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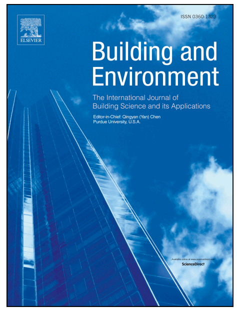
Reference:
Anaf Willemien, Schalm Olivier.- Climatic quality evaluation by peak analysis and segregation of low -, mid-, and high-frequency fluctuations, applied on a historic chapel
Building and environment - ISSN 0360-1323 - 148(2019), p. 286-293
Full text (Publisher's DOI): https://doi.org/10.1016/J.BUILDENV.2018.11.018
To cite this reference: https://hdl.handle.net/10067/1575690151162165141

Accepted Manuscript



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PII: S0360-1323(18)30713-3

DOI: https://doi.org/10.1016/j.buildenv.2018.11.018

Reference: BAE 5811

To appear in: *Building and Environment*

Received Date: 22 August 2018

Revised Date: 2 November 2018

Accepted Date: 14 November 2018

Please cite this article as: Anaf W, Schalm O, Climatic quality evaluation by peak analysis and segregation of low-, mid-, and high-frequency fluctuations, applied on a historic chapel, *Building and Environment* (2018), doi: https://doi.org/10.1016/j.buildenv.2018.11.018.

Climatic quality evaluation by peak analysis and segregation of low-, mid-, and high-frequency fluctuations, applied on a historic chapel

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Abstract
Heritage-related guidelines and standards recommend stable climatic conditions, since these contribute to the extension of heritage collections life. As a result, numerous museums and other heritage institutions implement (expensive) mitigation measures to achieve stable conditions. Nevertheless, temperature and relative humidity fluctuations are often still observed. This contribution demonstrates that the analysis of temperature and humidity peaks and drops helps to identify hazards which cause fluctuations in different frequency ranges. This hazard identification provides information on the type of mitigation actions that are required in the near future and in which order they need to be implemented. The approach is illustrated with a case study. A 22 month monitoring campaign was performed in a chapel in the center of Antwerp (Belgium) where the climatic conditions are controlled with a heating, ventilation and air conditioning (HVAC) system. Low-, mid- and high-frequency fluctuations were separated and discussed for their hazards.

Keywords

Climate assessment; peaks; fluctuations; hazard identification; decision-making; preventive conservation

1. Introduction
Environmental conditions have a profound impact on the degradation of heritage collections. Temperature and relative humidity are two main parameters that determine the climatic quality for heritage conservation. Recommended climatic conditions are specified in well-accepted heritage-related standards and guidelines [1-11]. A well-known example of such guideline is the one defined by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [1]. To prolong the lifetime of heritage objects and reach a high climatic quality, all guidelines recommend stable temperature and relative humidity conditions within a certain range. Within the heritage sector, the guidelines are widely used for general preservation recommendations, construction of new museums, or refurbishment of old monuments into buildings with contemporary preservation conditions [12].

Many heritage institutions evaluate their climatic quality by continuously monitoring temperature and relative humidity. Different methods exist to do such evaluation. One approach uses the ASHRAE guideline to evaluate the climatic quality by calculating the percentage of the collected data that corresponds with the different ASHRAE climate classes [13-15]. Alternative approaches define indexes that evaluate the climatic quality. The performance index, for example, is defined as the percentage of time in which a measured parameter such as relative humidity falls within a predefined (tolerance) range [12, 16, 17]. The time-weighted preservation index (TWPI), developed by the Image Permanence Institute, is a single value that captures the total cumulative effect over time of changing temperature and relative humidity conditions. It is based on the rate of chemical deterioration in collections [18, 19]. Other indexes were developed that, for example, estimate the effectiveness of the building's heating, ventilation and air conditioning (HVAC) system [17].

The methods described above, are relatively easy to apply and enable a fast climatic quality assessment. However, they are based on an averaged evaluation, underestimating the effects of brief but intense fluctuations. Such brief moments of inappropriate conditions can dominate the damage on heritage collections. To overcome this limitation, we propose an alternative and complementary approach that focuses on fluctuations in temperature and relative humidity data. Temperature and relative humidity graphs could be considered as a superposition of fluctuations at different frequencies: seasonal fluctuations, fluctuations due to weather changes, day-night fluctuations, fluctuations caused by an event, etc. This results in complex graphs that are hard to interpret. To better understand the fluctuations, we developed a method that isolates fluctuations of different frequency ranges. Such data processing helps in hazard identification, and supports the prioritization of decision alternatives. Moreover, it helps in the evaluation of the damage risk for hygroscopic objects. Indeed, fluctuations, mainly in relative humidity, could cause mechanical damage on hygroscopic objects such as wooden interior elements, paintings on canvas or wood, textiles, etc. due to swelling and shrinking of the material [20-26]. The extent of the damage is determined by the response time of the objects. This is the time an object needs to reach complete equilibrium with the new climatic conditions [27]. However, hygroscopic surfaces in direct contact with the surrounding atmosphere respond faster to changing conditions compared to the core of the object, creating internal tension [28-30]. Due to the wide range of response times of hygroscopic objects that often have to be covered in one space (e.g., historical interior), the proposed method to separate fluctuations in different frequency ranges also offers added value in the damage risk evaluation for these materials.

The method is illustrated on a case study in a historic chapel with an HVAC-system installed. During the last decades, many heritage institutions such as museums, archives, historic houses and churches have installed sophisticated and expensive heating or climate control systems that actively control the temperature and humidity conditions [31-35]. Such climate systems aim to control the level of temperature and relative humidity, and the rate and extent of their fluctuations. However, unstable conditions are regularly noticed, e.g., due to technical failure or improper regulation [35]. Moreover, in many cases, the climate control systems are not only meant to improve the indoor conditions for the conservation of the building and its contents, but also to provide thermal comfort for staff, visitors and worshippers [27, 36-40]. This often entails additional fluctuations in the climatic conditions, e.g. when a church is temporarily heated for a mass service, or when a museum is heated more during the day compared to the night. We used the data of temperature and relative humidity that was monitored in the historic chapel during a 22 month sampling campaign. We separated the fluctuations of both parameters for three frequency ranges, i.e., low-, mid-, and high-frequency fluctuations, in order to evaluate the climatic conditions in the chapel, identify the hazards for the fluctuations, and estimate the damage risk for the chapel's valuable heritage.

