The moving fluctuation range – a new analytical method for evaluation of climate fluctuations in historic buildings

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Abstract

Indoor climate has a strong influence on the preservation of interiors; the effects on the surfaces of valuable furnishing and artworks are of major concern. To evaluate the indoor climate thorough measurements have to be made. But how should this data be analysed? There are some established and some newer methods to evaluate measured climate data. The authors present here a new analytical method and its application on measured climate data from unheated historic buildings such as the King's House on the Schachen, Linderhof Palace and the small rural church of St. Margaretha in Roggersdorf. Within this new method a moving average is used for the analysis of short-term fluctuations of relative humidity and temperature. As a result a moving fluctuation range of relative humidity is obtained for example the maximum range in an hourly moving interval of 24 hours compared to the commonly used values of equidistant daily cycles. Conventional methods of statistical analysis are compared to the new method for different time periods. Advantages and disadvantages of the different approaches are discussed. A further result of this new method is the better understanding of the indoor environment and improved evaluation of measured data. A perspective is presented on possible applications of the moving fluctuation range method for investigations on the real physical behavior of collections due to fluctuations in relative humidity. The moving fluctuation range method can also be used in building simulation tools for evaluation of indoor climate conditions for collections.

Introduction

For several years there has been a major debate about the right values and allowable ranges of relative humidity (RH) and temperature for the indoor climate in museums and other buildings housing artworks. The two main arguments against maintaining a constant indoor climate of 50 % relative humidity and a temperature of 20 °C all year (which can only be achieved by an air-conditioning system), are the high risk of damage to old buildings with minor insulation standards, particularly in the winter and the huge energy demands. Beyond the knowledge that no fluctuations will cause no damage to artworks there is no strong physical evidence for these rigid values.

The discussed ranges of indoor climate are usually coupled to specific time periods. A major research question is the relevance and effect of short-term fluctuations of temperature and relative humidity on works of art. But how is a short-term fluctuation defined? How stable is the indoor environment in unheated historic buildings? When the data is analysed, the time periods considered generally correspond to annual, seasonal and daily periods and some in between, like weeks or months. The real physical behavior of materials is often not considered or only in a generalised way. Each material and composite material has its unique material characteristics and therefore has a different sensitivity to changes in humidity and temperature. Depending on their composition, dimension and thermal as well as hygric inertia some composite materials are affected immediately by short-term fluctuations. This paper highlights the effect of short-term fluctuations of relative humidity and temperature and proposes a new method of data analysis.

Climate fluctuations

The definition for allowable values was derived from a questionnaire on typical climates in museums. There are still many questions about the damaging effects to artworks stored in a particular climate. One damage mechanism is caused by the hygroscopic behavior of materials. The typical behavior of hygroscopic materials is to shrink and swell with changes in relative humidity and temperature. The aim of giving set points and allowable ranges of fluctuations for indoor climates is to prevent artworks from damage. Usually, very general recommendations are given, referring to the overall indoor environment. Short-term fluctuations of relative humidity and temperature can have a negative impact on thin sensitive hygroscopic materials in particular but also on the surfaces of artworks independent of their volume. Burmester [1] summarises the state of the art for museums. Short-term fluctuations of plus or minus 2.5 % RH and plus or minus 1 K within one hour and plus or minus 5 % RH within one day should not be exceeded. For several materials fluctuations of plus or minus 5 % RH during one week are still bearable. These specifications are given for the conditions of air in the vicinity of the objects.

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbook [2] prescribes for climate class AA, allowable short-term fluctuations of plus or minus 5 % in relative humidity and plus or minus 2 K for temperature, based on a set point of an annual average space gradient. In Class B, fluctuations of plus or minus 10 % RH and plus or minus 2 K for precision-controlled climates are permitted. Additional recommendations for seasonal changes are made. No further specific descriptions on the basis of a short-term fluctuation or seasonal changes are referred to. Further classifications are made without special requirements for buildings with no precision control. Although there are additional classifications, descriptions and information for buildings, there is no further distinction or advice for historic buildings with no climate control. Kilian [3] gives a detailed description and distinguishes between requirements for museum buildings with climate control and listed buildings and monuments.

