be related to the historical (simulation predicted) indoor climate. By relating the damage to the experienced historical climate, a better understanding of the long term risk profile of a particular indoor climate to a sensitive collection will be aimed at. The pilot study will be carried out in close cooperation with The Netherlands Institute for Cultural Heritage (ICN) and the Rijksmuseum.

4 Towards a continental scale level

4.1 Introduction

In this Section we present the ingredients that we already developed for the scale level of the Netherlands. A similar approach can be used towards a continental scale for indoor climate performance evaluation.

4.2 Scale level in The Netherlands

The first step was to use our database with measurements of historic buildings and museums:

All buildings were measured and characterized using the methodology developed by /14/. Much attention was paid to gain all data necessary to simulate the indoor climates of representative rooms at all above mentioned buildings. Furthermore, each building is investigated using the following method in order to get comparable results:

(a) A *quick scan* - consists of a first visit to the building and a conversation with the conservation specialist and the technical staff. This uncovers some initial climate problems and gives a first impression of the complexity of the building.

(b) *A full inventory* - is made of the situation. Floor plans, technical drawings and details of the building and the climate system are requested. The use of the building is examined. Also the positions of the artifacts are determined, and their vulnerability is noted. Finally, the building management system sensors are drawn up.

(c) *Measurement* - In the initial stage some short measurements are executed, e.g. infrared thermal imaging, short temperature and relative humidity checks and inlet air conditions. Together with the inventory, this leads to a full measurement setup for the whole building. Permanent measurements on air temperature, relative humidity and surface temperature are executed by a combined sensor. This sensor contains a transmitter that sends the measured data to a wireless data logger that is placed centrally in the building. The function of the logger is to temporarily store the data. A GSM connection is used to download the data from the logger to

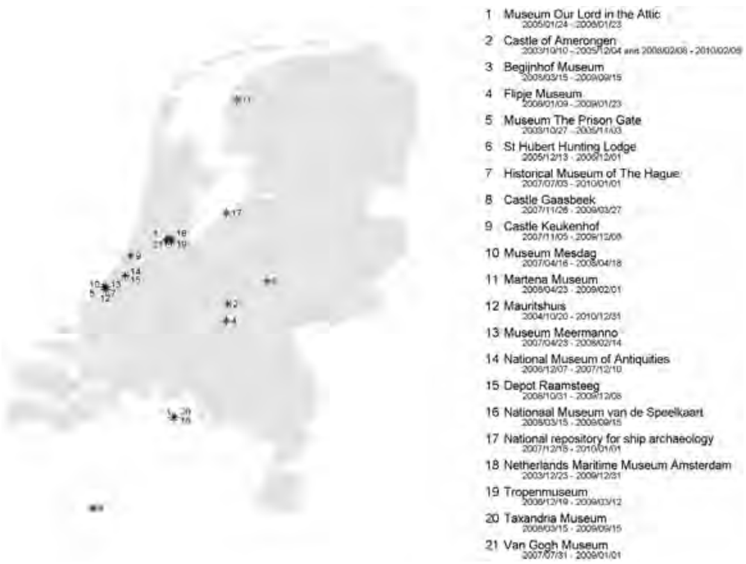

Figure 8: An overview of the locations of historic buildings and museums in our database including the measurement periods.

a central server. This server processes the data and makes it available on an Internet application.

(d) *Modeling* – The indoor climate model of Section 2.1 is used to calculate the indoor temperature and humidity based on the outdoor climate measured by the Royal Netherlands Meteorological Institute (KNMI). This output of the model is compared to the measured climate. The model can be used to determine some physical parameters e.g. the humidity buffering capacity. Differences between the model and reality are examined.

The computer model is also used to calculate the influence of changes that can be made to either the building or the climate system. The impact of each change is determined. This helps in advising to improve the climate.

(e) *Analysis* - Measurements and simulation results are analyzed. The physical behavior of the indoor climate in the building is assessed. The best strategy for improving the climate is discussed. Finally for each museum some conclusions and recommendations are given.

4.3 Classification

The second step was to develop a classification system that allows comparing similar buildings and especially indoor climates. The buildings are divided using the complexity of the construction as can be seen in Table 1: the number of materials and the method of construction. For the climate system the ventilation, thermal influence, hygric influence, the medium type and the control are assessed; the different types are displayed in table 2. When combining Table 1 and 2, a two dimensional figure appears as displayed in Figure 9. The buildings under research are placed in this matrix. The Dutch situation consists of various simple monumental buildings that have all types of climate systems. The newer, more complex buildings however show less diversity in their climate systems.

Table 1: Building complexity of the construction

	Glazing		**Brickwork**		**Wood**	**Iron**	**Concrete**			**Steel**		**Aluminum**		**Insulation**	**Alternative**
	Single	Double	No cavity	Cavity			Solid	Reinfor.	Pref	No insul.	Insulated	No insul.	Insulated		
< 1900	X		X		X	X									
1900 – 1945	X		X	X	X		X			X					
1945 – 1975	X			X	X		X	X		X		X			
> 1975		X		X	X		X	X	X		X		X	X	X

Table 2: Climate system complexity for the first 8 buildings of Figure 8.

Type	Ventilation		Thermal		Hygrical		Medium			Control		
	Natural	Mechanical	Heating	Cooling	Humidification	Dehumidification	None	Water	Air	Thermostat	Hygrostat	BMS
1	X						X					
2	X		X					X		X		
3	X		X		X	X		X		X	x	
4	X		X					X			X	
5	X		X		X	X		X			X	
6		X	X					X	X	X		
7		X	X	X				X	X	X		
8		X	X	X				X	X	X		X

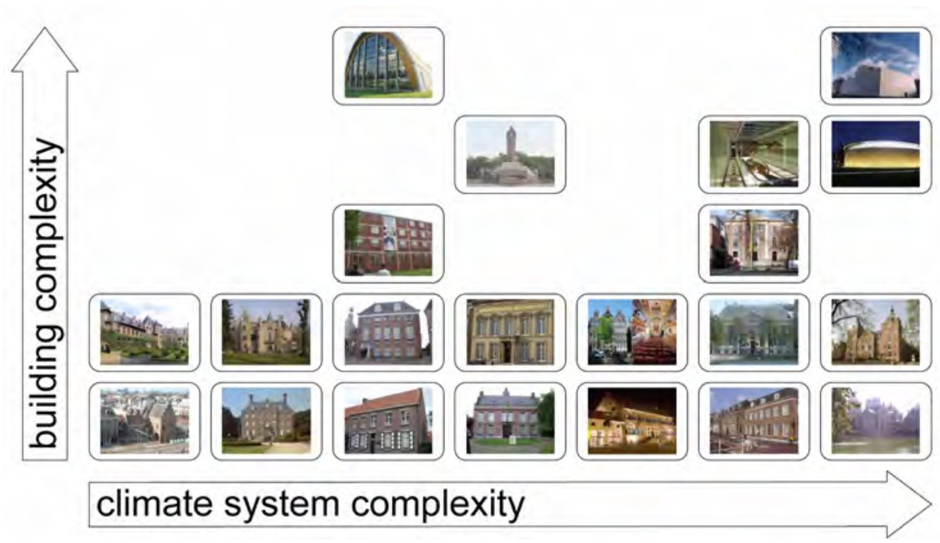

Figure 9: The classification system

4.4 Multi-buildings modeling

The third step was to include several buildings from the previous Section in a single multi-buildings model. We adapted our building model HAMBase (see Section 2.1) in such a way that we could simulate several buildings in a single model. Table 3 shows some details of the 11 historic buildings included in the model.

The model complexity is obvious: 93 indoor climate zones each including zonal climate control systems together with the heat and moisture gains, 776 walls and 210 windows. The output of the model i.e. indoor climates and heat and moisture flows of the systems are also complicated. The results of a preliminary application of the Multi-buildings model are shown in Figure 10. The top row presents 93 indoor climates (T and RH) of 11 buildings simulated during 10 days in winter including present systems and internal gains. All these data are validated. So they also represent the measured values in reality. However, what we almost never can measure (for obvious reasons: we are not allowed to do this), are the responses of the indoor climates in historic buildings without systems and internal gains. Such responses could be very important when trying to classify the indoor climates of historic buildings. In Figure 10, the bottom row shows the virtual free floating simulation results similar as the top row but now without systems and internal gains. These latter results also represent the influence of the external climate on the indoor climate. This could be an important tool when studying the effect of climate change.

Table 3: Details of 11 historic buildings included in the Multi-buildings model

Building Nr. From fig 8	# Zones	# Walls	# Windows	Systems
2	10	66	26	Heating
3	12	80	18	Heating
5	10	77	24	Heating
8	4	21	3	Heating
9	15	205	64	Heating
11	8	51	19	Full airco
12	3	36	7	Free Floating
13	10	46	13	Heating
16	11	86	20	Heating
20	6	52	14	Heating
21	4	56	2	Full airco
total	93	776	210	

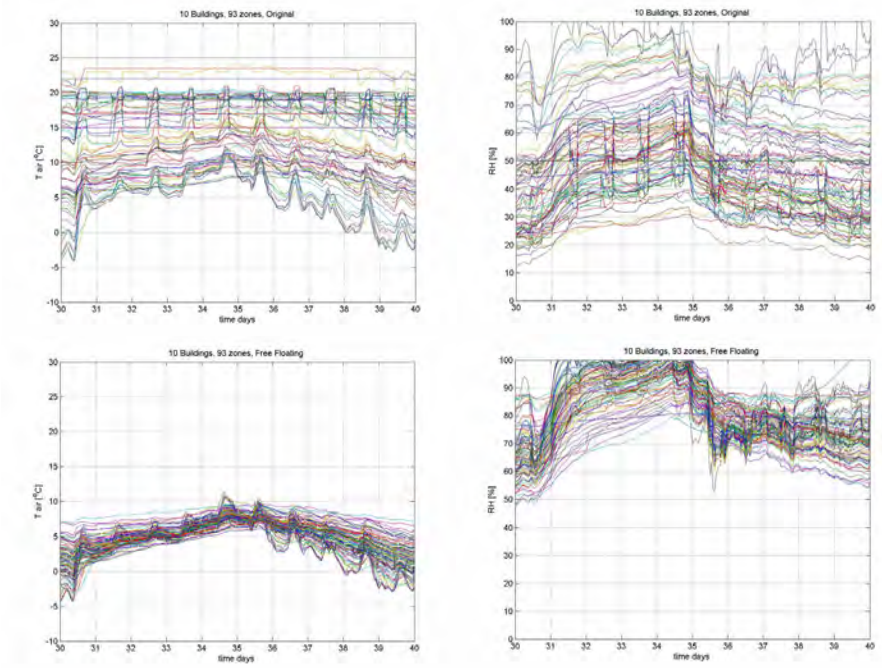

Figure 10: The simulated 96 indoor climates of 11 buildings during 10 days in winter. Top: 'As is' including present systems and internal gains, Left: Temperature, Right: Relative Humidity. Bottom: 'Virtual Free Floating' similar but now without systems and internal gains. Left: Temperature, Right: Relative Humidity.

4.5 Mapping and visualization

Finally, after applying the previous steps on a European scale level, we have data for the indoor climate impact for several locations spread over Europe. In order to visualize these results we have to interpolate results on a map of Europe. Figure 11 shows a demonstration of a European (with dummy data) map using the MatLab visualization tools.

The purpose of the figure 11 is to show *how* the impact of external climate change on indoor climates of similar buildings spread over Europe can be visualized.

5 Discussion and Conclusions

This paper presents the current and new modeling approaches, necessary for obtaining the simulation results on the possible impact of climate change on the built cultural heritage and its indoor environment. The approach consists of three main topics:

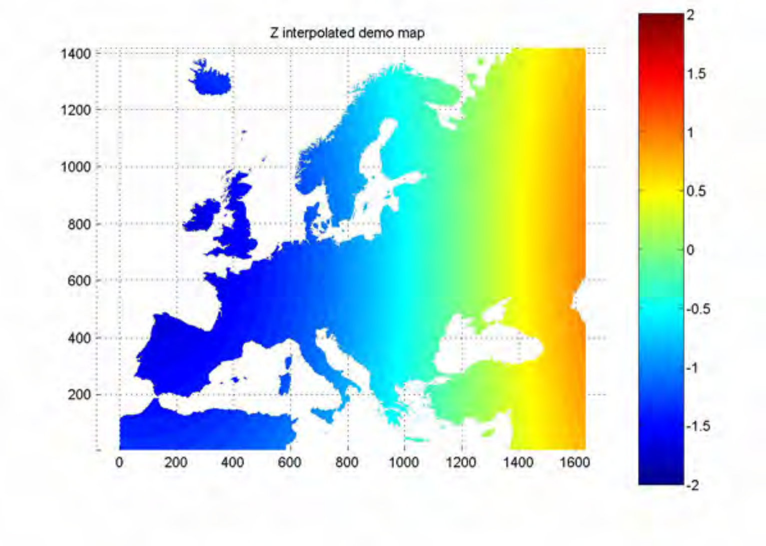

Figure 11: A demonstration map (with dummy data) of Europe using MatLab

Firstly, we provided an overview of the current state of the art on the modeling of historic buildings at several scales using scientific computational software. It is concluded that the presented modeling and simulation laboratory is well equipped for simulating heat, air and moisture transport at the scale levels ranging from materials to buildings.