2. Materials and methods

2.1 Monitoring location

The monitoring campaign is performed in a chapel in the city center of Antwerp (Belgium). The chapel originates from the 15th century and is part of a cloister building. Natural light enters the chapel from the south and north facade through stained glass windows. The chapel houses two valuable organs, wooden statues, paintings and medieval wall paintings. It is the setting for concerts, weddings and receptions. Climatic conditions in the chapel are regulated by an HVAC-installation (2009, Dalkia, EDF Group, Saint-André-lez-Lille, France). The installation aims to optimize the conservation conditions for the organ and the wooden interior decorations and also considers human comfort during concerts. The temperature is controlled by two thermostats that are installed near the two restored organs in the chapel. One organ is located above the entrance door in the west façade at around 7 meter height. The other organ is located in the choir at a height of around 20 meter. Their average temperature recording is considered to reach a set point of 18°C in the chapel. This temperature is required for the tuning of the organs [41]. During public events or to adjust the relative humidity, the temperature can be increased up to a maximum of 20°C, with a change rate of 2°C per hour. The stationary heating up to 18°C with short periods of additional heating brings the indoor temperature to a level that is comfortable for humans. On the contrary, it can cause a low and variable relative humidity, certainly in cold periods [31, 33]. Therefore, the installation also enables humidification by a steam humidifier with an aimed relative humidity range of 55 to 70%. Dehumidification is not possible.

2.2 Data collection and processing of the outdoor climate

Data of outdoor temperature (T), relative humidity (RH), quantity of rainfall and sunshine duration are used from the Belgian Royal Meteorological Institute. Data are collected with a time interval of 6 hours in a weather station at around 20 km south-southeast from the chapel. The data of this weather station is calibrated and reliable. In order to suppress high frequency fluctuations and to emphasize the effect of good and bad weather, a central 7-day moving average is applied on all four parameters. The seasonal trend for outdoor temperature and relative humidity is obtained by a central 30-day moving average.

2.3 Data collection and processing of the indoor climate

Temperature and relative humidity data are collected with a calibrated ATAL data logger (ATX-11, Atal, Purmerend, The Netherlands) using a time interval of 15 minutes. The logger has a resolution of 0.1°C and 0.1% and an accuracy of ±0.4°C and ±2.5% for temperature and relative humidity, respectively. The logger was positioned at the south façade, close to an extremely fragile secco mural painting. The painting suffers from flaking due to an earlier restoration treatment with an inappropriate product. The flaking is induced by the swelling and shrinkage of the applied restoration product under fluctuating climatic conditions. Data are collected from 13/12/2011 to 22/10/2013, covering a period of 22 months. The absolute humidity is calculated from the measured temperature and relative humidity.

In a first approach, the data streams are processed according to the standard EN15757:2010. This standard requires the use of entire multiples of a calendar year in order to avoid a bias due to an unbalanced number of different seasons. For that reason only the data of the year 2012 have been processed. The standard defines a fluctuation as the difference between a data point and the central 30-

day moving average. The deviations that exceed the 7th and 93th percentiles of the seasonal cycle of the data are considered as the periods with the highest risk for damage [2, 42].

An alternative approach considers the temperature and relative humidity graphs as a superposition of fluctuations at different frequencies, e.g., seasonal fluctuations, fluctuations due to good and bad weather, fluctuations of few hours due to an event, day-night fluctuations, etc. To isolate the different types of fluctuations, data processing has been performed based on moving averages. The isolation of the different frequencies simplifies the identification of the hazards causing them [43].

- **Low-frequency fluctuations:** Fluctuations that occur at long time scales (i.e., several months) are mainly due to seasonal cycles and are isolated by applying a central 30 day moving average on the raw data stream, considering 15 days before and after the data point of interest [2]. Following formula describes the low-frequency fluctuations:
$$X_{low,i} = \frac{1}{N} \sum_{j=i-(N-1)/2}^{j=i+(N-1)/2} X_j$$
In which X_{low} contains the contributions of the low-frequency fluctuations, X_i the raw data in position i of the time series, N the window size of the moving average that is in agreement with the number of data points in 30 days, and (N-1)/2 the number of data points to the left and right of X_i.
- **Mid-frequency fluctuations:** Fluctuations that occur at a time-scale of several days to weeks are isolated by subtracting the seasonal trend from the raw data. From this subtraction, high-frequency fluctuations (e.g., day-night fluctuations) have been suppressed using a central 24-hour moving average. The 24 hour moving average is calculated by considering a symmetrical window of 12 hours before and after the data point considered [44]. Following formula describes the mid-frequency fluctuations:
$$X_{mid,i} = \frac{1}{M} \sum_{j=i-(M-1)/2}^{j=i+(M-1)/2} (X_i - X_{low,i})_j$$
In which X_{mid} contains the contributions of the mid-frequency fluctuations, X_i is the raw data at position i in the data range, M is the window size of the moving average containing the number of data points within a period of 24 hours, and (M-1)/2 is the number of points to the left and right of the current data point X_i.
- **High-frequency fluctuations:** Fluctuations that occur at short time-scales (i.e., a matter of hours) are isolated by subtracting the low- and mid-frequency fluctuations from the raw data. Following formula describes the high-frequency fluctuations:
$$X_{high,i} = X_i - X_{low,i} - X_{mid,i}$$
In which X_{high} contains the contributions of the high-frequency fluctuations, and X_i is the raw data at position i in the time series.

3. Results

The low-, mid- and high-frequency fluctuations that are isolated with the proposed data processing method are treated in separate sections. The data processing following standard EN15757:2010 is discussed in the mid-frequency section.

