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MICROCLIMATE ANALYSIS OF TWO HISTORIC CHURCHES IN LUBLIN – OPTIMAL HYGROTHERMAL CONDITIONS FOR PRESERVATION OF CULTURAL HERITAGE

Ewelina FLIS-OLSZEWSKA[1,*]

[1] University of Life Sciences in Lublin, Department of Specific Plant Cultivation, Laboratory of Agrometeorology, 13 Akademicka Street, 20-950 Lublin, Poland

Abstract

This study concerns the microclimatic conditions in two historic churches of the temperate climatic zone located in Lublin, Poland: Lublin Cathedral and Post-Bridgettines Church, having regard to their underground crypts. The measurements of the air temperature and RH lasted all 2016 and were compared with optimal heritage protection values included, inter alia, in American instruction ASHRAE Handbook. Furthermore, for both buildings the historic climate was calculated, based on the European Standard EN 15757:2010, and the target ranges were specified.

Keywords: *Microclimate; Historic indoor climate; Heritage building; Cultural heritage; Church; Preservation of cultural property*

Introduction

Historic religious buildings are an important element of the world's material heritage. In most cases these buildings not only provide a source of knowledge about earlier historical epochs and tourist attractions, but also continue to function as houses of worship. Churches are extremely varied in terms of size, construction materials, and the number of people who visit them, which affects the microclimate inside them [1]. Different temperature and humidity conditions are found in small wooden churches [2], large brick churches [3, 4] and churches built of a combination of materials, such as wood and stone [5, 6]. In most cases, the presence of people causes significant short-term changes in interior conditions, particularly increases in air temperature and relative humidity [7-9], while the presence and type of heating systems accelerates the decrease in humidity and the increase in temperature [10-12]. The effects of outdoor conditions on the conditions inside the building must also be taken into account [13, 14]. In some cases, churches have underground crypts, which usually have a lower air temperature and high humidity, often exceeding 90% [15-17].

The high variability of microclimate conditions in churches can pose a threat to their construction and to the historic details of the interior, such as wooden altars, frescoes, or stained glass. Studies of the microclimate of religious buildings are increasingly carried out to compare current conditions with optimal values, as part of the process of conserving cultural heritage. Sometimes optimal conditions are determined using specific threshold values for a given climate zone, but in some cases recently developed official standards are used, such as European Standard EN 15757 [18, 19] and 15758 [20] or the American ASHRAE Handbook

* Corresponding author: ewelina.flis-olszewska@up.lublin.pl

[21, 22]. The present study, with the aim of conserving historic buildings, analysed the microclimatic conditions of two historic churches in the temperate climate zone, located in the city of Lublin in eastern Poland, in 2016.

Experimental part

Materials

Measurements of temperature and humidity were made in two churches in Lublin. The first, the Church of the Assumption of the Victorious Virgin Mary, known as the Post-Bridgettines Church (Fig. 1A), was built in the years 1412–1426. It has been rebuilt and renovated many times. Its current shape dates back to between 1430 and 1450. After 1530 the earlier presbytery vault was changed from a rib vault (visible only in the garret) to a barrel vault with lunettes with stucco decorations and paintings. The church combines two styles, Gothic and Lublin Renaissance, but also contains elements from other historical periods. The most important interior details include fragments of Gothic polychrome from 1430 and 1460–1470, a 15th-century painting of St. Bridget of Sweden, the 17th-century presbytery vault, a series of seventeen 17th-century paintings representing the life of St. Bridget, and the Gothic Revival wooden side altar.

Archaeological works in 2011 led to the discovery of eight crypts under the church, two of which were restored and opened for visitors. Their entrance is located in the floor in the middle of the nave, by the side pulpit. Over the hundreds of years of existence of the building, the ground surrounding the church has risen, leading to a significant, gradual deterioration of the natural ventilation of the underground part. For a long time, the walls of the crypts and their vaults were constantly damp.