Secondly, we presented a method on how to incorporate the effect of climate change into the building models by using artificial climate data. Currently, future climate scenarios for Europe are under development by researchers of the Max Plank institute. These artificial data will contain the hourly values of the necessary climate parameters for several locations spread over Europe. This enables us to simulate the effect of expected climate change on buildings in Europe in near future. Furthermore we provided visualization tools to compare indoor climates of building zones with each other.

Thirdly, we showed a preliminary method for up-scaling building spatial level models onto a continental level by the following steps: (1) Classification of buildings; (2) simulation of the same type of buildings at several locations spread over Europe; (3) simulation of the effect of climate change using artificial local climate data sets; (4) visualization of the results using EU maps. Currently we are able to apply step (1) and (2) for the Netherlands. For Europe, this can be done in the same way. Step (3) has been discussed in the previous paragraph. Step (4): We are able to produce maps for the Netherlands as well as for Europe. Overall we may conclude that this approach is very promising for simulating the impact of climate change on the indoor climates of historic buildings at several scale levels.

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Future Impacts of Climate Change on the Construction Industry in Germany

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Abstract

In the future, construction will be strongly influenced by climate change. This is particularly true for currently built structures of the infrastructure, which are planned for a service life of 70-100 years. Thus research projects in this area are particularly important in order to avoid processes in the construction industry which may accelerate climate change, or to minimize their number. Furthermore, adaptation strategies are to be developed in order build durable and functional constructions despite changing climate conditions. In this paper, results of a preliminary study will be presented which were used to identify those areas of construction, which will be particularly affected by climate change. It also shows that adaptation strategies are not limited to individual sections, but are to consider the entire life cycle.

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1 Construction in a changing climate

The threatening climate change is the subject of intense debate both in science as well as in politics. In the field of construction climate change was especially discussed in the context of building physics problems. Thus, intensive research has been conducted regarding the development of new insulation materials, construction methods and calculation methods /1/. Far less attention has been paid to developments that lead to a reduction of mass flows in the construction industry, e.g. by increasing the durability of materials or the use of recycled materials.

Studies on the effects of future climate changes on the construction industry have been presented rather rarely /2/. These studies describe the possible impact of climate change on buildings in general, but are not suitable to identify the areas of construction which will be affected in particular. Moreover, which consequences of climate change such as increased temperatures, drought or heavy rain are relevant for the different areas, cannot be understood from the studies.

Another difficulty also results from the complex mathematical modelling of the expected future climate change, as it is not clear whether the sensitivity of these models, which have been developed for the prediction of global and regional climate changes, are suitable for an estimation of the consequences to be expected in construction industry. This is due to the fact that these models are able to depict the real situation only to a certain extent. So far, these models have not yet been analysed regarding their adaptability to the construction industry. However, the development of appropriate adaptation strategies will depend on whether modern climate models can be linked with the specific conditions given in the different areas of construction industry. In some cases it may be necessary to modify the climate models and adapt them to the corresponding boundary conditions.

This paper presents the results of a preliminary study which will serve as the basis for a larger research project. In this subsequent project, the Institute for Prevention in Construction of the University of Applied Sciences Karlsruhe and the Institute for Meteorology and Climate Research, Karlsruhe Institute of Technology (KIT) will analyse the impact of climate change on selected areas of construction, using modern climate models, and adjust strategies regarding materials of construction and construction methods.

In the following, essential findings of previous activities will be presented and discussed.

2 Climate History

Since the formation of the earth about 4.5 billion years ago, the climate has been subject to large fluctuations. All parts of the earth system are exposed to constant change. During the first three billion years of Earth, the atmospheric composition was different from the contemporary one. The CO_2 content of the atmosphere represented the 100.000-fold, and O_2 was entirely absent. The energy input by the sun was much lower and the arrangement of the continents was different than

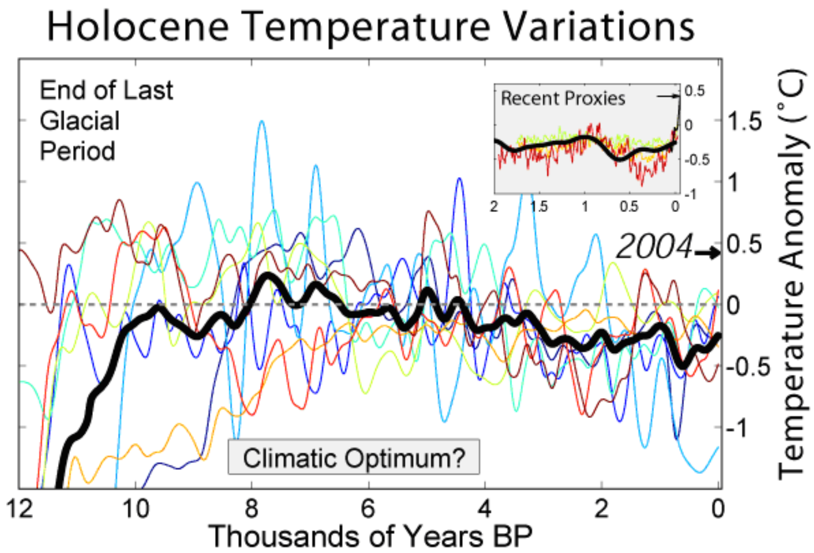

Figure 1: Temperature changes in the Holocene

today. Despite the entirely different conditions, there were probably similar climatic conditions on the young Earth as today. However, there were also several climate-related disasters, after which almost the entire planet was covered of ice and snow. The last of these so-called "Snowball Earth" events took place about 600 million years ago /3/. The photosynthetic bacteria operated only very slowly, reducing the CO_2 in the atmosphere and enriching it with O_2. During phases with a relatively high concentration of CO_2 it remained rather warm, whereas in periods of low CO_2 concentrations there were rather cold climatic conditions. The last approximately two million years have been marked by recurring 100.000 year ice age cycles. These are triggered by the cyclical nature of the earth's orbital parameters. The last ice age some 20,000 years ago reached its climax. Since about 11.000 years ago, we find ourselves in a warm phase, the so-called "Holocene." These last 11.000 years are characterized by a remarkable stability of the climatic conditions, with only very minor variations. Around 7.000 years ago, the "Holocene“ reached the climate optimum, and in the Middle Ages the earth was in the so-called "little ice age" which lasted until the mid-19th for centuries. Therefore, it can be said that the climate of the earth has always been subject to large fluctuations over a period of several 10,000 to 100,000 years ago. The current rapid climate change cannot be explained by natural phenomena. It is the people who are changing the climate! /4/.

In this context it should be stated that construction industry is responsible for the biggest man-made mass and energy flows which occurred in recent times. The cement industry alone causes approx. 5% of the amounts of CO_2 emitted worldwide every year. On the other hand, construction is also strongly influenced by climate change such as the increase in temperature or a long lasting dryness. Therefore, a key factor for the future construction industry will be the climate changes that are caused by greenhouse effect.

3 Greenhouse effect

3.1 Natural greenhouse effect

The earth's climate is the result of an energy balance between the incoming solar radiation and the radiating heat energy of the earth. This energy is not balanced, which results in a climate change. The incident solar radiation has a very short wavelength and is in a range of 100nm - 3500nm. The terrestrial radiation from the earth is very long-wavelength, however, lies in a range between 3.5 microns and 100 microns. The incident solar radiation can pass through the atmosphere and warm the earth's surface virtually unimpeded except for reflections of clouds and aerosols. The surface itself emits long-wave heat radiation. Gas molecules with more than two atoms absorb it and warm the lower atmosphere. Without this effect, the global average temperature would be around -18 ° C instead of the currently 15 ° C /5/.

3.2 Anthropogenic greenhouse effect

By the beginning of the industrialization in the mid-18th century industrial humans started the burning of fossil fuels for energy production and thus enriched the atmosphere with CO_2. Furthermore, due to intensive agriculture and animal husbandry CH_4 and N_2O as CFCs (used as propellants and refrigerants) and more greenhouse gases into the atmosphere. More and more long-wave heat radiation is absorbed from the trace gases and the atmosphere is heated even more. With this change, a chain reaction has been caused in the climate system. The sea is heated, ice starts to melt, the sea level rises and the vegetation is changing /6/. The interaction between construction and the man-made greenhouse effect has recently not been subject of intense scientific research. Activities in this field mainly focussed on saving energy by means of heat insulating materials and construction methods /5/.

4 Global climate change

Since the beginning of measuring the global mean temperature in 1850, it has increased by about 0.8 ° C. In particular, a significant increase in temperature over the past 50 years is clearly visible. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was founded to analyse the scientific knowledge of climate change, the human influence, the Impact on the environment and society and to propose reduction strategies. The findings of the working groups of IPCC are published in so-called progress reports. The last report was published in 2007 and the next release is scheduled for 2014. In addition to this, the panel developed so-

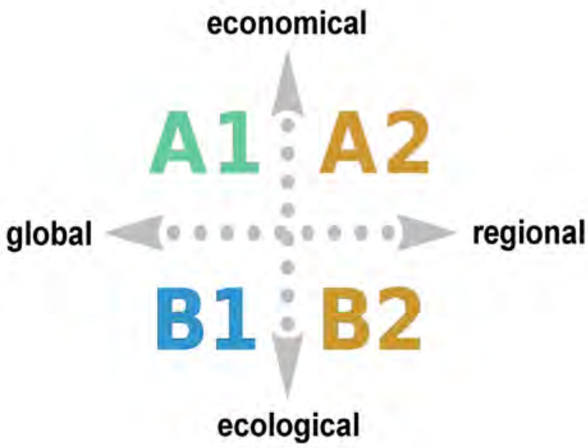

Figure 2: The schematic presentation of the SRES scenarios

called SRES scenarios (Special Report on Emissions Scenarios) taking in account the proposed development of the growth of the world population, the economic growth and the successful introduction of new-developed “green” technologies to outline the further development of the world and thus the emission of trace gases and other climate-related factors (Fig. 2).

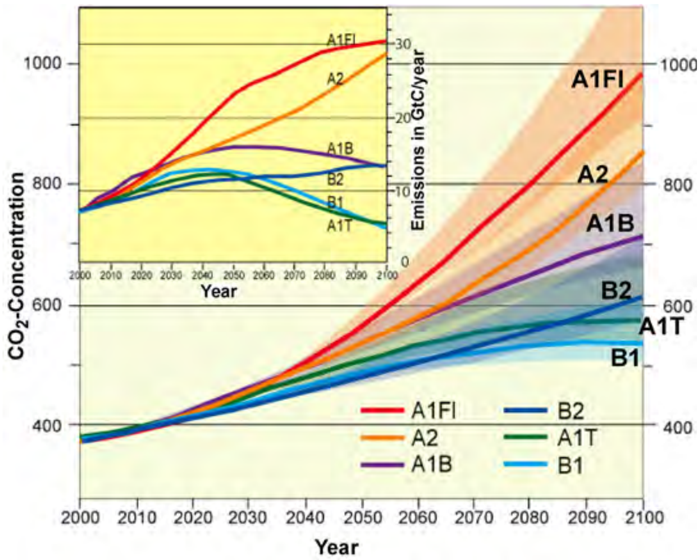

Figure 3: Change in CO_2 concentration and temperature as a function of emission scenarios, according to /6/

Scenario A 1 describes a world with strong economic growth and a fast growing of the world's population until the mid-21st century. After this, these trends will be regressive. The objective is an international cooperation for balancing regional differences in order to timely develop and use new and more efficient technologies. Depending on the different methods for energy generation there are several members of this scenario family such as A1F1 for fossil-intense, A1T for non-fossil energy sources and A1B for a well-balanced use of all sources. As for scenario A2 the regional differences remain, and economic growth and technology transfer are slowed down whereas the global population grows steadily.

Like in scenario A1 scenario B1 also predicts a fast globalisation, though focussing on global solution approaches for an economic, social and environmentally friendly sustainability.

In scenario B2 a world with a focus on local solutions resulting in a sustainable development is described, which is located at medium level as far as speed and extent are concerned. The global population grows more slowly than in scenario A2 but still steadily.

None of these scenarios assumes the implementation of international agreements such as the Kyoto Protocol.

By means of these scenarios comparable calculations regarding the global climate can be carried out. Important results of these calculations can be summarized as follows.