3.1 Low-frequency fluctuations

Fig. 1 gives an overview of the measured indoor temperature and relative humidity for the 22-month measuring period. The black line represents the raw data. The red and blue lines are the moving 30-day averages of the temperature and RH, respectively, and visualize the seasonal trend in the datasets. These trends are considered as low-frequency fluctuations because they cover periods of several months. The isolation of the seasonal trend is to some extent influenced by some large peaks and drops, especially in the RH. Therefore, the separation is not perfect but sufficient to give more insight in the overall climatic behavior inside the chapel. Following observations are made:

- **Temperature:** In all seasons, except the summer season, the temperature is around 18°C. This is the set point of the HVAC-installation. In late spring and summer, the average indoor temperature is higher than 18°C. This is due to the combination of elevated outdoor temperatures and the climate control system that is not able to cool down the chapel. Therefore, the seasonal trend shows two clear peaks during the late spring and summer months, while the rest of the year the temperature is relatively stable around 18°C.
- **Relative humidity:** The seasonal trend of the relative humidity shows more fluctuations compared to the seasonal trend in temperature. This is due to the interference between mid-frequency fluctuations and the seasonal trend. In general, summer periods are marked by a higher relative humidity (i.e., between 60% and 70%) compared to the other seasons (i.e., between 40% and 50%).

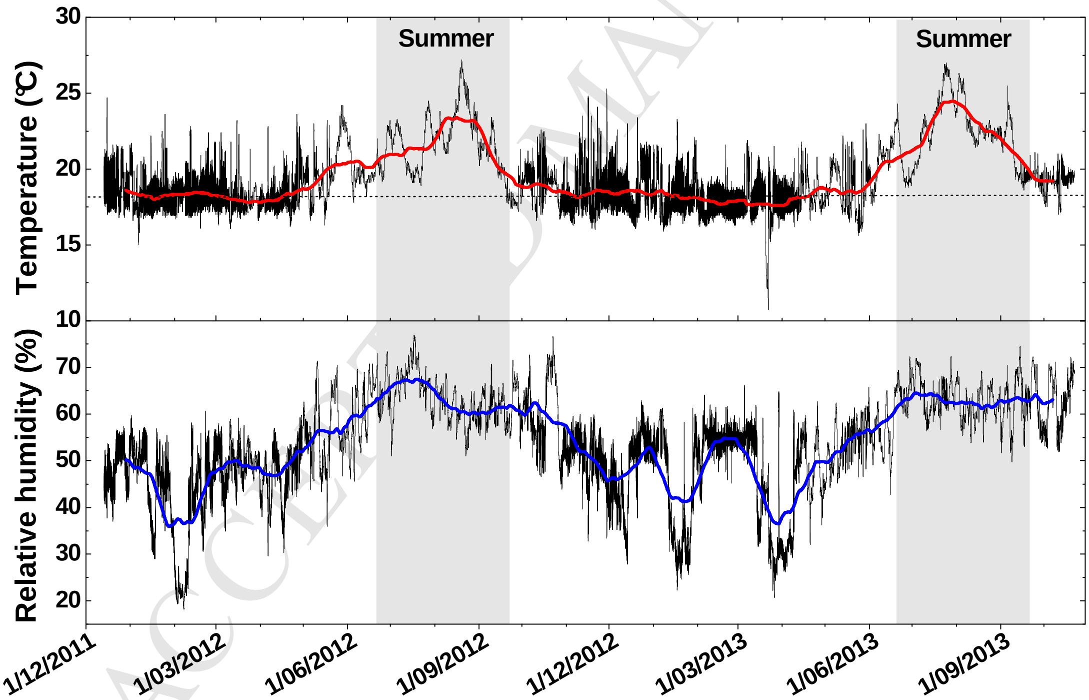

Fig. 1: Overview of the dataset of temperature and relative humidity from 13/12/2011 till 20/10/2013 in the chapel. The black line represents the raw data. The red and blue lines are the 30-day moving averages of temperature (T_{low}) and relative humidity (RH_{low}), respectively. [Color print requested]

The seasonal trend of the chapel's climate is compared with the outdoor climate to get more information. Fig. 2 shows the 30-day moving averages of the indoor and outdoor temperature and relative humidity data, and the 6 hour interval data of indoor and outdoor absolute humidity. The air exchange of the building has a clear influence on its indoor climate [36]. A detailed comparison gives the following information and enables the identification of several hazards:

- **Temperature:** Where the indoor temperature exceeds 18°C during late spring and summer periods, the shape of the graph corresponds with that of the outdoor temperature with a shift of about 5°C. It should be remarked that the outdoor temperature is measured outside the city and that local outdoor conditions were not measured in this study.
- **Humidity:** Although the climate control system consists of a humidification module, the monitored data suggest its improper working. The presence of several drops down to 20-30% indicates that a set point for a minimum RH could not be maintained. In winter and autumn periods, a remarkable correspondence is found between the indoor RH and the outdoor temperature. This can be explained as follows. The building has a low isolation level. The colder the outdoor temperature, the more the HVAC system needs to heat up the indoor air. Since warmer air can contain more water vapor, this results in a decrease in RH. Thus, the lower the outdoor temperature, the lower the indoor RH. The explanation is confirmed by the similar absolute humidity (AH) from in- and outdoor air for both winter and summer (Fig. 2). There is only one short period where the indoor air contains more moisture than the outdoor climate. That deviation is considered as a mid-frequency fluctuation and is discussed in the next paragraph.