Fig. 1. A: Church of the Assumption of the Victorious Virgin Mary (Post-Bridgettines Church); B: Metropolitan Cathedral of St. John the Baptist and John the Evangelist (Lublin Cathedral)

The second building analysed was the Metropolitan Cathedral of St. John the Baptist and John the Evangelist, known as the Lublin Cathedral (Fig. 1B). Its construction was begun in 1586 but was not completed until the 17th century. At that time, it was one of the largest churches in Poland. The cathedral was destroyed several times by fire, including in 1752, and also as a result of military hostilities, and did not acquire its present outer appearance until the 19th century. The interior mainly reveals baroque features with arched vaults with lunettes and several Renaissance details. The most important historic elements include a 14th-century baptismal font, the Tribunal Cross dating from the turn of the 17th century, the 17th-century wooden main altar, and 18th-century frescoes by Józef Meyer.

A general renovation of the Lublin Cathedral was begun in 1999, including the crypts underneath it (dating to the 16th century), which were opened to visitors. The crypts consist of three connected rooms and contain sarcophagi with the bodies of monks and individuals associated with the church.

Both churches are located in the centre of Lublin at similar altitudes: the Lublin Cathedral at 195 m above sea level, and the Post-Bridgettines Church at 197m. They are 450m apart in a straight line. The main entrance to the Cathedral is at its west end, while the entrance to the Post-Bridgettines Church faces north-west.

Methods

In each of the churches two measurement points were selected at similar locations – one near the main altar (Fig. 2) at the end of the nave and one in the underground crypts (Fig. 3). Air temperature and relative humidity (RH) were measured at 10-minute intervals using HOBO U23-001 Data Loggers in accordance with European standards EN 15757 and EN 15758 regarding the conservation of cultural property (from −40°C to +70°C and from 0% to 100% RH, resolution 0.04°C and 0.05% RH, accuracy ±0.2°C and ±2.5% RH). The data loggers were placed in shaded locations for 24 hours a day. Data obtained during the entire year of 2016 were used to analyse the magnitude of hour-to-hour changes in air temperature and relative humidity, compare current conditions with the range of optimal values, and determine the 'historical climate' of the buildings. The temperature and humidity values referred to in the paper, reflecting the weather conditions in Lublin in 2016, were obtained from the meteorological observatory in Litewski Square, located in the centre of the city less than 300 m from the Post-Bridgettines Church and less than 600m from the Lublin Cathedral.

The concept of optimal climate conditions in historic churches is not clear-cut. Threshold values adopted in the literature vary depending on the climate zone and type of building. In a church in Lisbon the optimal range of relative humidity values was taken to be 49.2–80.6%, with an air temperature range of 12.4–25.7°C [23], while in a Polish church in Frydman the most favourable conditions are considered to be temperature below 19°C and relative humidity below 70% [24]. *T. Cardinale et al.* [26], based on an analysis of the literature, suggest that the temperature in churches should generally range from 16 to 22°C, and relative humidity from 45to 55%. One of the sources specifying optimal values for temperature and relative humidity for the interior of museums, galleries, and libraries is the ASHRAE (American Society of Heating, Refrigeration and Air Conditioning Engineers) Handbook. Several classes of buildings are distinguished, with maximum temperature and humidity fluctuations specified for each class. In most cases, churches are assigned to class B, i.e. rooms with low or moderate risk of mechanical destruction. This class is intended especially for buildings located in a cool climate. The air temperature in class B buildings should be within the range of 15–25°C, with relative humidity of 40–60% [26, 27]. The ASHRAE handbook also gives the maximum temperature and humidity fluctuations within a day and from hour to hour, which should not exceed 5°C and 10% RH [28], but studies on the microclimate of churches adopt limits amounting to less than half of those values. According to *H.L. Schellen* [29], relative humidity in historic religious buildings should not vary more than 5% from hour to hour, while according to *J. Karaś* [30], changes in air temperature should not exceed 1.5 or 0.5°C in highly sensitive interiors.

In this study, based on the results of previous research in historic churches, 15–25°C was adopted as the optimal temperature range (in accordance with the ASHRAE Handbook), while optimal relative humidity was assumed to be above 40% (according to ASHRAE) and below

70% (the typical upper limit for churches in the temperate climate zone). The frequency of such optimal conditions was determined only for the points by the altars, which best represent the microclimate of the churches; in the crypts, due to their underground location and specific climate conditions, this parameter was not assessed. In addition, both for the points near the altars and in the crypts, the analysis took into account two variants of hour-to-hour changes in air temperature, above 1.5°C and above 0.5°C, and changes in relative humidity above 5%.