Depending on the scenario, the CO_2-concentration in the atmosphere will increase in the range between ca. 530 ppm (B1) and ca. 980 ppm (Fig. 3). As a result of this CO_2-shift in the atmosphere during the period 2090-2100 the temperature will increase from 1 to 6.4 ° C compared to the period1980-1999 as shown in Fig. 4.

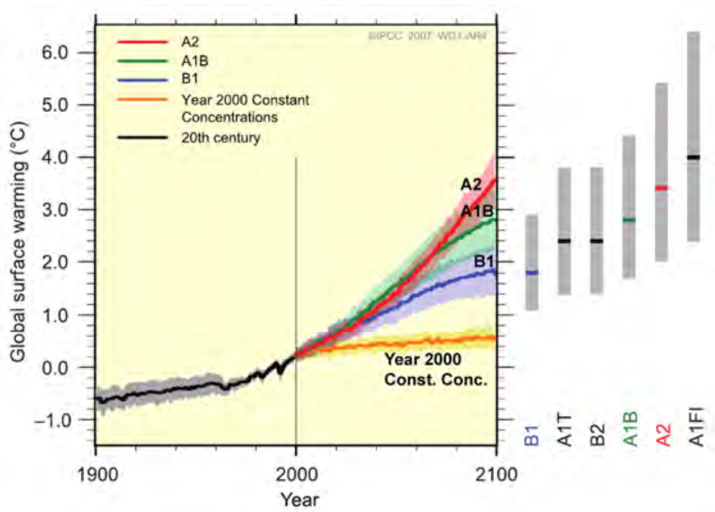

Figure 4: Multi-model averages and assessed ranges for global surface warming /6/

The results for the different scenarios represented by the solid lines are shown in Fig. 4. Shading denotes the ± 1 standard deviation range of the individual model. The orange line in fig. 4 is for the calculation where concentrations were held constant at year 2000 value. The grey bars at right indicate the best estimate (solid line) and the lilely range assessed by the different scenarios. The results of modelling show clearly that by comparing the actual concentration of CO_2 and the emission scenarios early trends can be detected. For example, if the actual development is calculated in the high emission scenarios, the global average temperature may increase by more than 5 °C by 2100 (Fig. 5).

Moreover, the global mean precipitation will increase due to climate change (Fig. 6). With a higher temperature of the atmosphere more water vapour will be held. Rainfall will increase greatly in high Northern latitudes and decrease in most subtropical countries up to 20%. In addition to that, there are strong differences in the seasonal distribution. The mid-latitudes will be affected during the summer months by a sharp decline /6/, /7/.

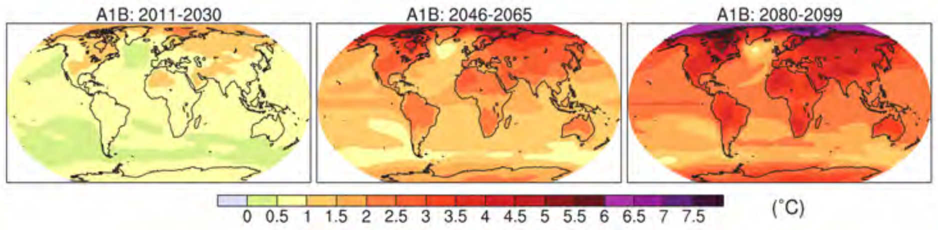

Figure 5: Change in temperature compared to the base period 1980 – 1999 /6/

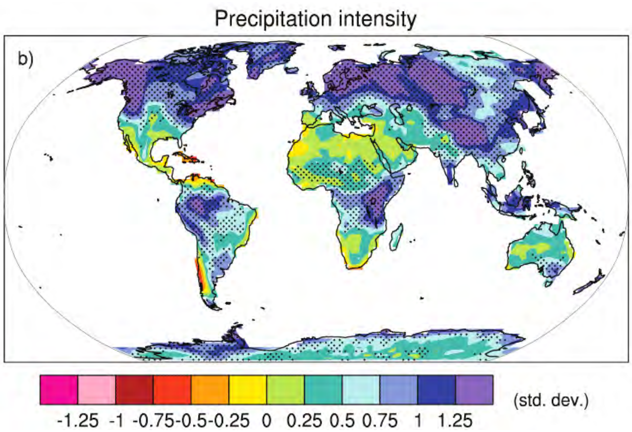

Figure 6: Change and intensity of precipitation for the period 2090 - 2099 compared to 1980 – 1999 The precipitation intensity is defined as the annual total precipitation divided by the numbers of wet days /6/

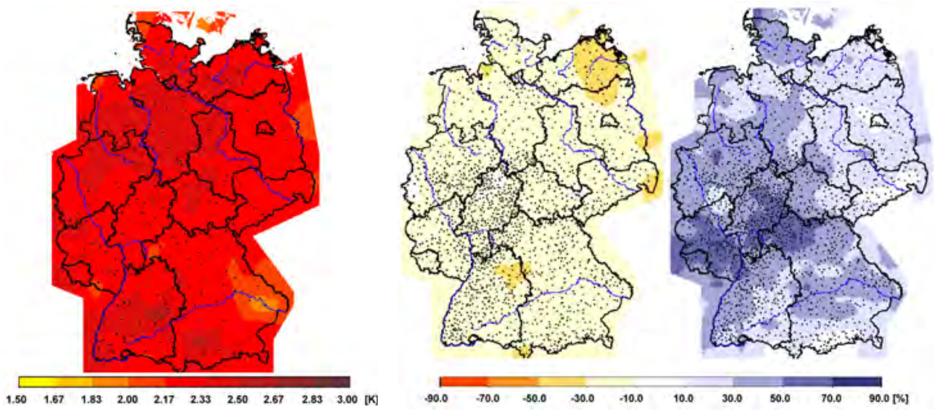

Figure 7: Temperature and precipitation development 2071-2100 (compared to the base period 1961-1990 (scenario A1B) /8/; mean annual temperature in K (left), change in summer precipitation in % (middle), and change in winter precipitation in % (right)

5 Climate change in Germany

Depending on the chosen emission scenario for Germany the average annual temperature will increase by 2.5 - 3.5 degrees °C by the year 2100. The winter months will heat up by up to 4 ° C by 2100. The smallest increase is observed in spring and is about 1.5-2 °C. Considering only the annual rainfall, there are only very small changes compared to the reference periods (± 10%). However, significant differences can be seen in a seasonal approach. In the fall, winter and spring a partly significant increase in precipitation can be observed. This increase in West Germany can be up to 40%. In summer, there a significant decrease in precipitation was expected. This can be seen with the decline in Baden-Wuerttemberg, Bavaria and North-East German lowlands with up to -40% (Fig. 7) /8/.

6 Climate Change and construction in Germany

In 21st century, building industry faces some major challenges. Globalization, the shortness of resources and climate change require further developments in this field. In particular, construction industry needs to solve these problems by means of new innovative materials and construction techniques. In this context, concepts such as Life-Cycle Management, Life Cycle Costing, public-private partnership, ecology, economics and sustainability will play a very important role.

In the future, climate change will have a major impact on construction worldwide. The effects in the different regions of the world will depend on local climatic conditions. In the preliminary study presented here, selected areas of civil engineering were initially analysed regarding climate-induced changes in Germany and their significant impact on the materials used for construction.

In order to quantitatively comprehend the influence of the expected climate change on construction it was necessary to identify those fields which are considered particularly sensitive due to the construction methods or materials used. Thus, the large number of individual cases can be reduced to those for which climate change will definitely lead to changes regarding the selection of materials or construction methods. For the different areas of civil engineering (e.g. urban water management, road construction) constructions have been selected for which considerable effects on production and use are expected due to climate change (table 1).

Table 1: Selected areas of civil engineering

Waterways	Urban Water Management	Structural Engineering	Civil engineering and road construction
River engineering · Low-water-management of waterways · Adjusting the flow cross-sections for rising winter mean water runoff · Creation of water balance models · Re-naturization of rivers **Coastal and flood protection** · Renewal, adaptation and construction of dykes, reservoirs and dams · Creation of retention areas (polders) **Hydropower** · Run-off management for effective utilization of the water · Water management for power plant cooling	**Water** · Protect water against pollution caused by heavy rain and floods · Adjustment of water treatment, storage and supply **Water Disposal / urban drainage / storm water management** · Adjustment of household spending on sewers · Cleaning effect of summer rainfall decrease · Accumulation of pollutants in the drainage and backflow · Segregation and mixing adapt to strong precipitation events · Caching heavy rains for the attenuation of floods	**High/commercial/ industrial construction** · Adaptation of the summer and winter thermal protection · Reduce energy consumption · Roofs and facades adapt to unusual weather conditions · Urban Development and Climate, avoidance of heat islands · Adjustment of the processing and finishing of cement based materials to the climate **Bridges / Civil Engineering** · Adapting the design to growing temperature ranges · Prevention against chemical and climatic influences	**Street / road / track construction** · Increased freight traffic (transit country Germany) - Adaptation of structures to rising temperature differences · Development of alternative methods of construction, the finite resource of oil (bitumen) · Preservation, renovation and expansion of infrastructure in Germany · Development of financial models (Puplic Private) Partnership **Basic / Low / tunneling** · Slope protection against extreme weather · Adapting to fluctuations in construction and alteration of the ground water table · Preservation of permafrost in the Alps

In a second step these areas were analysed with regard to the particular effects, which can be expected from the climate changes (increase in temperature, heat waves, lower or higher amounts of precipitation, heavy rain etc.) predicted by climate models. Here, special focus was laid on material properties such as concrete shrinkage or softening of bituminous materials, and use-related stress (table 2, Influence of Climate Change). This has been done largely in a qualitative way. The results of this preliminary study show that the individual climate changes will affect the various fields of construction engineering differently.

In a third step, it has been analysed which parts of the life cycle are particularly significant as far as the minimising of consequences of climate change regarding the production and sustainable use of the construction is concerned (table 2 Relevance of the life-cycle sections). Thus, already today it is possible to consider future climate effects when planning constructions. A typical example is the behaviour of bituminous pavements of highways when the differences between minimum or maximum temperatures in winter or summer increase. If the materials used for producing pavements during hot summers are optmised they will be too brittle for the cold winters. In this case, a material failure is to be expected which is illustrated by the large number of pavement damages on German roads. These links and the possibility to make use of the combination of a specific material behaviour with the expected climate change in order to define requirement profiles for climate-adapted materials can be shown by means of selected examples.

The increase in temperature is especially noticeable in the field of building and road construction. Moreover, the expected hot summers with low levels of humidity will make the application of plaster mortars on the facades of buildings much more difficult. This is to be considered for material selection but in particular during quality control. As a result, the requirement for developing a modified mortar with a better performance regarding shrinkage becomes evident. Furthermore, measurement concepts for routine monitoring of the processing conditions are to be developed.

As far as sewage systems are concerned in the planning phase not only demographic trends but also rather common events such as heavy rain are to be taken into account. The resulting changes regarding mechanical, chemical and physical effects (such as abrasion) are to be considered when determining the material properties selecting the materials. Onwards, the maintenance of existing systems will be necessary to meet these requirements.

The lowering of the ground water level especially in the sandy soils in Northern Germany will result in changed pre-conditions for the planning and execution of the foundation. This has a direct impact on materials and construction methods (such as pile foundations).

During the research activities those areas which have been identified as important are to be analysed in further detail focussing on the previously used materials and the influence of climate on performance and durability of these materials. For this purpose, the following questions have been elaborated:

Table 2: Influence of several climatic effects on various constructions areas and the relevance of the different life-cycle section for the reduction of the influence of climatic effects

			Influence of climate change										Relevance of the life-cycle-sections					
			Temperature			Precipitation					Wind	Sea	Life-Cycle					
			Temperature Rise	Increasing temperature difference	Heat waves	Precipitation decrease in summer	Increase in winter precipitation	Storms / hurricanes	Wet periods	Heavy precipitation	Storms / hurricanes	Sea level rise	Planning	Execution	Use	Repair	Material	Construction
Construction	Waterways	River engineering	x	o	xx	xx	xxx	x	xx	xxx	x	x	yyy	o	y	y	y	yy
		Coastal and flood protection	o	o	o	o	xx	xxx	x	xxx	xxx	xx	yyy	o	y	y	y	yy
		Hydropower	x	o	xx	xxx	x	x	x	xx	x	o	yy	o	yy	y	y	y
	Urban water management	Water	o	o	x	x	x	o	o	xx	o	o	y	o	yy	y	o	o
		Water Supply System / Sewage System	o	o	x	xx	xxx	o	o	xx	o	o	yy	o	y	yy	y	yy
		Drainage Pipes	o	o	o	x	xxx	xx	xx	xxx	xx	o	yy	o	y	yy	o	y
	Constructive civil engineering	Residential / office building	xx	xx	x	x	o	xx	o	x	xx	o	y	yy	y	yy	yy	yy
		Commercial and Industrial	xx	xx	x	xx	o	xx	o	x	xx	o	y	yy	y	yy	yy	yy
		Bridges / Civil Engineering	x	xx	x	xx	x	xx	x	xx	xx	o	yy	yy	y	yyy	yy	yy
	High / Road construction	Street / road / track construction	xx	xx	xxx	xx	x	x	x	xx	x	o	yy	yy	yy	y	yyy	yy
		Groundwater / soil structure	x	o	x	x	xx	x	xx	xx	x	x	yy	y	o	y	y	y
		Tunnel and under-ground engineering	o	o	o	x	x	o	xx	x	o	o	yy	o	o	yy	yy	yy

Climate change affects: xxx = very high, xx = high, x = medium, o = low – no
Relevance of the life-cycle-sections: yyy = high, yy = high, y = medium, o = low - no

1. How does climate influence the behaviour of construction material? (sensitivity analysis)
2. Which climate changes are to be expected in the next decades, which will affect future constructions in general and material development in particular?
3. In which fields will climate models have to be modified in order to trigger targeted developments in construction engineering?