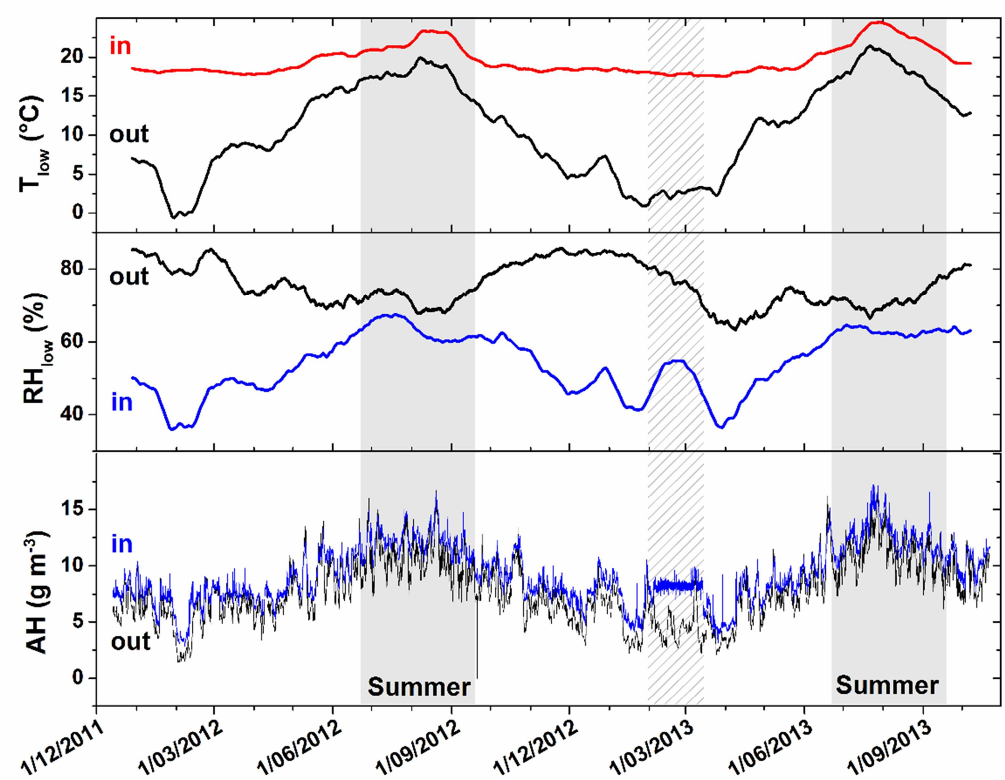

Fig. 2: 30-day moving averages of indoor and outdoor temperature (T_{low}) and relative humidity (RH_{low}) data. Absolute humidity (AH) in the chapel and outdoors. Summer periods are marked in grey. The shaded area marks the period where the indoor AH remarkably deviates from the outdoor AH.
[Color print requested]

3.2. Mid-frequency fluctuations

The standard EN15757:2010 focuses on moisture sensitive objects. It considers the seasonal trend not as harmful but as the climatic conditions to which a cultural heritage object has always been exposed: the objects have adapted to their historic climate. Fluctuations that depart more than the 7th and 93th percentile of the seasonal level are considered as a risk. If the percentiles are below 10% from the seasonal level, the 10% fluctuation should be considered as the safe range.[1] Fig. 3 shows the application of this approach on the data of the year 2012. Only the tops of the largest temperature peaks exceed the threshold lines. In the winter period, these are narrow peaks related to temporary additional heating. In the summer period, they are broader peaks due to elevated outdoor temperatures. The RH exceeds the threshold lines during the sudden drop in February 2012 and the large peak in October 2012. These large peaks and drops influence the behavior of the seasonal trend. However, they are considered as mid frequency fluctuations because their width is in the range of several days to weeks.

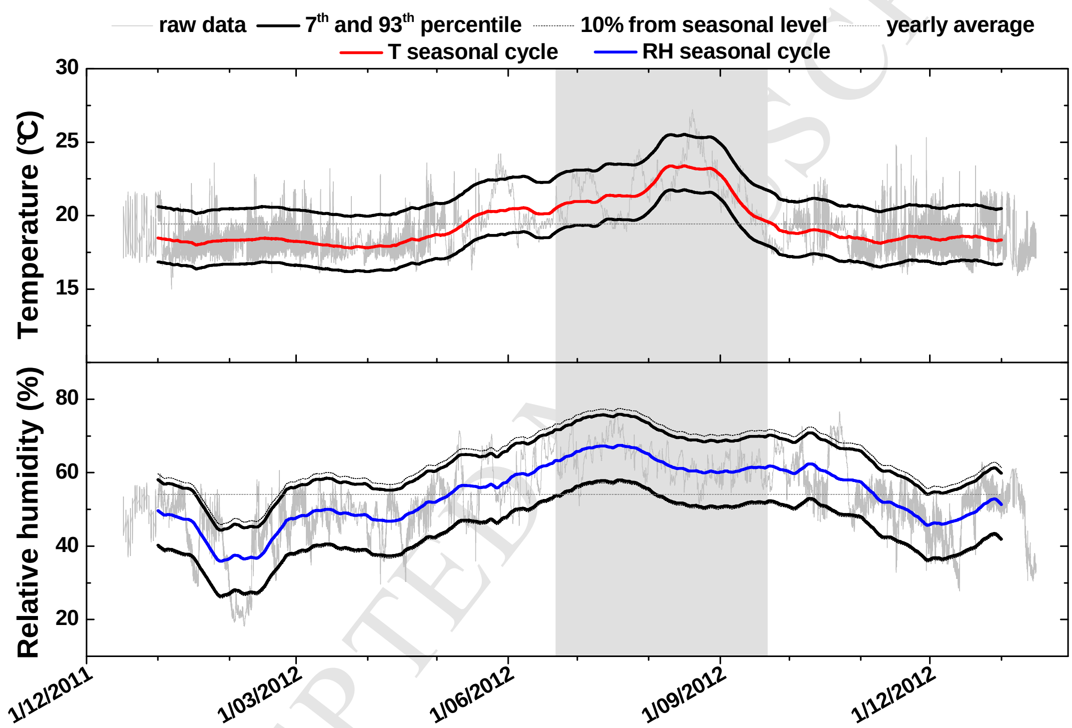

Fig. 3: Raw data of temperature and relative humidity of the year 2012 processed according to standard EN15757:2010. The summer period is marked in grey. [Color print requested]