Fig. 2. Measurement points by the altars in: A: the Post-Bridgettines Church; B: the Lublin Cathedral

Fig. 3. Measurement points in the crypts in: A: the Post-Bridgettines Church; B: the Lublin Cathedral

Based on the latest research on the microclimate of historic buildings, a 'historical climate' was specified for all measurement points, reflecting the conditions in which the building has remained for a long period (at least a year) and to which it has become acclimated (UE Standard EN15757: 2010). This can be determined for both unheated buildings and those already equipped with heating systems [31]. The measurement period based on which the historical climate is determined should be a full year, or at least one summer, and the intervals between measurements should not exceed one hour. As the churches analysed in this study have had interior heating systems without interruption for many years (floor heating in the Cathedral and air heating in the Post-Bridgettines Church), the calculations were made for a full calendar year, including the heating season, which is an integral element of the interior microclimate.

Determination of the target values of the historical climate of a given building requires previous determination of the average air temperature or relative humidity in a given period (in this case a single year), the seasonal cycle, and short-term fluctuations. The seasonal cycle is based on calculation of the 30-day central moving average (MA) for each reading, which smooths the short-term fluctuations and thus reveals long-term changes. To calculate MA for a full calendar year, the measurements must be extended by an additional 30 days (15 days before and 15 days after the selected period). The next step is to calculate short-term fluctuations, i.e. the difference between the 30-day moving average and the current reading of a given feature. Short-term fluctuations are the basis for determining the target range; its upper and lower limits are defined by the 7th and 93rd percentile, respectively, of all measurements, so that the most extreme 14% of values are excluded. When the target values of the fluctuations differ only slightly from the seasonal cycle, a fluctuation threshold of 10% is acceptable in the case of relative humidity and 5°C in the case of temperature, if this does not pose a threat to the materials inside the building. This was not done in the present study, in which the target values directly resulting from the calculations were used even if they were small.

Results and discussion

Optimal microclimatic conditions in churches

The frequency of hour-to-hour changes in temperature (0.5 and 1.5°C) and relative humidity (5% RH) in the churches was determined in 2016. The temperature in the interior of the buildings did not show substantial hour-to-hour variation (Table 1): changes above 0.5°C accounted for less than 3% of all cases in the Post-Bridgettines Church (less than 250 single cases) and 0.5% in the Cathedral (30 cases). Greater temperature changes, above 1.5°C in the course of an hour, were not recorded in the Cathedral during the entire year of 2016, while in the Post-Bridgettines Church they accounted for only 0.1% of all cases.

High hour-to-hour variations in relative humidity (above 5%) were recorded only occasionally, accounting for just 0.4% of all cases in both the Post-Bridgettines Church and the Cathedral.

Table 1. Frequency of cases of hour-to-hour changes in air temperature and relative humidity in 2016 at the points by the altars in the Post-Bridgettines Church and the Cathedral

	Hour-to-hour changes	**Post-Bridgettines Church**	**Lublin Cathedral**
Air temperature	> 0.5°C	2.8 %	0.5 %
	> 1.5°C	0.1 %	0.0 %
RH (%)	> 5.0	0.4	0.4

Optimal values for temperature and relative humidity for the interiors of the churches were specified based on the literature, and their frequency in 2016 was determined. As the churches are located in the temperate zone, these ranges were 15–25°C for temperature and 40–70% for relative humidity.

The graphs (Fig. 4) illustrate all 10-minute temperature and humidity measurements taken by the altars in 2016, represented by points. Horizontal and vertical lines represent threshold values of optimal temperature and relative humidity, and the light grey area represents measurements outside the range of acceptable conditions. In the Post-Bridgettines Church optimal temperature conditions were present in slightly over half of cases (55.5% of all 10-minute measurements); the other readings showed temperatures that were too low, i.e. below

15°C. The situation was less favourable in the case of relative humidity, as only 21.5% of all measurements were within the range of optimal values; the remaining values indicated excessive relative humidity.

Conditions were somewhat different in the Lublin Cathedral – all of the results for temperature were within the optimum range. Similarly, only 0.5% of all measurements of relative humidity were outside the optimal range; in these cases, relative humidity was too high (above 70% RH).