Holmberg [4] specifies that 15 % is an acceptable daily range of relative humidity variation in unheated buildings based on observations made on a wooden door. Many more definitions and specification are available in the literature. Common in these descriptions is an allowable range for relative humidity and temperature for a certain time interval. However, some elements are not defined within the specifications: why are these time cycles selected for evaluation, and how are data measured?

Measurement and analysis of short-term cycles

Measurement of the room climate

One typical method to evaluate the prevailing indoor climate is to measure the condition of indoor air with its parameters relative humidity and temperature. There are two main constraints in measuring these parameters: positioning and accuracy of the sensors.

As mentioned above the ASHRAE handbook [2] assumes some space gradients for the deviation of microclimates between the location of the sensors and object, in contrast Burmester [1] discusses values in the vicinity of the object. For general statements about the indoor climate, the equipment should be installed in the middle of the room. For an assessment of the condition of an object and to make judgements about risks posed by the environment, measurements near the artwork are necessary. However, all buildings with natural or controlled climates have many diverse microclimates which can differ significantly from the climate measured at a certain point, like the middle of a room. These microclimates would have to be considered separately.

The accuracy and response of the sensors is also important to proper measurement and evaluation of a climate. It is useless to discuss certain values or tight RH ranges if the calibration, accuracy and response of sensors are not sufficient for the evaluation in question; see also Camuffo [5] and Brown [6].

Existing methods for analysis of measured data to short-term fluctuations

Only a proper analysis of measured data can provide reliable statements concerning the prevailing climate and its potential to damage artworks. A common method is to evaluate the measured data for short-term fluctuations within a daily cycle. The maximum difference in relative humidity gives the maximum fluctuation for this day. With this derived data a graph can be drawn showing only the daily fluctuation range in a timeline for each day, or as a histogram plot sorted from the highest value to the lowest.

A newer method for the evaluation of indoor climate is given by EN 15787 [7]. Based on experimentally observed changes in painted wood, a method is introduced with a monthly moving average of relative humidity. This 30-day average stands for the seasonal cycle. A short-term fluctuation is defined as the difference between the measured data and the monthly moving average. On this average line, the 7th and 93rd percentile of measured data (equal to a standard deviation of 1.5) are defined as the border lines for the maximum distance of the acceptable range of short-term fluctuation (Figure 5). This method offers a combined evaluation of short- and long-term fluctuations. The monthly moving average shows the seasonal trend. This evaluation seems a better fit for the real behavior of hygroscopic materials with a certain thickness, for example painted wooden panels, than the usually rather generalised guidelines.

Yet it is not clear to which materials, combinations of materials or material characteristics and thickness this analysis method applies and if it is sufficient for the evaluation of damage potential.

Material characteristics of artworks

The right time period over which to evaluate the damage potential of the environment on artworks depends on the kind of artwork under consideration. From a physical perspective, there is no correlation between moisture sorption and a daily cycle. The moisture sorption from and to the air is mainly driven by the difference between the moisture equilibrium of the material and the relative humidity.

As different objects are made of different materials or also composite materials the reaction to a change in climate depends on the physical characteristics of the materials themselves. Diffusion-resistant parts like the paint layer in a pastose oil painting will behave differently from the very permeable canvas. Experiments show an immediate reaction in weight-change of a sensitive artwork like a painting on cardboard to a change in relative humidity (Figure 1).

Concerning the hygrothermal characteristics of artworks, only a few values are available, for example, the water vapour diffusion resistance or isotherms for reconstructed historic composite materials from Wehle [8], Worch [9] and Rachwał [10]. Reliable data for combined inhomogeneous materials and their uncertainty ranges are completely unknown.

Time cycles and measuring periods

Typical periods for analysing climate data are one hour, one day, several days, one week, one month and one year. The one-day period is an alternating cycle of relative humidity depending on day and night. In most regions of the world, a one-year period is also a real cycle with seasonal changes in relative humidity and temperature overlaying the daily cycle. Cycles of one hour, several days, one week or month are mainly arbitrary and serve as an aid to describe intermediate cycles. They give the typical cycles of human anthropology, but not necessarily of material behavior. The different cycles serve as an aid to match to the different time constants of different materials. For example, a sheet of parchment or an oil painting on cardboard will react very quickly to changes in RH and therefore shorter time intervals should be chosen for evaluation compared to a painted panel as mentioned above.