The most important mid-frequency peaks and drops seem to be governed by the outdoor climate. Therefore, the change in weather is suspected to be an important hazard. Fig. 4 gives an alternative method to analyze the mid frequency fluctuations is given. It gives an overview of the raw data from which the seasonal trend has been subtracted and where high frequency fluctuations have been removed using a 24-hour moving average (i.e., T_{mid} and RH_{mid}). The remaining fluctuations should be caused by hazards that cause fluctuations with a width of more than one day. The standard deviation

[1] Standard EN15757:2010 is not straightforward concerning these less strict threshold levels. It mentions "*if the above procedure [i.e., the use of the 7th and 93th percentile] determines that RH fluctuations depart by less than 10% from the seasonal RH level, the calculated limit is considered unnecessarily strict and can be disregarded. The 10% RH threshold can be accepted ...*". We interpreted this as a level where RH-values in %-units of +10 and -10 are subtracted from the seasonal average. A similar approach is not mentioned for the temperature data and is therefore not shown in Fig. 3.

for the T and RH mid-frequency fluctuations are 1 and 5, respectively. The mid-frequency fluctuations of the indoor data are compared with the outdoor data. High frequency fluctuations are suppressed using a 7 day moving average. Sunshine duration data are plotted with outdoor temperature, since it is expected to mainly influence the temperature. Moreover, sunshine is able to warm up the chapel through the windows. Rainfall, on the other hand, is plotted with the RH. The arrows in Fig. 4 indicate several indoor peaks that are clearly related to outdoor peaks. The most important mid-frequency fluctuations are discussed in the list below:

- **Temperature peaks in the summer periods:** The outdoor temperature is typically a superposition of a seasonal trend, fluctuations due to weather changes and day-night cycles. Small but warm periods do occur. Outdoor temperature peaks often correspond to periods of high sunshine duration. Due to a high correlation between indoor and outdoor temperature during the summer period (see Fig. 2) these warm periods result in indoor temperature peaks. The tops of some of these peaks exceed the threshold lines as defined by the standard EN15757:2010 (Fig. 3). Indoor-outdoor peak correlations are mainly observed in late spring and summer periods, since the rest of the year, mid-frequency temperature fluctuations are smoothed due to the artificial heating of the chapel.
- **Sudden drop in relative humidity at the beginning of February 2012:** One of the largest drops in RH can be noticed between January 27, 2012 and February 10, 2012 with a width of 14 days. Within one week, the RH dropped almost 35%, which corresponds to an average daily decrease of 5%. In this period, the RH reaches a minimum of 18.2%. During this period, the outdoor temperatures go below the freezing point with a minimum of -14°C on February 4. The additional heating of incoming outdoor air resulted in a strong decrease in indoor relative humidity. It is clear that the humidification module did not function at that time. Similar drops can be seen in January 2012, February 2013 and March 2013. These drops are to be considered as a severe risk to the historic furniture inside the chapel. Wood for example, can endure relatively large fluctuations without noticeable damage in the mid-RH region, but the allowable domain narrows in the extreme RH-regions [45].
- **Stable AH plateau in February-March 2013**: There is one period in February-March 2013 where the outdoor AH shows a fluctuating pattern, while the indoor AH is remarkably stable (Fig. 2). This period is characterized by a clear indoor RH peak while no outdoor T peak is observed. This suggests that only in that period the humidification module appears to function or that another temporary humidity source was present. Apart from this stable indoor AH plateau, there is a good correlation between the outdoor and indoor mid-frequency fluctuations for AH ($R^2 = 0.84$).
- **Limited influence of rainfall on the indoor relative humidity:** Intuitively one would expect an increase in indoor relative humidity when people enter the church with wet clothes. However, no clear relation was observed between rainfall and indoor relative humidity in the chapel. This suggests that the influence of wet clothes on the chapel's RH is limited. The indoor relative humidity seems to a large extent dominated by the outdoor absolute humidity and not by rainfall.