For this purpose, not only chemical-physical methods for material analysis and development (“Computational Chemistry“) but also region-specific, high-resolution climate models can be used /9 - 11/.

7 Conclusions

Based on the aforementioned results of the preliminary study with the theme "Building and Climate Change" the following conclusions can be drawn:

- Climate change will have different effects in different areas of construction engineering during the service life of constructions.
- For each area of construction adaptation strategies must be developed to ensure the long-term use of buildings without maintenance or climate-adapted maintenance.
- By means of the results of this preliminary study and further planned studies describe above, it will be possible to develop requirements for climate-adapted materials and construction methods.

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Climate Change and High-Resolution Whole-Building Numerical Modelling

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Abstract

This paper briefly discusses the need of high-resolution whole-building numerical modelling in the context of climate change. High-resolution whole-building numerical modelling can be used for detailed analysis of the potential consequences of climate change on buildings and to evaluate remedial measures. This discussion is certainly not intended to be complete. Rather it is intended to provide some views on climate change and built environment from a computational building physics perspective. After this brief discussion, a case study of application and validation of a high-resolution sub-model is presented, in which Computational Fluid Dynamics (CFD) is used to calculate wind-driven rain (WDR) deposition on a monumental tower building in the Netherlands.

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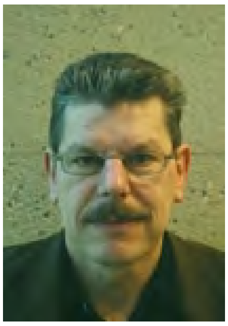

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1 Introduction

Climate change is expected to bring higher temperatures and increased extreme precipitation amounts (e.g. /1,2/). In urban environments, the global increase of temperatures will add to the local increase caused by the urban heat island effect. Increased precipitation amounts will increase risk of flooding, influence groundwater levels and can increase the wind-driven rain loading of building facades (e.g., /3/). Changes of environmental parameters in the outdoor environment will be translated, through the building envelope, to changes in the indoor environment. In absence of cooling, higher outdoor temperatures will lead to higher indoor air temperatures. This will have a major impact on the existing stock of free-running naturally ventilated buildings and will strongly increase the risk of overheating (/3,4/). The majority of buildings in many European countries belong to this category. Research indicates that a major European heat wave, such as that of 2003, could become a common event by 2040 (/5/), with the associated increases in mortality especially amongst the elderly (/6/). Outdoor temperature increases will also increase energy consumption for cooling in air-conditioned buildings – with more emission of greenhouse gases (if transition to cleaner energy sources remains insufficient) – and decrease thermal comfort, productivity and health in free-running buildings. The latter is aggravated because higher indoor temperatures will also reduce the effectiveness of natural ventilation due to decreased stack effect (/7/).

Actions in response to climate change consist of mitigation and/or adaptation. Mitigation refers to reducing the causes for climate change, e.g. by the reduction of energy consumption. However, despite all international, national and local initiatives to mitigate climate change, a certain degree of climate change is unavoidable. Adaptation refers to the actions intended to deal with this unavoidable part of climate change.

Climate change acts on various scales, from global to local (microclimate – building scale). The same – evidently – holds for mitigation and adaptation measures. Especially at the local scale and building scale, the greatest synergies exist between adaptation and mitigation and these should be exploited wherever possible (/8/).

This paper focuses on adaptation at the building scale. Adaptation research in the built environment consist of studying the (urban) climate change including different climate scenarios, analysing the impacts of these scenarios, evaluating remedial measures and implementing these measures (governance). For the built environment, attention is on the outdoor environment, the building envelope and the indoor environment. These three spatial domains are strongly interrelated. Outdoor temperature increase will change the thermal loading of building facades and roofs and increase indoor temperature in free-running buildings. Passive cooling is recommended, in which also building facades and roofs (albedo value, indirect evaporative cooling, green facades and roofs) and their interaction with the outdoor environment play an important role. Increased wind-driven rain intensities change the hygrothermal loading of – especially – building facades and can increase relative humidity inside, especially in historical buildings. As such it can initiate mould growth, structural cracking due to hygrothermal gradients, salt efflorescence, etc.

2 High-resolution whole-building modelling

Analysis of the impacts of climate change on buildings and potential remedial measures requires accurate knowledge on the interaction between outdoor environment, building envelope and indoor environment. As mentioned above, temperatures in urban environments are increasing due to the combined effect of global warming and the local urban heat island effect. Buildings have to be adapted to deal with these temperature increases without compromising mitigation efforts and without compromising human health, comfort and productivity. For overheating, two important adaptation measures are convective sensible heat transfer and latent heat transfer (indirect evaporative cooling - IEC) from the exterior surfaces of building facades and roofs. For evaluating both types of measures, detailed modelling of the surface heat and mass transfer in interaction with the outdoor environment and building envelope is required.
Traditionally, numerical simulation in building physics has been focused on one of the spatial domains (outdoor, building envelope or indoor). This is reflected in the three main categories of numerical models that have been developed and used in the past: (1) Building Energy Simulation (BES) models for the indoor environment (thermal comfort, energy consumption); (2) Building Envelope Heat-Air-Moisture (BEHAM) transfer models for the building envelope (hygrothermal behaviour, durability); and (3) Computational Fluid Dynamics (CFD) for either the outdoor or the indoor environment (outdoor and indoor air flow, etc.). In each model category that focuses on its own spatial domain, the other domains are only taken into account in a simplified way. However, for an accurate translation of outdoor environment to building indoor environment, all three spatial domains need to be accurately taken into account. This can be achieved using a *high-resolution whole-building approach* in which all domains are represented as accurately as possible by combining results from each model category (BES / BEHAM / CFD). This is performed by either combining models (/9/) or coupling models (e.g., /10,11,12,13/). This can lead to significantly improved model performance. For example, BEHAM programs use simplified and constant convective heat and moisture transfer coefficients at the building envelope surfaces. Previous research has shown that this assumption is invalid and can give rise to significant errors (/12/). CFD on the other hand allows a detailed determination of these coefficients (/11,12,14/), and coupling BEHAM and CFD can avoid these errors (/11,12/). Note that Akbari et al. /15/, in estimating the effect of albedo changes on cooling energy use, found differences between BES and measurements of up to a factor two, which can likely be attributed to the use of simplified convective heat transfer coefficients in the BES program, apart from sky radiation discrepancies.

Indirect evaporative cooling (IEC) of the indoor (and outdoor) environment refers to cooling down the exterior building surfaces by evaporation, in order to reduce the indoor air temperature. IEC by maintaining a water film over the roof is well known in literature (e.g. /16/). Recently, a new IEC technology to combat the UHI has been developed, which consists of sprinkling water on external wall and roof surfaces covered by super-hydrophilic TiO_2 coating. This coating promotes the formation of a water film at the surfaces (/17/). However, it should be noted that recent experimental research has shown that hydrophobic, rather than hydrophilic surfaces, promote stronger surface evaporation (/18/). The reason is that hydrophobic surfaces retain more water at the surface in the form of water drops with contact angle larger than 90°. This not only increases the amount of water at the surface, but it also drastically increases the total water-air evaporation surface, raising the effectiveness of this technique.

The same *high-resolution whole-building approach* can be applied for the impingement of wind-driven rain (WDR) on building facades, the subsequent uptake of the rainwater by porous building materials and its possible transfer to the indoor environment. A CFD model for WDR was developed by Choi (/19,20/) and extended into the time domain by Blocken and Carmeliet (/21/). The model was successfully validated based on full-scale experiments for different types of isolated buildings (/21,22,23,24,25,26,27/). First efforts to combine the CFD model results with BEHAM models were reported by Blocken et al. (/9/) and Janssen et al. (/28/), and later also by Abuku et al. (/29/). Up to now however, the building envelope was considered isotropic and homogeneous and detailed information on exterior heat and mass transfer coefficients (/14,30/) has not yet been included in these modelling efforts.

3 Modelling of wind-driven rain impact on Hunting Lodge St. Hubertus

3.1 Introduction

Before coupling and combining models, the different models need to be validated based on high-quality experimental data. In the remainder of this paper, such a validation effort in which the CFD WDR model is applied to a monumental tower building is presented. More details on this work can be found in the corresponding journal paper (/27/).

Hunting Lodge St. Hubertus (Fig. 1a) is a monumental building in the care of the Rijksgebouwendienst (Dutch Government Building Agency), situated in the National Park “De Hoge Veluwe”. Especially the south-west facade of the building shows severe deterioration caused by WDR and subsequent phenomena such as rain penetration, mould growth, frost damage, salt crystallization and efflorescence, and cracking due to hygrothermal gradients (Fig. 1b-e). The CFD WDR simulations are important to obtain accurate spatial and temporal distribution records of WDR, to be used as input for numerical BEHAM transfer simulations. These simulations will be used in a later stage to analyse the causes of the moisture problems and to assess the impact of remedial measures. Validation of the CFD simulations is performed by WDR measurements at a few selected locations at the south-west facade.

3.2 Wind-driven rain: definitions and parameters

The quantities that are used to describe the WDR intensity in numerical simulations are the specific catch ratio $\eta_d(d)$, related to the raindrop diameter d, and the catch ratio η, related to the entire spectrum of raindrop diameters /21/:

$$\eta_d(d) = \frac{R_{wdr}(d)}{R_h(d)}; \quad \eta = \frac{R_{wdr}}{R_h} \tag{1}$$

where $R_{wdr}(d)$ and $R_h(d)$ are the specific WDR intensity on the building and the specific unobstructed horizontal rainfall intensity (for raindrop diameter d), respectively. R_{wdr} and R_h are the WDR intensity on the building and the unobstructed horizontal rainfall intensity, integrated over all raindrop diameters. The unobstructed horizontal rainfall intensity is the intensity of rainfall through a horizontal plane situated outside the wind-flow pattern that is disturbed by the presence of the building. All rain intensities are given in mm/h.

The catch ratio η is a complicated function of time and space. The six basic influencing parameters for η are: (1) the building geometry (including environment topography), (2) the position on the building facade, (3) the reference wind speed, (4) the reference wind direction, (5) the horizontal rainfall intensity and (6) the horizontal raindrop-size distribution. The turbulent dispersion of raindrops is an additional parameter, which is often neglected. Turbulent dispersion means that raindrop trajectories will deviate from those that would be calculated based on the mean wind-velocity field only. The turbulent dispersion of raindrops is neglected in this study, based on the findings by Choi /31/, by Blocken and Carmeliet /21/ and on a review of the literature /22/. The reference wind speed U (m/s) is taken as the horizontal component of the wind-velocity vector at 10 m height in the upstream undisturbed flow (U_{10}). The reference wind direction φ_{10} (degrees from north) refers to the direction of the reference wind speed at 10 m height. The horizontal raindrop-size distribution $f_h(d)$ refers to the raindrop-size distribution falling through a horizontal plane /22/.

3.3 Building geometry and surrounding topography

Hunting Lodge St. Hubertus consists of a low-rise rectangular volume with wings that stretch out diagonally and with a characteristic tower in the middle of the building of 34.5 m height (Figs. 1a and 2). From the fourth floor up, the tower has a rectangular floor plan with dimensions 4.8 x 4.2 m^2. The outer parts of the south-west facade of the tower shaft, from the third till the seventh floor, are recessed compared to the middle part of this facade (Fig. 2a). Narrow recessed windows are present in the middle part. A loggia is present on each corner of the top floor of the tower. Furthermore, the tower is equipped with a chimney on the north-east side, and has a pitched roof.

The building is located at the northern side of the Dutch National Park “De Hoge Veluwe”, longitude 52°07’ and latitude 5°49’, at approximately 42 m above sea level. The highest point in the area is found near Rheden, at 110 m above sea level. Rheden is situated 15 km south-east of the Hunting Lodge. The North Sea coast is about 100 km westwards of the park. Figure 3 shows an aerial view of the surroundings. There are no other buildings in the immediate vicinity of the Hunting Lodge. It is however surrounded by a forest. An elongated clear-cut in the forest is present south-west of the building, with a large pond, situated directly south-west of it.