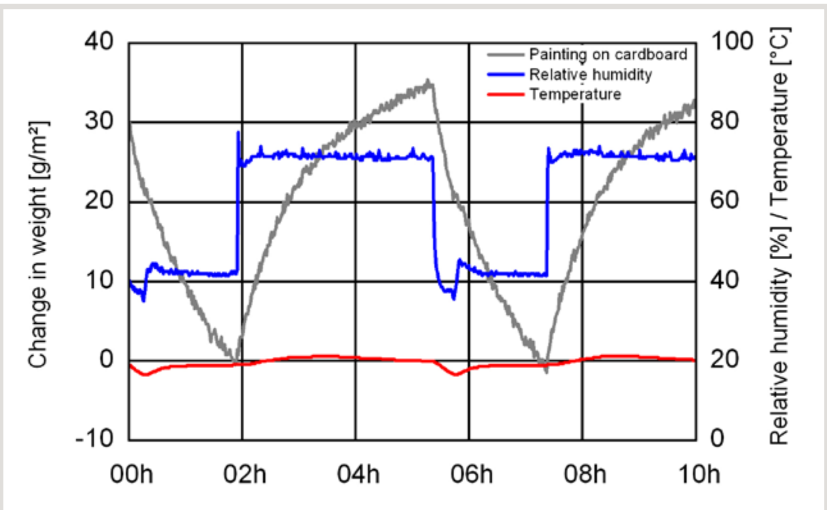

Figure 1. Change in weight for an oil painting on cardboard, when subjected to cyclical changes in relative humidity from 40 to 70 % at 19 to 20 °C

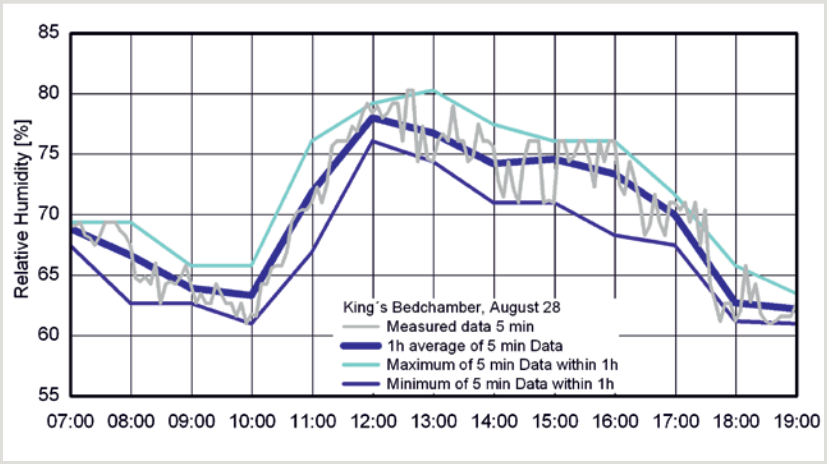

Figure 2. The graph shows a typical day in the summer in the King's bedchamber in Linderhof Palace. In the morning, the windows were opened just before the visitors came in. Both influences have a certain impact in relative humidity and cause strong fluctuations. The blue and light blue graphs show the maximum value within one hour and the minimum relative humidity. The dark blue centre graph shows the hourly average of the 5-minute measured data (grey line).

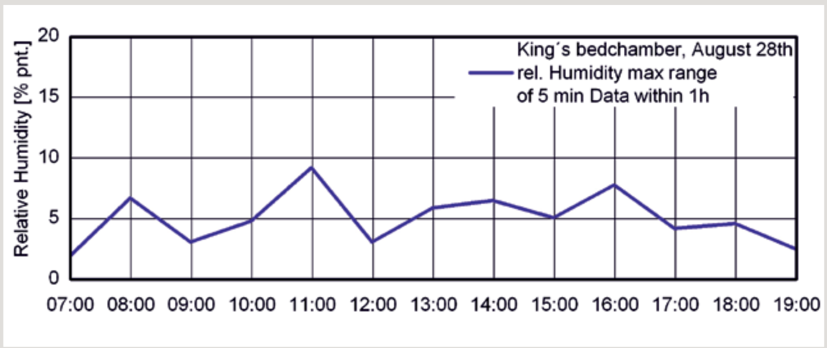

Figure 3. The relative humidity fluctuations reach up to 9 % RH within one hour with 5-minute measured data

There is also a question about the most appropriate duration of a condition in relation to the time intervals being studied. What is the correct time duration of a condition in relation to 24 hours? A common time interval is one hour but consideration of different durations may also be useful. But how often should the indoor air conditions be measured within one hour to get sufficient information?