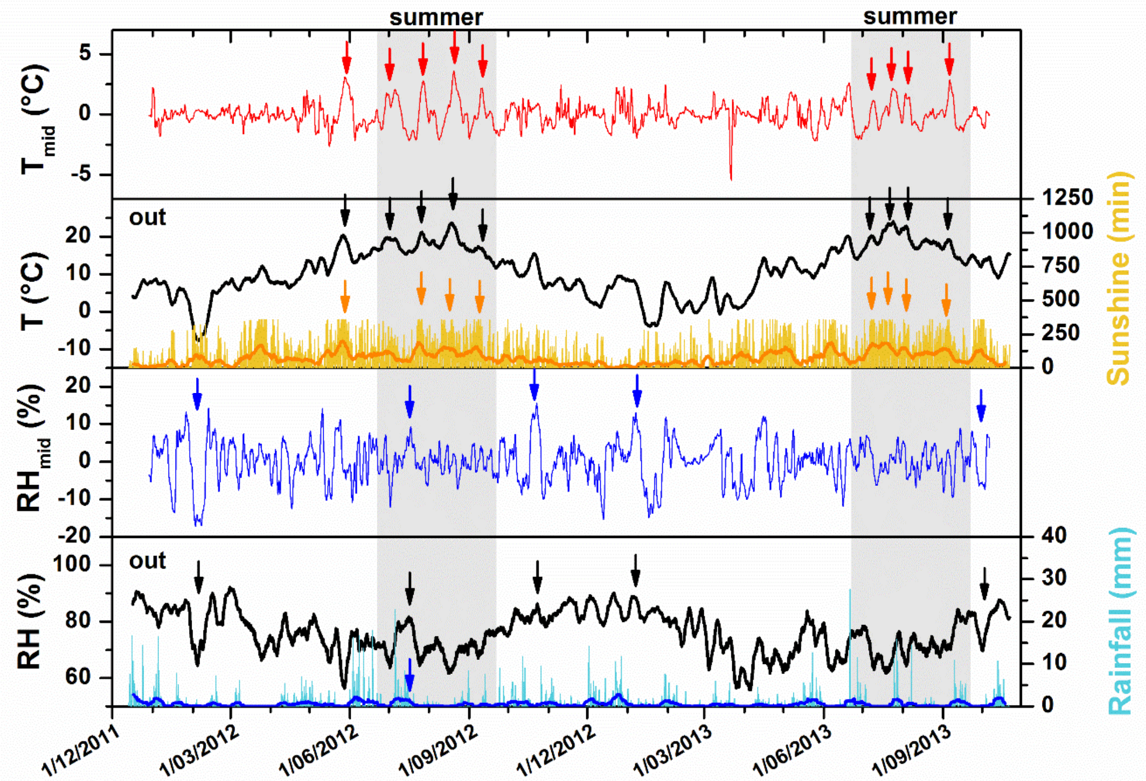

Fig. 4: Mid-frequency fluctuations, determined by subtracting the seasonal trend from the data set for indoor climatic conditions, and subsequently applying a 24-hour moving average (T_{mid} and RH_{mid}). Comparison with the 6-hour interval outdoor data for temperature (black), relative humidity (black), sunshine duration (orange) and quantity of rainfall (blue) and after application of a 7-day moving average. Summer periods are marked in grey. Remarkable peak correspondences between outdoor and indoor data are marked with arrows. [Color print requested]

3.3. High-frequency fluctuations

The remaining high-frequency fluctuations are sudden changes that occur in a matter of hours. Fig. 5 gives an overview of the raw data from which the seasonal trend and mid-frequency fluctuations have been subtracted. The remaining signal is more constant but clearly shows high frequency fluctuations. The temperature and relative humidity fluctuations are characterized by a standard deviation of 0.7 and 2, respectively. The high-frequency fluctuations are clearly lower in height during the summer periods.

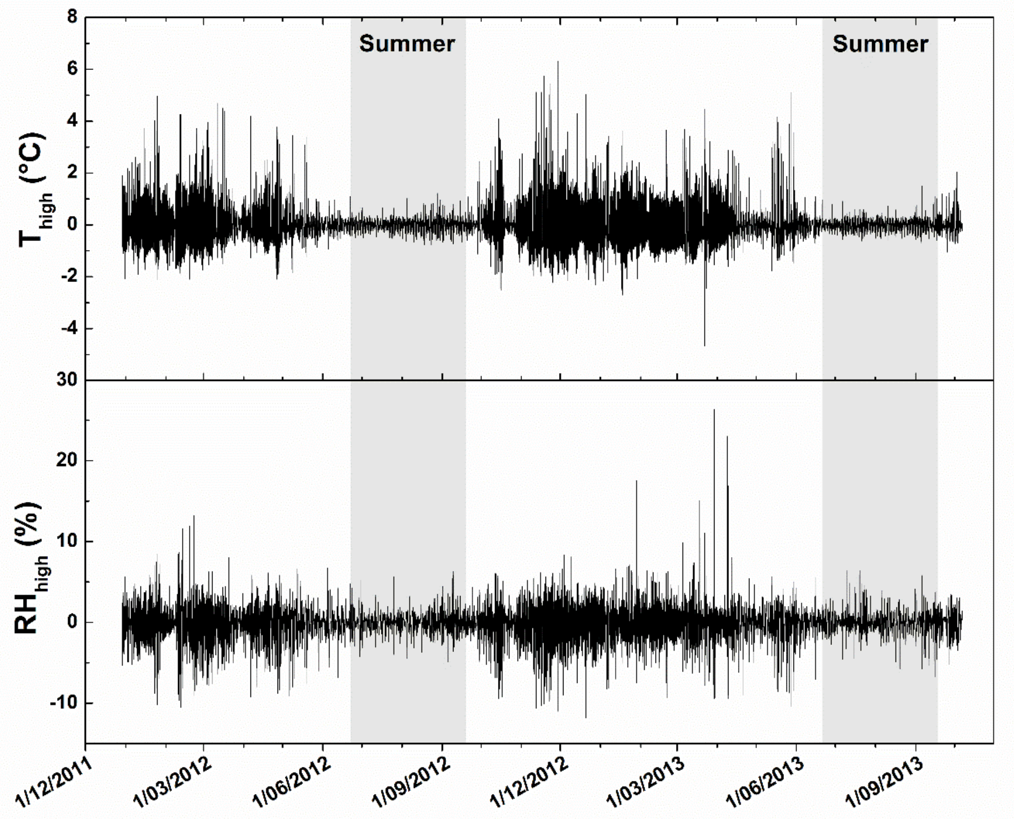

Fig. 5: Overview of the dataset of temperature and relative humidity from 13/12/2011 till 20/10/2013 from which the seasonal trends and mid-frequency fluctuations have been subtracted (T_{high} and RH_{high}). Grey filled areas mark the summer periods.

In order to identify the hazards of the high-frequency fluctuations, a 7 day detail of the dataset has been selected from Fig. 5, one in winter and one in summer (Fig. 6). In the winter periods, a fast fluctuating signal appears for both temperature and relative humidity. In the summer periods, the pattern is totally different. Both periods are discussed below:

- **Winter period:** A fast fluctuating signal appears for both temperature and relative humidity. This is related to the fast response of the climate control installation in order to maintain the chapel's temperature at 18°C. The RH shows a reverse fast fluctuating pattern. At several moments, the chapel's temperature is deliberately increased to around 21-23°C for a public event, for periods of around 3 hours. This results in a clear decrease in RH with ca. 10% in the same 3-hour period. After the event, the indoor temperature is cooled down again to 18°C. The cooling is expected to be a result from the mixture of warm indoor air with cold outdoor air, while the heating system is temporarily switched off. With a constant amount of moisture in the air, the relative humidity increases when temperature drops, with even an overcompensation in RH.
- **Summer period:** A high-frequency cycle in temperature and relative humidity can be noticed with peak-to-peak values that are clearly smaller than those in winter period. In the one-week period shown, 7 day-night cycles for temperature can be noticed. For relative humidity, more peaks are present. Some of these peaks are clearly anti-correlated with the temperature peaks, while others are correlated, or show a totally different pattern. This means that the RH-peaks

are not completely governed by day-night cycles but are also influenced by weather changes or events in the chapel.