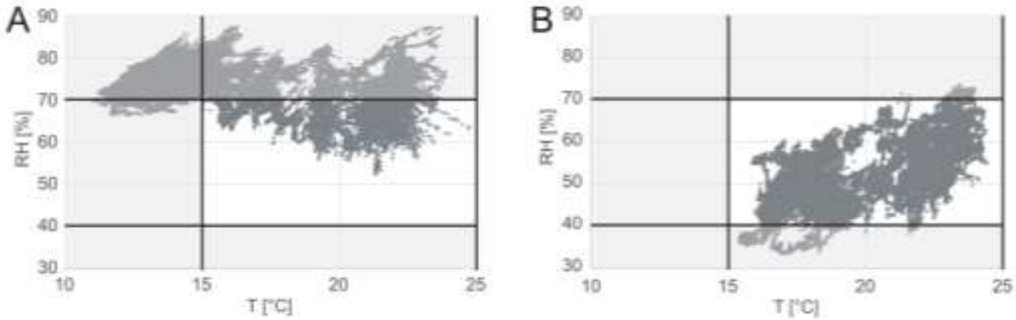

Fig. 4. Distribution of 10-minute temperature and relative humidity values at the points by the altars in the Post-Bridgettines Church (A) and Lublin Cathedral (B) in 2016, with optimal values indicated

Based on the optimal values chosen for historic interiors, the temperature and humidity in the Cathedral can be regarded as nearly ideal, whereas the microclimate in the Post-Bridgettines Church diverges significantly from the optimal conditions. It should be borne in mind, however, that the same acceptable values were adopted for both churches, based on the literature and the international ASHRAE Handbook, but the two churches differ in their construction (different shape and volume) and in the heating systems used for many years. Adjusting the conditions in the Post-Bridgettines Church to align with the conditions adopted as optimal, i.e. temperature 15–25°C and relative humidity 40–70%, currently accounting for a distinct minority of cases, would entail radical changes, which would expose the interior to significant stress. Therefore, the historical climate, described above, was determined for both churches.

Historical climate in the churches

In 2016 the average air temperature in Lublin was 9.7°C. The warmest month was July (20.1°C), and the coldest was January (−3.6°C). The average annual relative humidity was 72.4%, the highest monthly average was in December (90%), and the lowest was in June (57.4%). Compared to the long-term average (1951–2010), the year 2016 in Lublin was 1.4°C warmer and about 5% less humid. In the Post-Bridgettines Church the average air temperature by the altar was 16.7°C and relative humidity was 73.1%, while the corresponding values in the Lublin Cathedral were 19.4 and 51.4%.

The actual air temperature in the Post-Bridgettines Church at the point by the altar ranged from 11.0 to 24.7°C during the measurement period, while the range for the 30-day moving average (MA) was narrowed to values from 12.2°C in January to 22°C in July (Fig. 5A), on average 16.6°C. In the Cathedral, the temperature readings by the altar did not fall below 15.4°C and did not exceed 24.4°C, while the seasonal cycle ranged from 15.4°C in December to 23.2°C in August, on average 19.3°C. Short-term temperature fluctuations (Fig. 5B) in the Post-Bridgettines Church ranged from −1.7 to 4.0°C, while in the Cathedral the deviation from the MA was somewhat larger, from −2.4 to 4.1°C. After the 7th and 93rd percentiles were determined, the optimal ranges of fluctuations were obtained: −0.9/+0.9°C in the Post-Bridgettines Church and −1.5/+1.9°C in the Cathedral. They indicate that the deviations of the actual values from the MA are several times larger than they should be. The graph in figure 5C presents the full range of acceptable values in relation to the ongoing readings in 2016. This range (dotted lines) was obtained by adding or subtracting the optimal range of fluctuations calculated in the previous step from the seasonal cycle values (black line) for each of the churches. Analysis of the upper and lower limits for temperature in the Post-Bridgettines Church shows that it should not fall below 11.3 or exceed 23.3°C, while in the Cathedral it should remain between 13.9 and 25.1°C. In both churches there were cases in which the actual temperature was below the specified lower limit, which means that such large drops in temperature should be avoided. In contrast, in the Post-Bridgettines Church the temperature sometimes exceeded the upper limit, so according to the historical climate its increase during the summer should be discouraged. In the Cathedral, the highest temperatures are not a problem, because the upper limit was above the values of the readings for nearly the entire year.