3.4 Field measurements

The measurements of wind speed, wind direction, horizontal rainfall intensity and WDR were conducted at the building site from May until November 2007. All data were gathered on a 1-minute basis and were afterwards averaged over a time interval of 10 minutes. This choice is based on the results of a study by Blocken and Carmeliet /32/, the conclusion of which was that high-resolution data (e.g. 10-minute data) should be used for accurate WDR calculations. The details of the measurement equipment and measurement data are reported in /27/. The measurements were performed using the guidelines for WDR gauge design and for executing WDR measurements published by Blocken and Carmeliet /18,33/.

3.5 Numerical wind-driven rain simulation

The WDR measurements at the few discrete positions do not give enough information to obtain a complete picture of the spatial distribution of WDR on the south-west facade of the tower. Therefore, they are supplemented with numerical simulations. The numerical method for simulation of WDR on buildings was developed by Choi /19,20/ and extended by Blocken and Carmeliet /21,32/. It consists of five steps:

1. The steady-state wind-flow pattern around the building is calculated using RANS CFD.
2. Raindrop trajectories are obtained by injecting raindrops of different sizes in the calculated wind-flow pattern and by solving their equations of motion.
3. The specific catch ratio is determined based on the configuration of the calculated raindrop trajectories.
4. The catch ratio is calculated from the specific catch ratio and from the horizontal raindrop-size distribution.

Figure 1: (a) Hunting Lodge St. Hubertus and (b-e) moisture damage at the tower due to wind-driven rain: (b) salt efflorescence; (c) cracking/blistering due to salt crystallisation; (d) rain penetration and discolouration; (e) cracking at inside surface.

5. From the data in step 4, catch-ratio charts are constructed for different positions at the building facade. The experimental data record of reference wind speed, reference wind direction and horizontal rainfall intensity for a given rain event is combined with the appropriate catch-ratio charts to determine the corresponding spatial and temporal distribution of WDR on the building facade. For more information on this step, the reader is referred to /21,32/.

3.5.1 Building geometry, computational domain and grid

A computational domain with dimensions L X B X H = 350 x 350 x 205 m^3 is chosen. The blockage ratio (cross-sectional area of the building divided by the cross-sectional area of the domain) is about 0.7%. Two different building models have

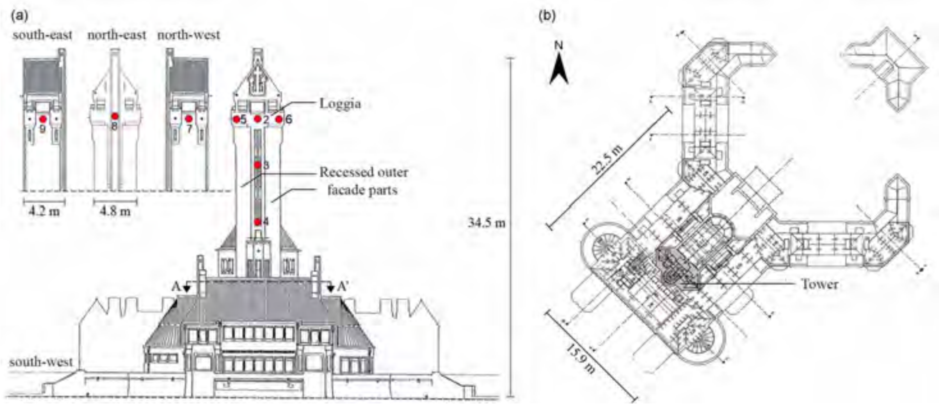

Figure 2: (a) Building dimensions and positions and numbers of the wind-driven rain gauges at the facades of the tower; (b) cross section A-A’ (indicated in Fig. 2a) of the building.

Figure 3: Aerial view of the topography surrounding the Hunting Lodge.

been used to determine the influence of the level of including geometrical facade details on the simulation results. The building geometry was simplified for the initial simulation to limit the computational cost (Fig. 4a). An unstructured mesh with tetrahedral cells was generated for this model, based on grid-sensitivity analysis with use of three different grids with a linear refinement factor 2. The analysis indicated that the grid with a total of 650,000 cells was appropriate. A part of this initial grid is shown in Figure 4c. It is expected that simplification of the building geometry will provide an underestimation of the wind speed at the measurement positions 5 and 6 near the openings that are present above the parapets of the loggias (Fig. 2a), which are not included in the simplified model. The underestimation of the local wind speed would cause an underestimation of the local WDR intensity (catch ratios). To investigate this, a second building model was created. This model includes the details of the loggias on the corners of the top floor of the tower. It also includes the open spaces that are present behind the WDR gauges on the lower part of the tower shaft due to the recession of the windows and the recession of the outer facade parts (Fig. 4b). The unstructured mesh for this building model was again generated based on grid-sensitivity analysis. Three grids were constructed, a basic grid and a coarser and finer grid (linear refinement factor 2). By comparing the results on the three grids, it was decided to retain the finest grid with a total of 2,110,012 cells for further study. In this paper, only results for the second (detail) model are shown.

3.5.2 Boundary conditions

The boundary conditions represent the influence of the surroundings that are cut off by the computational domain. The inlet of the domain is defined as a velocity inlet. The definition of the approach-flow profile of the mean wind speed that is imposed at the inlet is explained in the next subsection. Symmetry is prescribed at the top and at both sides of the domain. A constant static pressure of 0 Pa (relative to the operating pressure: 101320 Pa) is used at the outflow boundary. The standard wall functions by Launder and Spalding /34/ with appropriate ground roughness specification /35/ are used at the bottom of the domain.

3.5.2.1Approach-flow profile of the mean wind speed

The approach-flow profile of the mean wind speed imposed at the inlet should be representative of the roughness characteristics of the upstream part of the domain that is cut off by the inlet plane. This is expressed by the presence of the appropriate aerodynamic roughness length y_0 of this terrain in the expression of the logarithmic inlet profile of mean wind speed:

$$U(y) = \frac{u^{*}_{ABL}}{\kappa} \ln\left(\frac{y + y_0}{y_0}\right) \quad (2)$$

where U(y) is the mean streamwise wind speed at height y (m) above the ground plane (m/s), u^*_{ABL} the ABL friction velocity (m/s), κ the von Karman constant (0.42 in this study) and y_0 the aerodynamic roughness length (m). The ABL friction velocity is taken so that for the initial simulation a reference wind speed (U_{10}) of 10 m/s at a height of 10 m is obtained. The aerodynamic roughness length y_0 is visually estimated from aerial views of the surrounding terrain in combination with the updated Davenport roughness classification /36/. A roughness length of 1 m represents a landscape that is totally and quite regularly covered with similar-size large obstacles, with open spaces comparable to the obstacle heights. This roughness length could be used to represent the terrain surrounding the Hunting Lodge, which is a rather dense forest with a height of approximately 20 m and some large open areas at larger distances.

3.5.2.2Approach-flow profiles of turbulence quantities

For y_0 = 1 m, the turbulence intensity I_u (-) is taken 31% at a height of 2 m and 8% at the top of the domain in this study. The turbulent kinetic energy k (m^2/s^2) is calculated from I_u (Eq. 3), assuming $\sigma_u^2 \approx \sigma_v^2 + \sigma_w^2$. The inlet profile of the turbulence dissipation rate ε(y) (m^2/s^3) is given by Equation 4.

$$k(y) = \frac{1}{2}(\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \approx \sigma_u^2 = (I_u \cdot U(y))^2 \tag{3}$$

$$\varepsilon(y) = \frac{{u^{*3}}_{ABL}}{\kappa(y + y_0)} \tag{4}$$

3.5.2.3 Wall functions

The standard wall functions by Launder and Spalding /34/ with the equivalent sand-grain roughness (k_S) modifications according to the formulae by Cebeci and Bradshaw are used. The roughness constant C_S is user-defined in this study to obtain horizontal homogeneity, which means that the inlet profiles, the approach-flow profiles and the incident profiles are similar /35/. The required relationship between the equivalent sand-grain roughness height k_S (m), the aerodynamic roughness length y_0 (m) and the roughness constant C_S was derived by Blocken et al. / 35/ for Fluent 6.3:

$$k_s = \frac{9.793 \cdot y_0}{C_s} \tag{5}$$

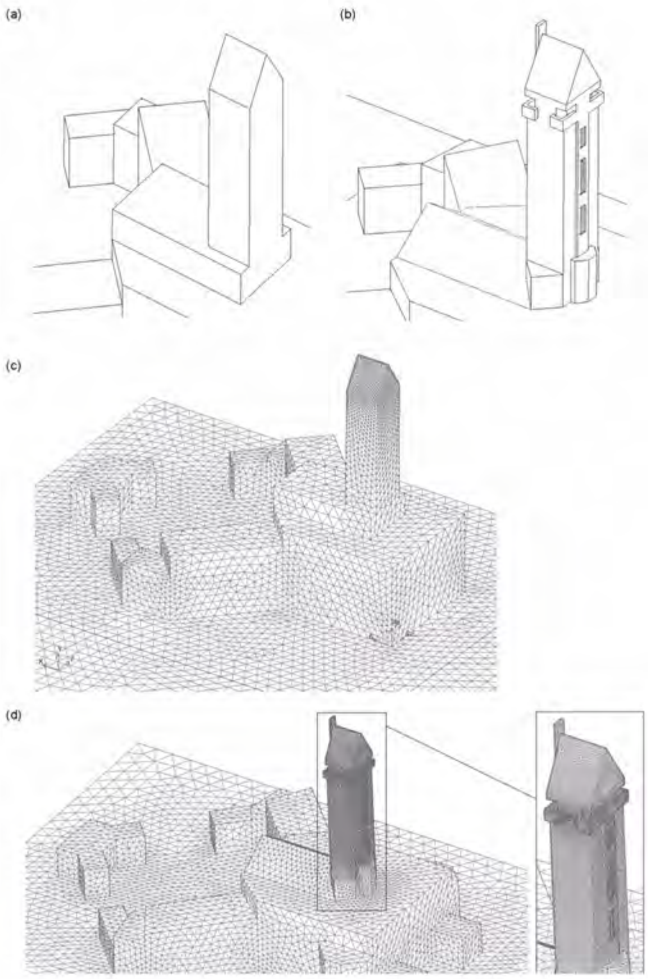

Figure 4: Part of the building models and surface grids used for calculation of the wind flow pattern around the building. (a) Initial model; (b) detailed model; (c) grid used for the initial building model (650,000 cells); (d) grid used for the detailed building model (2,110,012 cells).

3.5.3 Solver

The simulations of the steady-state wind-flow pattern were performed with the commercial CFD code Fluent 6.3 that employs the control-volume method. The wind-flow pattern around the Hunting Lodge is obtained by solving the Reynolds-Averaged Navier-Stokes (RANS) equations. This wind-flow pattern will be used to model the behaviour of raindrops impinging on the windward (south-west) facade of the tower. This is why the focus is mainly on the wind-flow pattern upstream of the building. The wind-flow pattern is calculated with the realizable k-ε model /37/ and standard wall functions /34/, based on results from earlier research /24/. Pressure-velocity coupling is taken care of by the SIMPLE algorithm. Pressure interpolation is second order. Second-order discretization schemes are used for both the convection terms and the viscous terms of the governing equations. The numerical simulation of the wind-flow pattern is performed for a reference wind speed U_{10} = 10 m/s. The wind-velocity vector fields for other reference wind speed values, needed for the tracking of raindrops, are obtained by linear scaling with U_{10}.

3.5.4 Numerical modelling of wind-driven rain

The raindrop trajectories are obtained by injecting raindrops of different sizes (diameters ranging from 0.5 to 1 mm in steps of 0.1 mm, from 1 to 2 mm in steps of 0.2 mm and from 2 to 6 mm in steps of 1 mm) in the calculated wind-flow pattern. Calculations of raindrop motions are conducted in flow patterns with U_{10} = 1, 2, 3, 5 and 10 m/s.

The south-west facade of the building is divided into small square zones of approximately 0.08 x 0.08 m^2 to obtain results with a high spatial resolution. The specific catch ratio is calculated for each zone, for all raindrop diameters and for each wind speed value. The catch ratios, integrated over all raindrop diameters, are calculated by adopting the raindrop-size distribution by Best /38/, modified for horizontal rain fluxes as described in /22/. This raindrop-size distribution is a function of the horizontal rainfall intensity. For the calculation of the catch ratios, 16 values of horizontal rainfall intensity are used: 0, 0.1, 0.5, 1, 2, 3, 4, 5, 6, 8, 10, 12, 15, 20, 25 and 30 mm/h.