Figure 2 shows a graph of measured data of relative humidity in the unheated Linderhof Palace for one day during opening time. Due to open windows and entering visitors the relative humidity changes very quickly. The five-minute measured data (grey line) are compared to their hourly average value (dark blue line). Additionally two lines are shown in the graph with the maximum and minimum RH for each hour of the five-minute data. The relative humidity changes quite quickly in this example. There are short-term fluctuations up to 9 % RH per day though for the most part values of about 5 % RH fluctuation can be observed (Figure 3).

A variation in average values depending on the number of data used per hour is shown in figure 4. The average values are calculated from 5-minute interval data by taking every second, third and sixth value. This means the average value is calculated with 10 minutes measured data interval and also with 15 minutes, and 30 minutes. That gives an estimation of the necessary measuring frequency for one-hour values and how much information gets lost. The maximum deviation to the 5-minute average value to the average line made of 30-minute measured values is nearly to 2 % RH in this example. For a longer period deviations of up to 3 % RH were observed for the King's bedchamber. This is only of interest for investigations of short-term fluctuations. The long-term means of both average values are

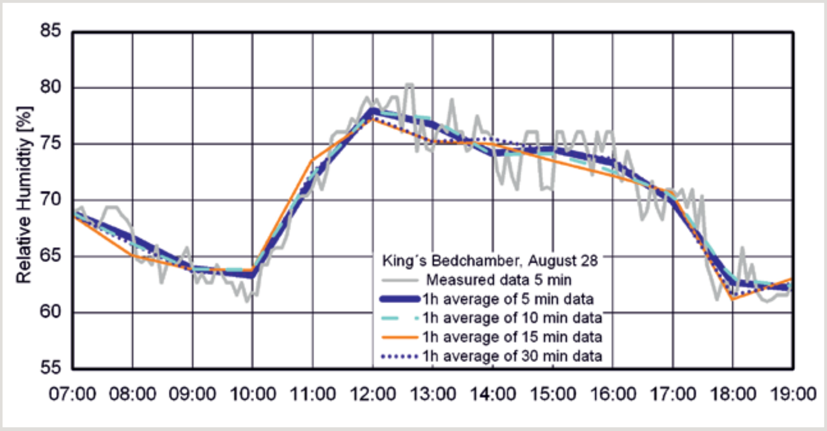

Figure 4. Average values with different time intervals are compared with each other. The average lines are based on the same measured data. With only two measured data in one hour too much information gets lost. In this example a deviation of 2 % RH occurs compared with the average line of 5-minute data

almost matching. The example of the unheated Linderhof Palace with more than 3000 visitors shows a rapidly changing indoor climate. It also shows possible deviation of relative humidity values depending on the frequency of measurement. During closing times without visitors and less ventilation before and after opening time we can observe only small fluctuations with less dependency on measuring frequency.

For buildings like Linderhof with large variations in visitor numbers and ventilation rates, short measuring intervals of 5 or 10 minutes are necessary to get sufficient information.

A newly developed method for evaluation of measured data for short-term fluctuations

For further evaluation of the data we will examine a longer time interval. Figure 5 shows a one-hour average value of relative humidity based on data measured over 5-minute intervals in Linderhof Palace. The light blue graph shows the annual average of a one-year period from December 2009 to December 2010. The red line is the 30-day moving average and the broken line shows the 1.5 standard deviation (sd) as recommended in EN 15787. The 1.5 sd for the measured year equates, for the King's bedroom, to plus or minus 10.4 % RH forming a relatively 'safe' zone around the moving average, relatively 'safe' because the standard is meant to be used only if no damage is present, which is not the case for Linderhof Palace. The three dashed arrows indicate a vast change in RH which exceeds a one-day period. If we analyse a one-day period on its maximum range of RH we cannot recognise changes