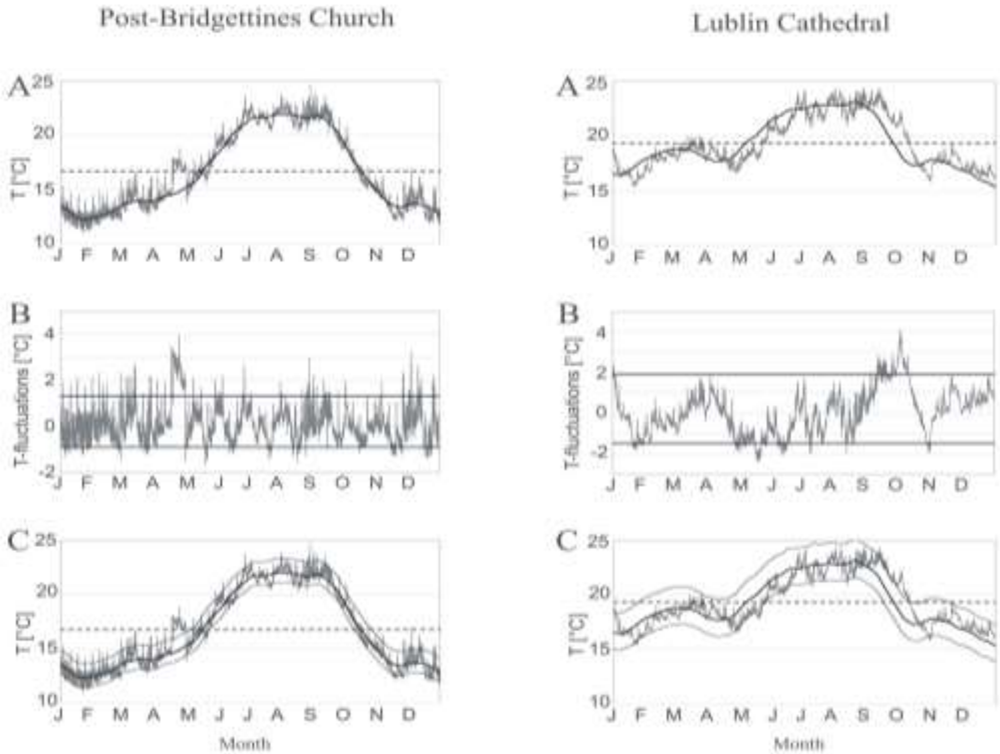

Fig. 5. A: Indoor 10-minute air temperature (grey line) near the altar, seasonal cycle (black line) and annual average (horizontal black dashed line) in 2016; B: Short-term fluctuations of air temperature around the seasonal cycle with lower and upper limits as 7th and 93rd percentiles (black lines); C: Target air temperature level and range (black dotted lines)

In the Post-Bridgettines Church the actual relative humidity was generally higher (52–87% in 2016) than in the Cathedral (33–73%), which significantly influenced the ultimate range of values for the historical climate of the buildings. The relative humidity MA at the point by the altar in the Post-Bridgettines Church ranged from 65.9% in September to 77.9% in April (on average 73.1%), while in the Lublin Cathedral the values ranged from 40% in January to 60.9 in July (on average 51.5%) (Fig. 6A). Short-term fluctuations in relative humidity were similar in the two buildings, ranging from −18.1 to 14.3% in the Post-Bridgettines Church and from −21.0 to 15.2% in the Cathedral. The optimum range of fluctuations (Fig. 6B), after removing the 14% most extreme values, was −5.5/+5.6% in the Post-Bridgettines Church and −7.0/+7.1% in the Cathedral. As in the case of temperature, the range of short-term fluctuations should be approximately half of the actual values.

On the graph in Figure 6C, dotted lines represent the upper and lower limit of acceptable relative humidity for both churches based on actual data from 2016. In the Cathedral, relative humidity can fall to even 33% without posing any risk, while in the Post-Bridgettines Church it should not be lower than 60.4%. With regard to the highest values, humidity should not exceed 68% in the Cathedral, while in the Post-Bridgettines Church it can be as high as 83.5%. It can be seen that the ranges of values in both churches barely overlap at all (the acceptable maximum in the Cathedral is close to the minimum in the Post-Bridgettines Church), in contrast to the optimal temperature range, which is similar in the two churches (although the threshold values in the Lublin Cathedral are about 2°C higher than in the other building).