The last step of the numerical WDR simulation method consists of combining the results with the experimental data record of reference wind speed U_{10}, reference wind direction φ_{10} and horizontal rainfall intensity R_h for a given rain event. First, catch-ratio charts are constructed for each 0.08 x 0.08 m² position at the building facade, including those where the WDR measurements were performed. These three-dimensional charts show the catch ratio η as a function of U_{10} and R_h /21/. The spatial distribution of WDR on the south-west facade is determined for different rain events. These rain events have been selected carefully, to minimize measurement errors /33/. Only the results for two rain events are presented here. For the first rain event, September 17th, 2007, the record of U_{10}, φ_{10} and R_h is given in Figure 5a. This rain event is composed of a few rain showers. The total horizontal rainfall amount S_h at the end of the rain event is 10.0 mm. The wind direction has generally been close to south-west (225° from north) during the rain event. For the analysis of the measurement errors, the reader is referred to Briggen et al. /27/. For the second rain event, September 25th, 2007, the record of U_{10}, φ_{10} and R_h is given in Figure 5b. S_h at the end of this rain event is 7.0 mm. The wind direction has been nearly south-west (225° from north) during the rain event. Also the error analysis for this rain event is given in /27/.

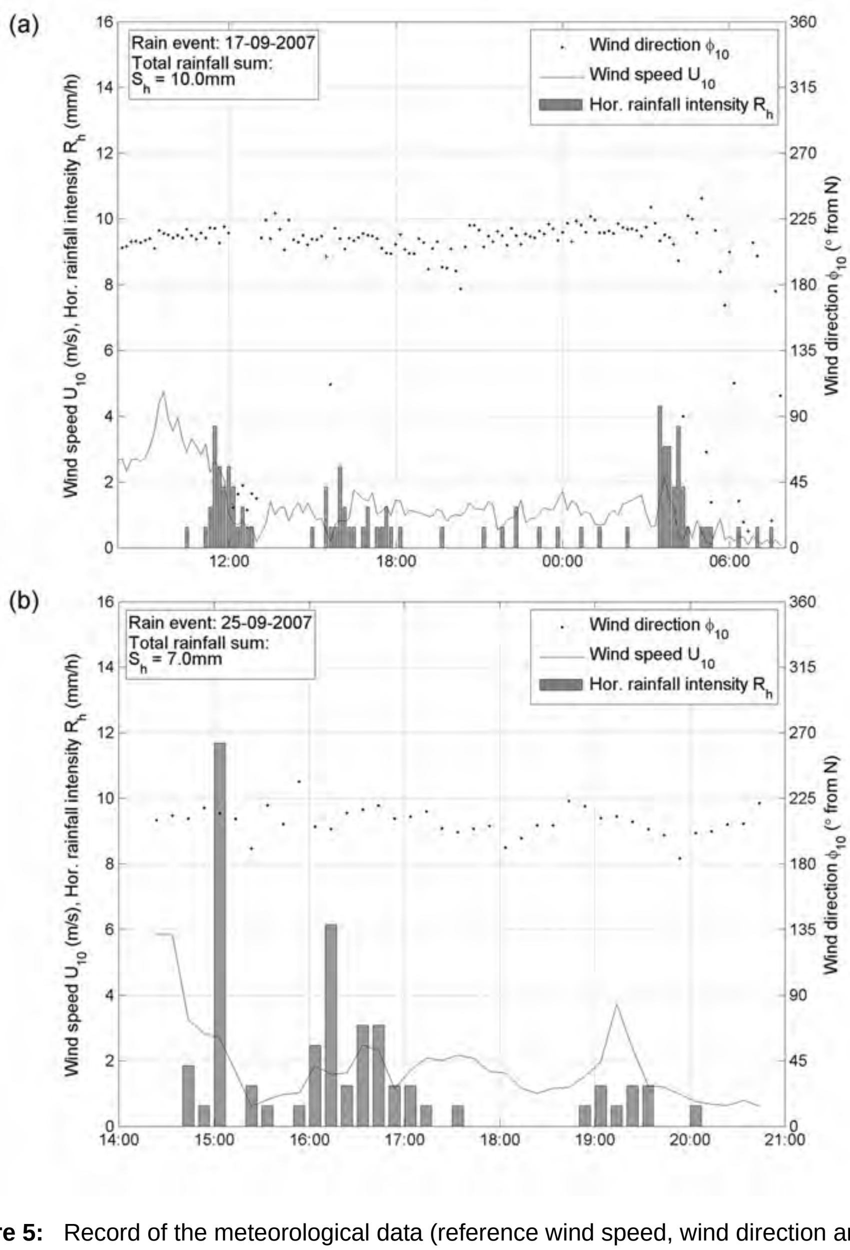

Figure 5: Record of the meteorological data (reference wind speed, wind direction and horizontal rainfall intensity) for two rain events. (a) September 17th, 2007; (b) September 25th, 2007.

3.6 Results

The spatial distribution of the catch ratio at the end of both rain events is shown in Figure 6. The numerical results are those obtained with the detailed building model. The experimental results are shown on the left-hand side of the figures, the numerical results on the right. The “classic” WDR wetting pattern is found /22/: wetting increases from bottom to top and from the middle to the sides. At the top of the facade, the differences between the simulations and the measurements, for the Sept. 17th rain event, are 30%, 14% and 21% at positions 2, 5 and 6, respectively (Fig. 6a).

For the Sept. 25th rain event, the differences at these positions are 18%, 20% and 26%, respectively (Fig. 6b). Considering the complex nature of WDR and the large amount of influencing parameters, this can be considered a fair overall agreement between the experimental and the numerical results. Larger discrepancies however are found at position 4, where the catch ratios are underestimated by more than 50% by the simulations. This can be explained by Figure 7a. The raindrop trajectories ending at the lower part of the facade are bent away from the facade towards the vertical. This is especially the case for low wind speed (e.g., U_{10} = 2 m/s) in combination with the smaller raindrop diameters (e.g., d = 0.5 mm). Near the lower part of the facade, these raindrop trajectories are almost parallel to the facade, and do not always intersect with the surface, as shown in Figure 7a. Turbulent dispersion in the streamwise direction can cause these raindrops to deviate from their “mean” trajectory and to hit the facade anyway. Since turbulent dispersion is not modelled in this study, (more) rain will impinge on the lower part of the facade in reality than calculated with the numerical method. This statement is corroborated by an earlier study by Lakehal et al. /39/ and by Figure 7b. Lakehal et al. /39/ found that turbulent dispersion is an important factor increasing WDR on vertical walls in cases with weak upstream wind flow, such as in a street canyon. For the present study, Figure 7b displays the simulated profiles of the streamwise mean wind speed U and the streamwise turbulence intensity I_u (= $(2k/3)^{0.5}/U$) along a vertical line at a distance of 0.5 m from the facade, for U_{10} = 2 m/s. For the largest part of the facade, it indeed shows weak upstream wind flow (U < 0.05 m/s) and high turbulence intensity (I_u > 100%), which are the conditions for which the conclusions of Lakehal et al. apply. Note that, apart from this effect, the calculation of the specific catch ratio at the lower part of the facade is considered less accurate due to the small intersection angle between the facade and the trajectories of those drops that do reach this lower part.

4 Discussion and conclusions

This paper has briefly discussed some benefits of high-resolution whole-building numerical modelling in the context of climate change. High-resolution whole-building numerical modelling can be used for detailed analysis of the potential consequences of climate change on buildings and to evaluate remedial measures. This discussion was certainly not intended to be complete. Rather it was intended to

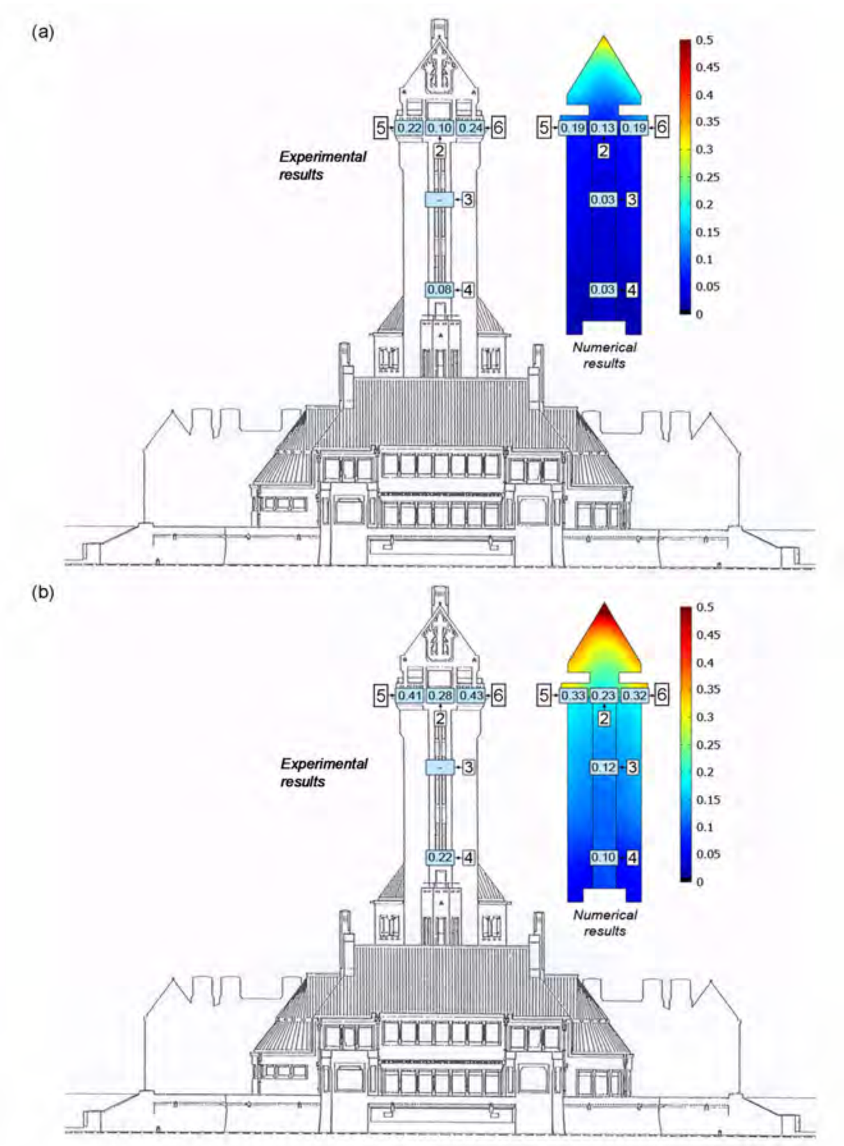

Figure 6: Spatial distribution of the catch ratio at the end of the two rain events. The experimental results at the locations of the wind-driven rain gauges are shown on the left, the numerical results are shown on the right. (a) September 17th, 2007; (b) September 25th, 2007

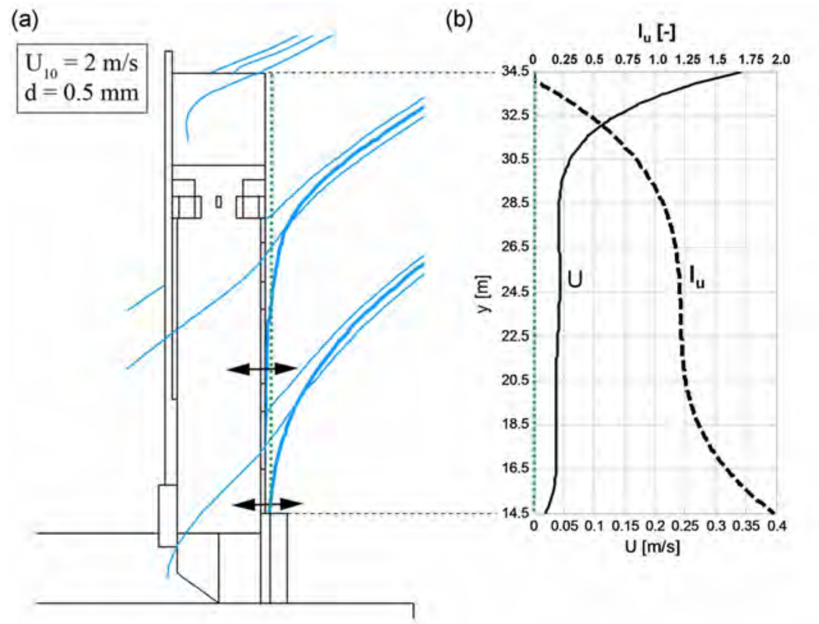

Figure 7: (a) Raindrop trajectories of d = 0.5 mm in the U10 = 2 m/s wind field. Turbulent dispersion in the streamwise direction (indicated by the arrows) can cause raindrops to hit the facade. (b) streamwise mean wind speed U and streamwise turbulence intensity Iu along a vertical line at a distance of 0.5 m from the windward facade.

provide some views on climate change and built environment from a computational building physics perspective. While some of the high-resolution sub-models for whole-building modelling have been validated, others are not, or not completely. The CFD WDR model outlined in this paper has been successfully validated for isolated buildings, such as the Hunting Lodge St. Hubertus, but validation efforts need to be extended to building clusters in which the wind-flow patterns are significantly more complex. In addition, while several of the high-resolution sub-models have been combined or coupled in the past, much work remains to be done to analyse the coupling requirements and to validate the coupled models. This is the subject of ongoing research.