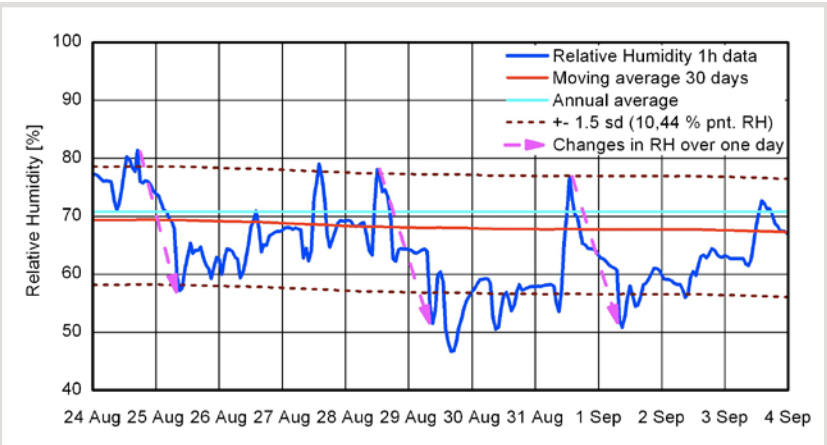

Figure 5. The blue line shows the one-hour average value of the five-minute measured RH in the King's bedchamber in Linderhof Palace. The 7th and 93rd percentile or 1.5 sd around the moving average are shown [7]. The light red arrows show vast changes in RH over a one-day period

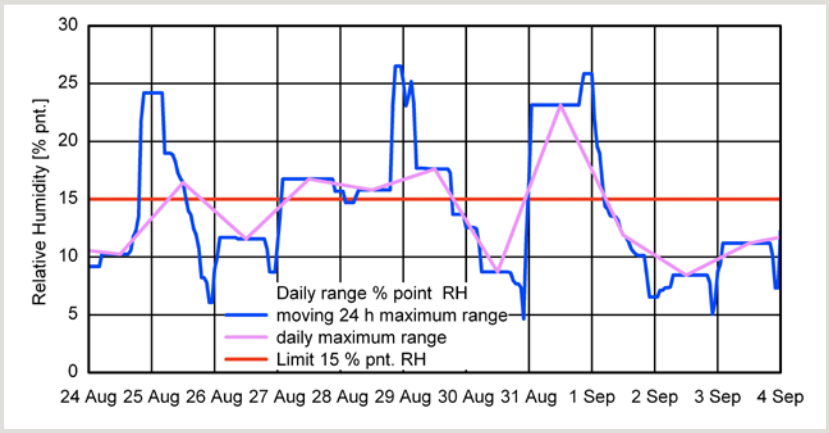

Figure 6. The RH fluctuations of measured data collected in the King's bedchamber in Linderhof Palace are analysed. The blue line shows the moving 24-hour fluctuation range. The light red graph shows the maximum fluctuation within one day from 1:00 am to 0:00 pm for each day

exceeding one day. By moving this 24-hour period by an hourly step it is possible to make changes exceeding one day visible.

Figure 6 compares both methods of equidistant analysis and an hourly moving 24-hour interval. The blue line shows the hourly moving maximum fluctuation range within 24 hours. The light red graph shows the fluctuation range within equidistant 24 hours from 1:00 am to 0:00 pm for 11 days. The maximum range of RH in a moving 24-hour interval in figure 6 is up to 9 % RH higher than with the equidistant daily method calculated. The examined data is a one-hour average value of relative humidity based on a 5-minute interval of data measured in the King's bedchamber in Linderhof Palace in 2010.

Examples of climate data examined with the new method of the moving 24-hour maximum fluctuation range of relative humidity

Case study: Linderhof Palace

For a detailed description of the climate in Linderhof palace see [11]. Figure 7, left graph shows the maximum range of relative humidity analysed with two methods. One method is the moving 24-hour interval (blue line), the other method is the commonly used daily equidistant interval (light red line) with 365 values. The data were collected in the King's bedroom in Linderhof Palace from December 2009 to December 2010. Each fluctuation beyond 15 % RH is seen as critical for the original furnishing in Linderhof Palace. If each event beyond 15 % RH range (red line) is counted, 8 % of the days in one year exceed this range. With the moving maximum fluctuation range, fluctuations beyond the critical line