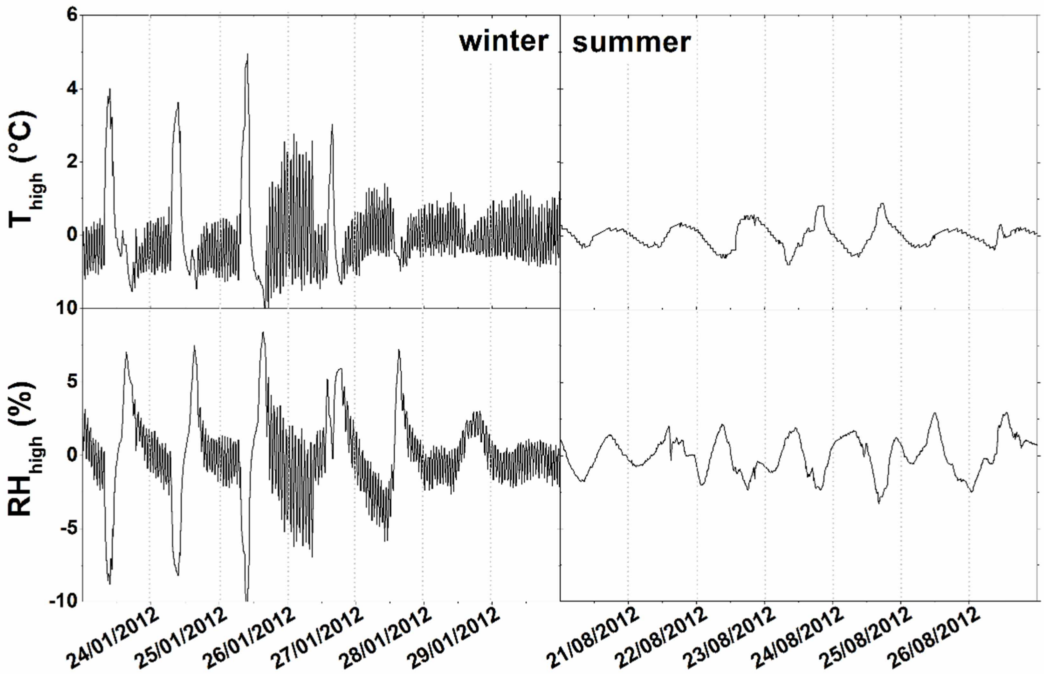

Fig. 6: Details of the graphs in Fig. 5. Winter period from Monday 23/01/2012 till Sunday 29/01/2012 (i.e., 1 week). Summer period from Monday 20/08/2012 until Sunday 27/08/2012.

The highly different behavior in fluctuations with and without heating is clear. To summarize and compare both periods, Table I gives an overview of several statistical characteristics for the three different frequencies. For both the period with and without heating, the average with standard deviation, and the minimum and maximum values in the data sets are given for temperature and relative humidity. For example, consider the relative humidity for the mid-frequency fluctuations. For both the period with and without heating, the average of the data equals 0, since the values fluctuate around this value. The standard deviations are 6 and 4 for the period with and without heating, respectively. The higher standard deviation for the period with heating should be interpreted as a higher instability. The minimum and maximum values indicate the most extreme values in this mid-frequency domain. The range in which the RH fluctuates is remarkable larger in the period with heating (-17.2 to 15.5%) compared to the period without heating (-12.1 to 9.2%).

Many of the chapels furniture is made of hygroscopic materials that are most sensitive to relative humidity fluctuations compared to temperature fluctuations. Therefore, the most remarkable observation from Table I is that for the low-, mid- and high-frequency fluctuations the standard deviation for relative humidity is higher in the periods with heating. This means that the objects exposed in the chapel are exposed to less stable conditions in these periods. The level of risk caused by the different frequency fluctuations is dependent on the objects response time [1]. The results observed for the Antwerp chapel are in agreement with an elaborate study that analyzed the hygrothermal conditions in 30 Estonian churches. Based on average peak to peak amplitudes of the indoor temperature and relative humidity on daily, weekly and monthly level, higher amplitudes were observed in churches with heating compared to churches without heating [28].

		With heating*				Without heating (summer)			
Frequency		*Avg*	*Stdev*	*Min*	*Max*	*Avg*	*Stdev*	*Min*	*Max*
Low	**T**	18.6	0.7	17.6	20.7	22	1	19.6	24.5
	RH	51	7	35.9	64.2	63	2	59.9	67.5
Mid	**T**	0	1	-5.5	3.1	0	1	-2.1	3.6
	RH	0	6	-17.2	15.5	0	4	-12.1	9.2
High	**T**	0	1	-4.7	6.3	0	0.2	-0.8	1.5
	RH	0	2	-11.8	26.5	0	1	-6.8	6.9

** All data except of summer data (21/06 until 20/09) were considered.*

Table I: Comparison between periods with and without heating, for the low-, mid- and high-frequency fluctuations. Used abbreviations: Avg – average, Stdev – standard deviation, Min – minimum, Max – maximum.

4. Discussion

The temperature and relative humidity graphs can be read as a complex superposition of responses to a large series of hazards. The fluctuations are reflected as peaks and drops in the graphs, and are considered as undesired situations because they are associated with well-defined periods of elevated risk. The identification of the (individual) hazards that are responsible for the fluctuations is facilitated when the fluctuations of different frequency ranges are isolated. The low-frequency fluctuations are disturbances that take place in a period of months; the mid-frequency fluctuations typically take place in a period of days to weeks, while the high-frequency fluctuations take place within hours. The case study clearly shows the presence of large mid- and high frequency changes in RH of more than 20%. Such fast and strong changes could affect the wooden objects in the chapel [45, 46].