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Impact of Climate Change on the Performance of Building Materials Loaded by Salt Mixtures

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Abstract

Crystallization of salts is a major factor of degradation of building materials. In this paper different methods for the determination of the salt load of building materials are compared. The method based on a thermodynamic model, ECOS, capable of predicting the crystallization behaviour of salt mixtures as a tool to predict environmental conditions to minimise salt damage is demonstrated for two case studies, the ice houses in the region of Brussels and a farm in a rural environment. The model uses the results from quantitative ion analyses of the aqueous extract of the salt contaminated material under study. The investigation aims to predict environmental conditions that would minimise salt damage to brickwork.

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Ir. Roald Hayen graduated in 1997 as civil engineer at the catholic university of Leuven, K.U. Leuven. Thereafter, he followed the master course in Conservation of Historic Towns and Buildings at the Raymond Lemaire Centre at the same institute. His professional career started at the K.U. Leuven, civil engineering department, as well, where he joined in 1999 as a researcher the EU-funded research project 'Pointing', dedicated to the damage-analysis and repair of pointing in our cultural built heritage. When the project ended, he worked for several years as the technical-commercial responsible for an international distributor of lime mortars and mineral paints. Since November 2008 he's working at the Royal Institute for Cultural Heritage, a federal scientific institution dedicated to the study, conservation and development of Belgium's cultural heritage, where he combines research and on-site services for specific restoration projects.
He gained a broad experience both in the field of research and practical advice with regard to the restoration and conservation of our cultural built heritage. His research fields mainly concentrate on the characterisation of (historic) mortars and renders, the study of the mechanical, physical and chemical aspects of the compatibility of building materials encountered in historic masonry structures and the hygrothermal behaviour of buildings as a whole.

1 Introduction

Salts are commonly found in the stones of monuments, especially in urban, industrial and marine environments. Crystallization of salts is recognized to be a major factor of the degradation of porous materials in built heritage. Salt weathering is a universal phenomenon affecting rock types and man made material all around the world. There is an overwhelming literature on the simulation of salt damage effects. Since the early reports on the pressure generated by growing crystals, several models and equations have been developed that allow the evaluation of the crystallization pressures exerted by crystals growing in a pore /1-4/. Several researchers derived independently equations for the calculations of crystallization pressures considering the degree of supersaturation of the solutions. However, despite these efforts, the processes and pathways of salt damage are still incompletely understood.

In the absence of a liquid moisture source, such as rain water penetration, capillary rising damp and condensation, crystal growth in a porous material is always the result of a phase transition reaction induced by changes in temperature or relative humidity (RH) /5,6/. Hence, unfavourable environmental conditions may cause repeated cycles of deliquescence-crystallization or hydration-dehydration, which can lead to the decay of building materials. RH-X-Ray diffraction measurements /7/ to examine deliquescence reactions using glass fibres loaded with sodium chloride revealed that quite short-time variations of relative humidity, e.g. the typical daily variation of ambient relative humidity, may be sufficient to cause dissolution of crystalline salts in the pore space close the surface /8/. A subsequent decrease in relative humidity may cause crystallization and the generation of stress in the materials. Much longer reaction times may be necessary for the deliquescence of salt crystals in greater depths of porous materials. This implies that the dynamics of deliquescence-crystallization cycles in building materials is strongly affected by both frequency and amplitude of the humidity variation as well as the moisture exchange properties between the material and the environment.

A recent research on the probable evolution of salt weathering during the 21st century in Europe based on climate data to predict the number of salt transitions under past, present and future climate projections revealed an overall increase in phase transitions /9/. The calculations are based on the number of times the RH in two successive days crosses the critical RH of sodium chloride transition, 75 %, on one hand, and the number of days that tenardite could convert to mirabilite, on the other hand.

However, situations get more complicated if one passes from single salts, of which the deliquescence points are well documented /10/, to real practice situation. An inventory of the type of cations and anions in almost 1000 samples taken from Belgian historic buildings proved that building materials seldom contain one particular type of salt, but rather a complex mixture of ions. Recent research has shown that threshold values of salt contents up to which no damage is obtained, resulting from salt crystallization tests on samples contaminated with single salts, generally are no longer valid in case of combination with other types of salts. In fact, the prediction of the behaviour of salts in a mixture is complex due to the formation of double salts /11, 12/.

Preventive conservation can be defined as all indirect actions aimed at increasing the life expectance of objects and collections which requires the assessment of deterioration agents and the environmental context. The term covers all cultural heritage, be it movable or immovable, and aims to keep an object in a preferred state where minimum damage and/or deterioration occurs, as well as addressing the assessment and management of potential risks.

The assessment of the critical environmental conditions of salt loaded porous building materials, and hence potential risks of salt damage, requires the knowledge of the thermodynamics of the relevant phase transition reactions /13/. In the framework of a research project funded by the European Commission, a computer program ECOS (Environmental Control of Salts) was developed capable of predicting the crystallization behaviour of salt mixtures as a tool to predict environmental conditions to minimise salt damage /14,15,16,17/. To use the model, the concentration of a range of ions that are present in an aqueous extract of the salt contaminated material in question is required as input. The program is then able to predict from a thermodynamic point of view which minerals will exist in the solid state under specified conditions of relative humidity and temperature. This enables the user to determine 'safe' ranges of relative humidity and temperature in which phase transitions are kept to a minimum on one hand and predict the impact of climate change on the behaviour of the performance of building materials loaded with a particular salt mixture on the other hand.

In this article, the results of two case studies dealing with the experimental determination of the salt content of building materials in the framework of a proper rehabilitation and the prediction of the behaviour of the salt mixture using ECOS-model are discussed.

2 Methods of salt analyses

Different methods exist and are regularly applied for the experimental determination of the moisture and salt load of building materials. A first one is based on the determination of the conductivity of an aqueous extract from salt loaded building materials. The conductivity results from charged soluble fragments in the extract, mainly due to the presence of soluble salts. This method is to be interpreted as a preliminary and comparative approach of the salt contamination of the monumental complex and hence as a first screening prior to the selection of zones to be submitted to a detailed salt contamination analysis. Besides that, the hygroscopic salt content of previously dried samples conditioned at high relative humidity (95%) till constant weight is often determined /18/. In some cases, the determination of the hygroscopic moisture content can explain the actual moisture content properties. E.g. a high actual moisture content of a building material that is not as such suffering from a liquid moisture source, such as capillary rising damp, can be explained

by means of the hygroscopic properties of the material in question. This method, as far as the hygroscopicity of the porous material as such can be ruled out, might be useful from a comparative point of view in case of a series of samples lifted from a same type of building material as to explain a possible damage phenomenon. Especially nitrates and chlorides are linked to hygroscopic behaviour. Figure 1 compares the hygroscopic moisture content with the total content of nitrates and chlorides of a series of samples lifted from one and the same monumental construction containing gypsum besides chlorides and nitrates. Although a general tendency towards a higher hygroscopic moisture content for higher chloride and nitrate content is noticed, quite some exceptions are obtained, in a sense that high hygroscopic moisture contents are obtained for samples containing quite a low nitrate and chloride content and vice versa. Salts have a different hygroscopic behaviour depending on the type of cation on which they are linked to /10/ as well as the composition of the salt mixture.
In practice, Merckoquant test strips to determine nitrate, sulphate or chloride content are widely used. The method, only capable of detecting the anions with a limited accuracy present in an aqueous extract of the salt contaminated material in question, can not be considered as an adequate indicator for the crystallization behaviour of mixed salt solutions necessary for recommendations for conservation measures on one hand and environmental management on the other hand. They can however be useful to follow up a salt extraction procedure of building materials for which the type of salt contamination as well as its destructive properties are known in advance.

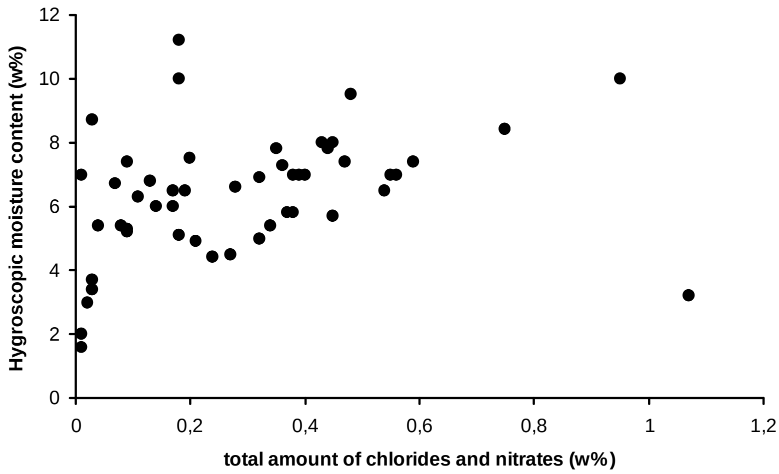

Figure 1: the hygroscopic moisture (w%) content as a function of the total content of nitrates and chlorides (w%) of a series of samples lifted from the ice houses in Oudergem (Brussels).

The determination of the types of salts present in drilled samples of building materials as such using techniques as X-ray Diffraction (XRD) is useful in case of a high salt load (>1w%). This technique can be applied as well for the identification of salts deposited at the surface. However, the type of efflorescing salts is not systematically representative for the salt load in the building material itself. Salt distribution in the porous structure of building materials is triggered by complex physical phenomena such as solubility, diffusability and moisture exchange with the environment.

To determine the salt distribution of monumental constructions, samples are preferentially lifted by means of powder drilling at different heights and depths and this as a function of the architectural concept, construction phase, historical functionality and location. A quantitative evaluation of the salt load is obtained by means of the determination of the soluble ion content of the aqueous extract through ionchromatography (IC) and (inductive coupled plasma) atomic emission spectroscopic techniques. The authors of this article use IC (Metrohm) as to quantitatively determine the amount of ions in the aqueous extract of building materials. The output of quantitative salt analyses is a series of cations and anions present in the aqueous extract. The way these ions were initially combined, and hence the type of salts present, can generally not (completely) be derived. To interpret these quantitative results and translate them into safe conservation and restoration concepts, often the worst case scenario was applied until recently. From the statement that not all salts are as destructive or hygroscopic, several combinations between anions and cations are tried out and each of them evaluated. In case ionchromatography reveals the presence of sodium and magnesium as well as sulphates, their combination resulting in sodium and magnesium sulphate for instance, known from their destructive properties /19/, was considered. Results from this rather empirical methodology might however not reflect the real conditions of salt damage. A thermodynamical approach is necessary as to evaluate the crystallization behaviour of salt mixtures and hence to predict potential risks of future damage related to climate conditions.

The computer program ECOS (Environmental Control of Salts) is capable of predicting the crystallization behaviour of salt mixtures. The user is required to input the concentrations of a range of cations and anions present in the aqueous extract. The program is then able to predict which minerals will exist in the solid state under specific conditions of RH and temperature. Hence, the behaviour of a salt mixture present in building materials submitted to a changing climate can be evaluated. It should be kept in mind that ECOS requires a perfect anion/cation balance. In case of the presence of hydrogen carbonates, which are as such not detected by ionchromatography and not covered by the ECOS program, the “autobalance” facility may misrepresent the real salt contamination. The user needs to evaluate at first the quantitative anion and cation content and correct for the presence of soluble minerals not covered by the ECOS program. This is also the case for alkaline compounds present in building materials for which only the cation is detected by ionchromatography. A further inconvenience with ECOS concerns its unsystematic inability to handle calcium and sulphates simultaneously and hence requirement of the removal of gypsum, for which there is no explanation /20/.

3 Case studies – environmental assessment

Environmental assessment /21/ includes a survey of sources of liquid water, measurement and analysis of moisture and salts combined with the environmental monitoring aiming for an environmental management and modification. The word "environmental control" is more useful for indoor objects and museums, whereas in the case of historical buildings and outdoor objects it is more realistic to aim for a beneficial environmental modification. The environmental assessment implies knowledge on the behaviour of the salt mixture contaminating the building materials, in relation to the climate monitoring as to interpret salt damage in practice. It is assumed that due to its low solubility, gypsum will not contribute significantly to crystallization damage.