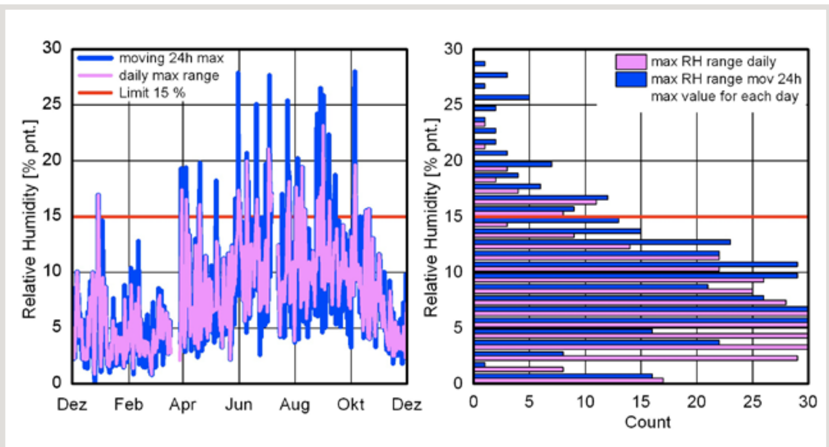

Figure 7. Maximum range of relative humidity within a 24-hour moving interval for each hour (blue line) and with an equidistant interval of one day for each day (light red line). The data were collected in the King's bedroom in Linderhof Palace from December 2009 to December 2010

on 12 % of the days within this year are counted. Much stronger fluctuations, by up to 10 % are made visible by the new method. The histogram in figure 7 counts each maximum fluctuation per day. For the 24-hour moving fluctuation, if a vast single fluctuation happens over two days, a double count may occur. This phenomenon is explained in figure 5 by the arrows. The calculated mean value of all RH fluctuation beyond 15 % of the new method is 4.0 % RH higher when compared with the calculated mean RH fluctuation of the common equidistant method. With the new method 1.5 times as many occurrences beyond 15 % RH can be detected compared to the common method.

Case study: the Turkish Hall in the King's House on Schachen

The King's House on Schachen built by King Ludwig II. of Bavaria (1869–1872) is situated in the Bavarian mountains at a height of 1876 m above sea level. It is open to visitors for four months during summer, the rest of the time it is closed due to the snow. Intensive conservation assessments [12] as well as a building simulation and climate studies have been done [8], [13]. Applying the new moving 24-hour method shows that the values exceeding the limit are much lower than in Linderhof Palace. Still there are some occurrences beyond the 15 % fluctuation range, which may be dangerous for the historic interiors in the Turkish Hall. With the new method, 2.1 times as many occurrences beyond 15 % RH can be detected compared with the common method. The method with the moving 24-hour interval also reveals stronger fluctuations than the equidistant method. The maximum distance between the two methods is 7.7 % RH at a fluctuation beyond 15% RH (Figure 8). The difference of the mean RH ranges beyond 15 % between the two methods is 3.0 % RH.

Case study: Church St. Margaretha in Roggersdorf

The small church of St. Margaretha in Roggersdorf was built in the seventeenth century and is still unheated. The indoor climate shows high average humidity [15] and very large fluctuation ranges of up to 37 % RH points. The method with the moving 24-hour interval reveals stronger fluctuations than the equidistant method. Applying the new method, 1.9 times as many events with fluctuations beyond 15 % RH can be detected compared with the common method (Figure 9). The maximum distance between the two methods is 13 % RH at a fluctuation beyond 15 % RH. The difference of the mean RH ranges beyond 15 % RH between the two methods is 3.4 % RH.

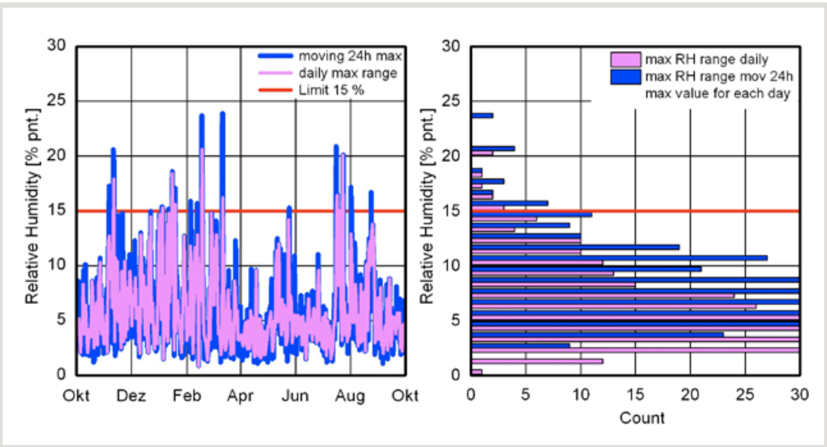

Figure 8. Maximum range of relative humidity within a 24-hour moving interval for each hour (blue line) and with an equidistant interval of one day for each day (light red line). The data were taken from the Turkish Hall in the King's House on Schachen from October 2006 to October 2007