When performing climate assessments, it is important to consider the impact of fluctuations on the overall climatic conditions. Some peaks or drops only cover a negligible fraction of the total measured period. This could result in overlooking or neglecting these periods during data processing as suggested by some (averaging) indexes. Moreover, one should keep in mind that rarely occurring hazards might fall outside the measuring period and will not contribute to the apparent indoor environmental quality. In addition, fluctuations are not only observed for temperature and relative humidity but for all environmental parameters [47]. With monitoring campaigns that consider only temperature and humidity such as performed in the discussed case study, many fluctuations remain invisible although they might contribute to the total harm of the collection. The invisible fluctuations could also lead to an overestimation of the indoor air quality.

The level of risk of the fluctuations on a heritage collection can be estimated from the height of the peaks and drops. That idea is considered in the approach of standard EN15757:2010 where the tops and bottoms of the most risky fluctuations do not fit in the bandwidth of acceptable fluctuations. By comparing that height with warning and alarm lines as defined by some standards, the peaks can be classified as dangerous occurrences (i.e., below the warning line), events (i.e., between the warning and alarm line) or incidents (i.e., passing the alarm line) [47].

The level of risk of the fluctuations is also determined by the time-scale or the width of the fluctuations. Depending on the objects response time, certain frequency fluctuations will be worse compared to others. The low frequency fluctuations are often slow enough to allow stress relaxation in the objects [1, 48]. For that reason they are not considered as an important risk. This is also reflected in standard EN15757:2010. The mid-frequency fluctuations should be considered as dangerous for objects with response times in the range of days to weeks, such as a wooden cupboard with open doors that has a response time of around 6 days [27]. High-frequency fluctuations could be a considerable risk for objects with a fast response time, such as a sheet of paper which reacts in the order of minutes [27].

Hazards can reoccur in future with a possible higher level of risk. Therefore, it is advised to perform mitigation actions to avoid or reduce the identified hazards to occur in future, and, as such, reduce the level or risk to which the heritage collections will be exposed. Thus, the identification of undesirable situations contains valuable information for preventive conservation and should not be neglected, even when they did not cause any noticeable harm so far.

The case study illustrates that the implementation of mitigation actions can induce new hazards. Several years ago, the installation of an HVAC-system was common sense in the heritage sector. However, such systems are energy consuming, require a good management and maintenance, and are not always reliable due to technical failures. In churches and chapels, heating installations are often installed from the visitor’s thermal comfort rather than from a conservation point of view. The current case study shows that a high temperature set point requires heating during almost 8-9 months a year. Since humidification seems to fail, this induces low RH values, certainly in winter when the outdoor temperature is low. Since the heating installation does not switch on during warm summer days, the summer indoor RH reaches elevated values, since it follows the outdoor RH. The fluctuations for all frequencies are more pronounced during the periods with heating. Thus, the heating installation induces more unstable RH-conditions.

5. Conclusion

Several methods that analyze the indoor climate quality are based on the calculation of the percentage of time the environmental parameters fall within a specific range. Such methods are popular because they enable easy and fast climatic quality assessments. For heritage collections, this method must be used with caution because the damage on heritage collections can be dominated by brief moments of inappropriate conditions. An example of such moments are the severe drops in RH for a period of about 14 days seen in the case study, which can have a major contribution to the total accumulated damage of the furniture. Therefore, climatic quality evaluation based on averages or overall indexes could underestimate the risk of damage. Moreover, these methods provide little practical guidance in the decision making to improve the preservation conditions.

We proposed an alternative and complementary approach to analyze climatic conditions by focusing on peaks and drops in environmental data graphs. Such graphs are often the result of a high number of superimposed fluctuations due to a complex combination of hazards. This impedes easy hazard identification. Therefore, we introduced a method to isolate low-, mid-, and high-frequency fluctuations. The isolation of the different frequencies is not perfect but the interference is sufficiently small. The proposed data processing gives insights in the hazards that cause the fluctuations, the moments these hazards occur, and the level of risk they provoke. Such information is particularly valuable when the heritage guardian must decide whether mitigation actions are needed, which action must be implemented first, and when the implementation of mitigation actions needs to be planned. Therefore, the proposed method supports decision-making.

We applied the developed method on a case study of a chapel with an HVAC-climate control system. Monitored data of temperature and relative humidity of a 22 month sampling campaign were used. First, the low-frequency fluctuations related to seasonal variations were isolated from the raw data. They have a substantial effect on the trends in the graphs due to their high amplitude. Most standards do not consider seasonal fluctuations as harmful for heritage objects. Subsequently, the mid-frequency fluctuations were isolated, giving insights in fluctuations with a duration of days to weeks. From this frequency range, it became clear that the humidifier module of the HVAC system was not working properly, resulting in severe drops in relative humidity during outdoor freezing periods. Finally, high-frequency fluctuations (matter of hours) were studied. A clear difference was noticed between periods with and without the HVAC-system working. The risk towards high- and mid-frequency fluctuations depends on the response time of the objects. However, the mid-frequency fluctuations should be considered as the ones with the highest risk to cause damage to the moisture-sensitive heritage objects inside the chapel. It can be concluded that the installation of an HVAC system should not only be considered as a solution that improves the preservation conditions but also introduces new risks due to machine failure, inability to stabilize climatic conditions or to improper maintenance. These hazards need to be considered as well when invasive renovations are planned. Finally, many of these hazards generate sudden changes in the environmental conditions, which can be seen as well-defined moments in the mid- and high-frequency fluctuations.

Acknowlegdements

The authors acknowledge the financial support of the Belgian Federal Public Planning Service Science Policy (BELSPO) under project number BR/132/A6/AIRCHECQ. The authors thank the people that provided logistic support at the measurement location, in particular Sarah De Smedt.

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Highlights

- Stable climate conditions are recommended for heritage preservation.
- We developed a methodology that focuses on peaks and drops in climate data.
- We isolate low-, mid-, and high-frequency fluctuations to simplify hazard identification.
- This supports the selection of mitigation actions that improve conservation conditions.
- We demonstrate the method on data of a 22 month monitoring campaign in a chapel.