3.1 Ice houses-Oudergem (Brussels, Figure 2)

The two ice houses at Oudergem were constructed in respectively 1874 and 1894 to stock ice for industrial purposes. Their function disappeared together with the development of modern cooling systems like refrigerators. Completely constructed

Figure 2: Ice houses, Oudergem (Brussels, 1874)

in brickwork, the ice houses comprise a unique industrial heritage and witness of historical industrial activities typical for that region. Monitoring of the climate during several months of this non ventilated underground built construction revealed a temperature between 15 and 18°C and a relative humidity not lower than 90 %. In such humid conditions, almost all salts are dissolved in hygroscopic moisture and hence invisible. Today, the question rises concerning the state of conservation in conditions of drying, which might occur in case comfortable climate conditions (RH between 30 and 70% and a temperature between 20 and 26°C /22/) are requested and a ventilation and/or a heating system is installed. Actually, as part of a major built construction plan, an underground parking place around the ice cellars might cause an important change of the environment and a drying out of the brick masonry construction. Therefore, an environmental assessment was requested as to define the possible environmental modifications as a function of the actual salt load of the porous building materials.

Samples were lifted at different locations, as a function of the architectural concept at different heights and depths. Figure 3 presents a typical crystallization sequence of soluble salts present in a sample lifted from the ice cellars at Oudergem. Apart from gypsum, determined from the quantitative ion analysis, it is clear that in case of decreasing relative humidity and hence drying, little or no salts will crystallize if the ambient RH remains above 40% and crystallization only starts when the RH drops as low as 35%. A discrepancy is noticed concerning the relative humidity at which sodium chloride crystallizes (41 %) in this salt mixture while the pure salt crystallizes at 75 % RH. At another zone, the ECOS output shows that in case of drying, some sodium chloride start to crystallize at 53 %RH while most salts do crystallize around 30% RH (figure 4).

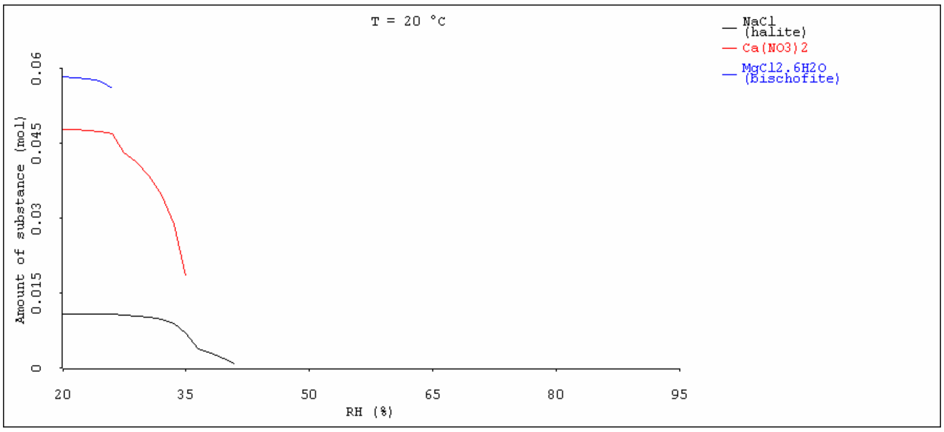

Figure 3: Crystallization sequence of soluble salts using ECOS (mortar, 150 cm height, 0-1 cm depth).

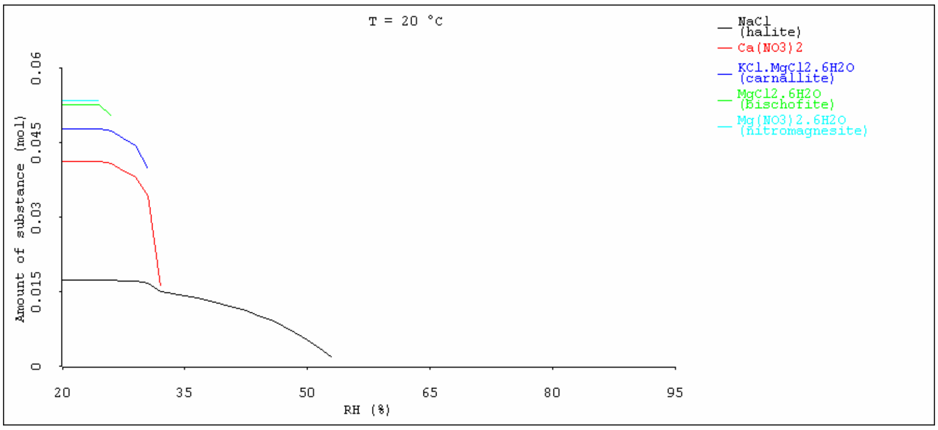

Figure 4: Crystallization sequence of soluble salts using ECOS (mortar,15 cm height, 0-1 cm depth)

From this research it was shown that the recommended climate of the ice houses to minimize salt damage is as such that the relative humidity should be at least 50 %. Lately, a natural ventilation was activated and a monitoring campaign is running as to further follow up the influence of the external climate on the indoor climate. In the future, the follow up of the influence of the construction of a modern built complex with underground parking place around the ice houses is planned.

3.2 Farm at Opvelp

The farm in the rural environment of Flanders, Opvelp, is one of the numerous examples where the properties of building materials are not necessarily in favour of architectural restoration concepts. Typically for such restoration projects is the

Figure 5: farm at Opvelp.

transformation of former stables into offices or meeting rooms. But has one ever considered whether this is in agreement with the properties of the built materials, more specific the salt contamination?

A systematic pre-investigation was carried out as to evaluate the salt contamination of brickwork as a function of the architectural concept and the history of this farm. A visual inspection was carried out prior to the selection of 10 zones for sampling on the interior part of brick facades. In this article, only some examples are presented.

Figure 6 presents the crystallization sequence of the soluble salts present in the mortar within zone I situated at the front and inside part of the farm (figure 5). It can be concluded that in case of decreasing RH, crystallization of sodium chloride starts at 52% RH. It could be noticed that a constant amount of sodium chloride of 0.6 g% is detected till a depth of 5 cm. From 32% RH on, calcium and potassium nitrate start to crystallize. Once more, the discrepancy of the RH at which single salts crystallize in the salt mixture compared to the value as pure salt can be noticed. For this zone, a relative humidity above 50 % is recommended as environmental modification.

Zone V is located at the front and outside part of the farm, at a few meters from zone I. The salt contamination is as such that in case of drying sodium chloride crystallizes from 70% RH (figure 7). Further drying results in a further crystallization of this salt. From 34 % RH on, calcium nitrate will be deposited, and the double-salt potassium-magnesium sulphate at 31%. For this area, little or no damage will occur in case the RH remains above 70 % at 20°C. .

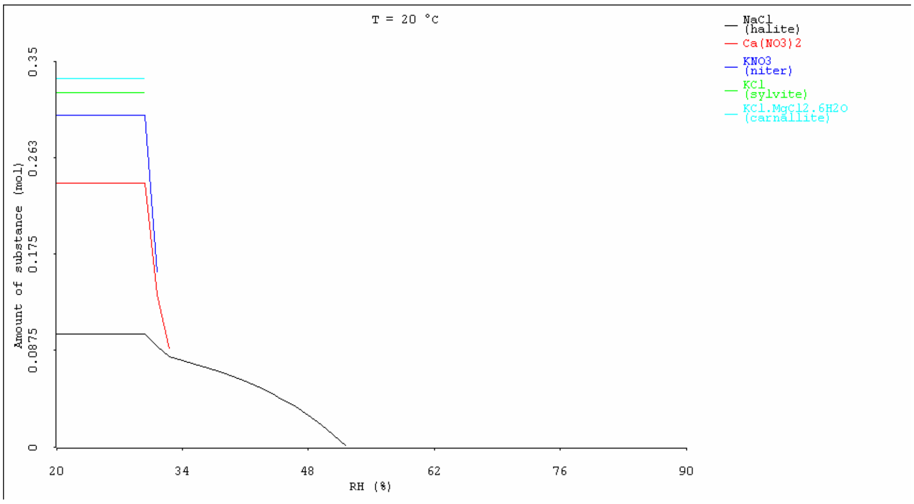

Figure 6: Crystallization sequence of soluble salts using ECOS (mortar, zone I, 110 cm height, 0-1 cm depth)

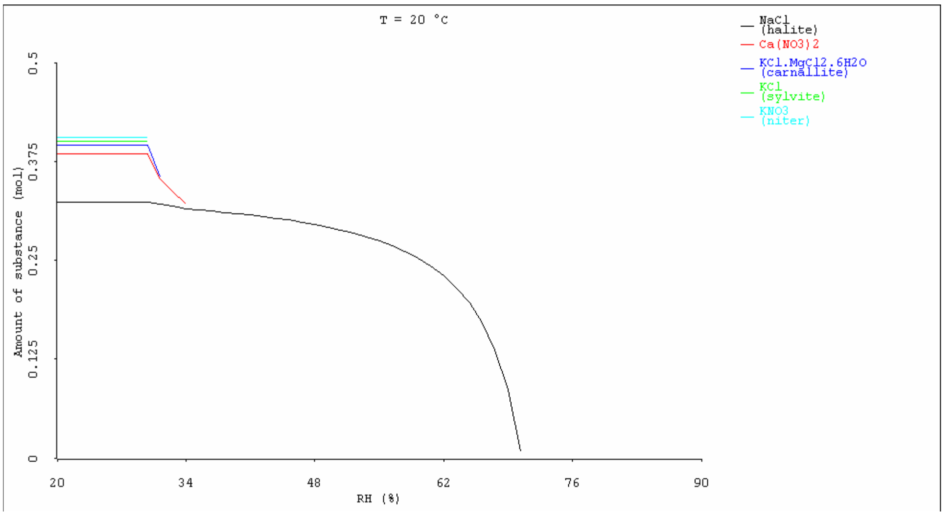

Figure 7: Crystallization sequence of soluble salts using ECOS (mortar, zone V, 127 cm height, 0-1 cm depth)

Zone IX is located at the back and inside part of the farm in a part where the architect plans the installation of a swimming pool. From a thermodynamical point of view, potassium nitrate, being present at a content of 4,5 w%, starts to crystallize at a high RH (92 %) (figure 8). Furthermore, a plateau of relative safe conditi-

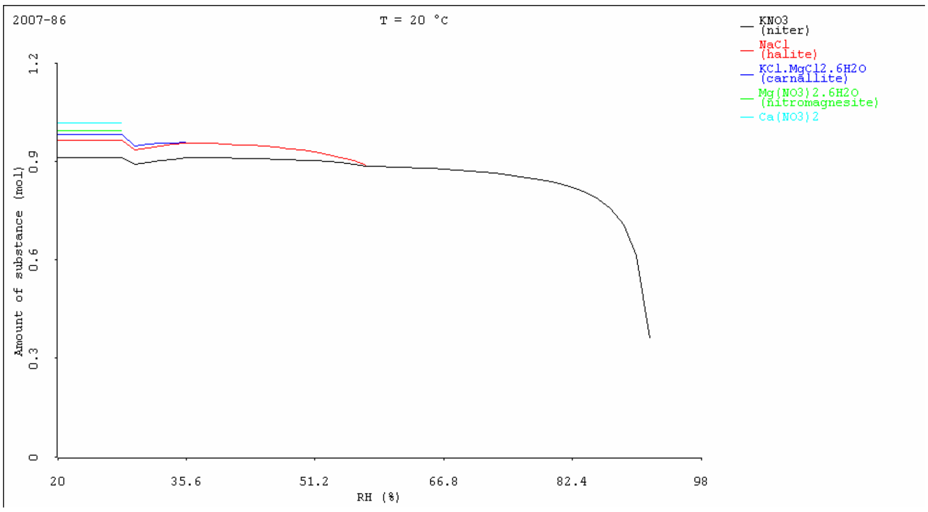

Figure 8: Crystallization sequence of soluble salts using ECOS (mortar, zone IX, 58 cm height, 0-1 cm depth).

ons between 60 and 90 % RH can be observed, where the total volume of salts is steady. Ideally, the RH should constantly be above 93 % or between 60 and 90 %. It is questionable whether this climate is in agreement with that of a room in which a swimming pool will be installed

4 Conclusions

This paper compares different methods for the determination of the salt load of building materials. The method based on a quantitative ion analysis and a thermodynamic model ECOS is demonstrated for two case studies, the ice houses in the region of Brussels and a farm in a rural environment. The investigation aims to predict environmental conditions that would minimise salt damage to the brickwork.

Both case studies have shown that crystallization of salts in a mixture takes place over a range of relative humidities and that individual minerals may crystallize out at relative humidities far lower than their equilibrium RH as a single salt. This was already demonstrated empirically in previous studies /19/. Moreover, depending on the architectural concept, construction phase, historical functionality and location, monumental constructions present variable salt loads even in adjacent locations.

Predicting the influence of climate change on the number of phase transitions of pure salts, as is done for sodium chloride and sulphate in /9/, may be criticized since the behaviour of a salt depends on the composition of the salt mixture. Moreover, for outdoor constructions, the environmental control should not only focus on hygrothermal conditions stability. Air movement as well as direct solar radiation can influence the transition process without traceable indications in the ambient temperature. Furthermore, rainfall comprises an important environmental parameter.

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