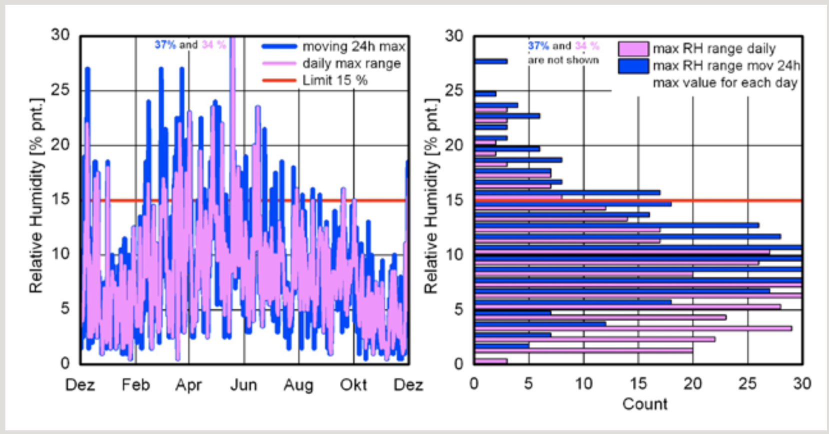

Figure 9. Maximum range of relative humidity within a 24-hour moving interval for each hour (blue line) and with an equidistant interval of one day for each day (light red line). The data was measured in Roggersdorf from December 2004 to December 2005

Conclusion and outlook

The new method of evaluation of short-term fluctuations with a moving fluctuation range makes the real maximum fluctuation of a particular climate visible. In all of the three examples there are up to two times more fluctuations beyond 15 % RH detectable when compared with the equidistant daily method, see table 1. Also, much wider short-term fluctuations were revealed, up to 13 % RH higher with a mean difference of mean values of RH ranges of up to 4 % RH, see table 2. The new method has been successfully applied to assess the indoor climates of three unheated monuments with different local ambient climates and visitor numbers. With the new method, the real climate conditions

Table 1. Results of three examples on evaluation of maximum fluctuation range in relative humidity with two different methods, number of days exceeding 15 % RH fluctuation

	number of equidistant 1-day range ≥ 15 % RH	number of moving 24-h range ≥ 15 % RH	difference	factor of difference (multiplier)
	[days]	[days]	[days]	[-]
Schachen	9	19	10	2.1
Roggersdorf	36	68	32	1.9
Linderhof	30	45	15	1.5
mean multiplier				1.8

Table 2. Results of three examples on evaluation of maximum fluctuation range in relative humidity with two different methods, mean difference and maximum value

	mean difference between equidistant 1-day range minus moving 24-h range in values ≥ 15 % RH	Maximum difference of RH range between the two methods
	[% RH]	[% RH]
Schachen	3.0	7.7
Roggersdorf	3.4	13.0
Linderhof	4.0	11.0
mean multiplier	3.5	-

can be captured more accurately. This is an important conclusion when assessing damage caused to artworks by short-term environmental fluctuations. For the examples of the Linderhof Palace, the King's House on Schachen and the Church of St. Margaretha in Roggersdorf the limit of changes considered to pose a risk was set to 15 % point RH due to the condition assessments which had been undertaken on these buildings. Here the analysis was done for relative humidity but the method can also be used for the examination of temperature differences. Broader fluctuation values should be expected here too. The new method has also been used successfully to validate simulated data generated during a simulated climate exercise for preventive conservation purposes at the Linderhof Palace [14].

Further investigations are necessary to determine the limits of non-hazardous short-term fluctuations as evidence. The new method to analyse climate data should be further developed as a standard tool. This work will need to include a critical review of the definition of short-term fluctuation, the response of different materials and the applicability of experimental data obtained by step functions in climate chambers in comparison with real climates.

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