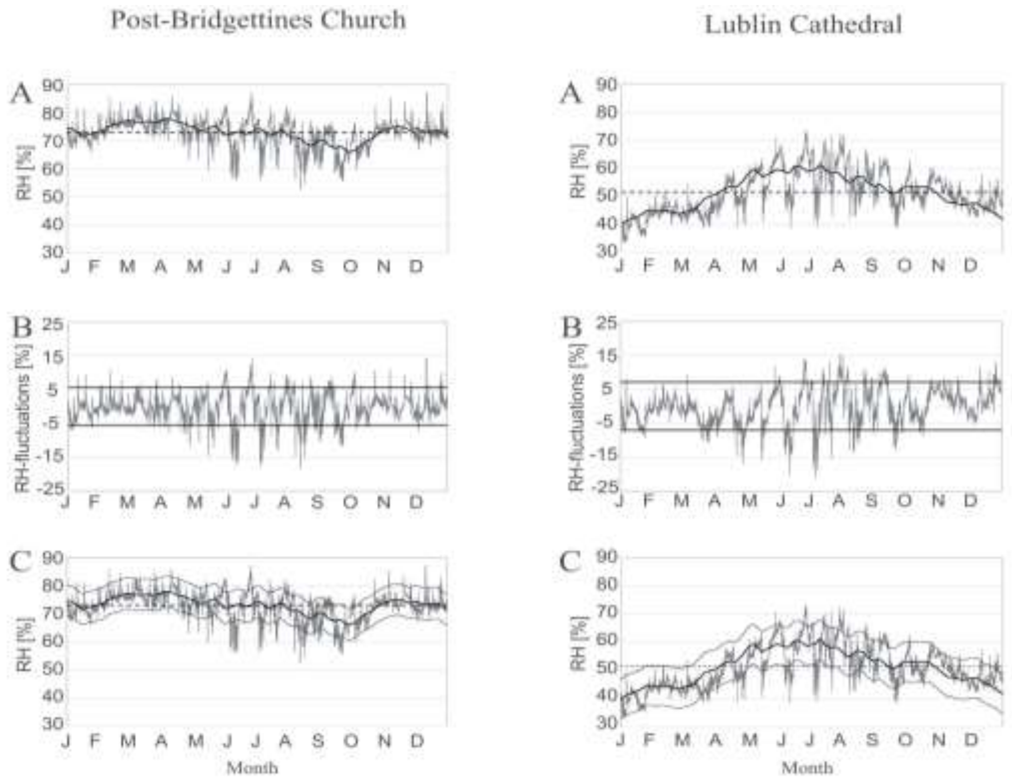

Fig. 6. A: Indoor 10-minute RH near the altar (grey line), seasonal cycle (black line), and annual average (horizontal black dashed line) in 2016; B: Short-term fluctuations of RH around the seasonal cycle with lower and upper limits as 7th and 93rd percentiles (black lines); C: Target RH level and range (black dotted lines)

Conditions and historical climate in the crypts

Temperature and humidity in the crypts of the Post-Bridgettines Church were much more varied than in the crypts in the Cathedral; nevertheless, the changes in the values were relatively slow and were not perceptible in hour-to-hour intervals. In the crypts of the Post-Bridgettines Church in 2016 there were only 18 cases of an increase or decrease in temperature amounting to more than 0.5°C and a few cases of variation greater than 1.5°C. In the crypts in the Cathedral this did not occur at any time during the study period. In addition, no changes in relative humidity greater than 5% in the course of an hour were noted in the crypts of either building.

The ranges of actual temperature values were similar in the crypts of the two buildings. The seasonal cycle values in the crypts of the Post-Bridgettines Church ranged from 12.8°C in

February to 20.5°C in August, while in the Cathedral crypts the MA ranged from 11.6°C in December to 19.6°C in August (Fig. 7A). The graph in Figure 7B presents the upper and lower limits of acceptable temperature deviations from the MA in both locations. In the crypts of the Cathedral the range of optimal values is more narrow (−1.0/+1.8°C) than in the other building (−1.5/+2.0°C). Comparison of the limits with actual values shows that the temperature in the crypts should range from 11.9°C to 21.4°C in the Post-Bridgettines Church and from 10.8°C to 20.8°C in the Cathedral (Fig. 7C).

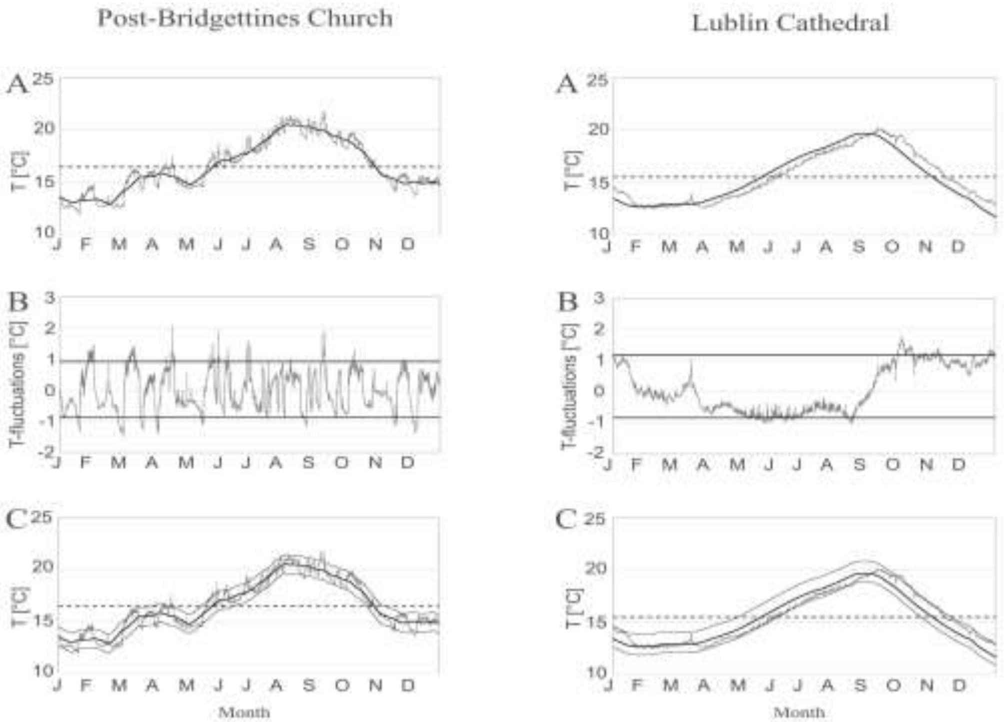

Fig. 7.A. Indoor 10-minute air temperature (grey line), seasonal cycle (black line), and annual average (horizontal black dashed line) in the crypts in 2016; B. Short-term fluctuations of air temperature around the seasonal cycle with lower and upper limits as 7th and 93rd percentiles (black lines); C. Air temperature target level and range (black dotted lines)

Relative humidity measured in the crypts in the Post-Bridgettines Church showed a much wider range than in the Cathedral. In the crypts of both churches the maximum relative humidity exceeded 90% on many occasions, while its minimum values fell to 72% in the Cathedral and even to 57% in the Post-Bridgettines Church (Fig. 8A). These differences could also be seen when the historical climate of the underground rooms was determined.

The values for the seasonal cycle in the crypts of the Post-Bridgettines Church ranged from 65.2% in December to 88.7% in August, while in the crypts of the Cathedral it ranged from 73.1% in December to 90.1% in August. The optimal range of fluctuations in the case of relative humidity, due to the differences in actual values, is highly varied: in the crypts in the Post-Bridgettines Church the deviations from the MA should be within a range of −13.3/+12.4%, while in the crypts in the Cathedral the range should be half of that size, i.e. −6.1/+7.6% (Fig. 8B). The target range of relative humidity in the crypts is from 56.8% to 95.7% in the case of the Post-Bridgettines Church and from 70.4% to 94% for the Cathedral (Fig. 8C).

The defined acceptable values indicate that the crypts in the Post-Bridgettines Church, which have a smaller area, are naturally subject to greater fluctuations in microclimate conditions, especially humidity, and that they have become acclimated to these conditions.

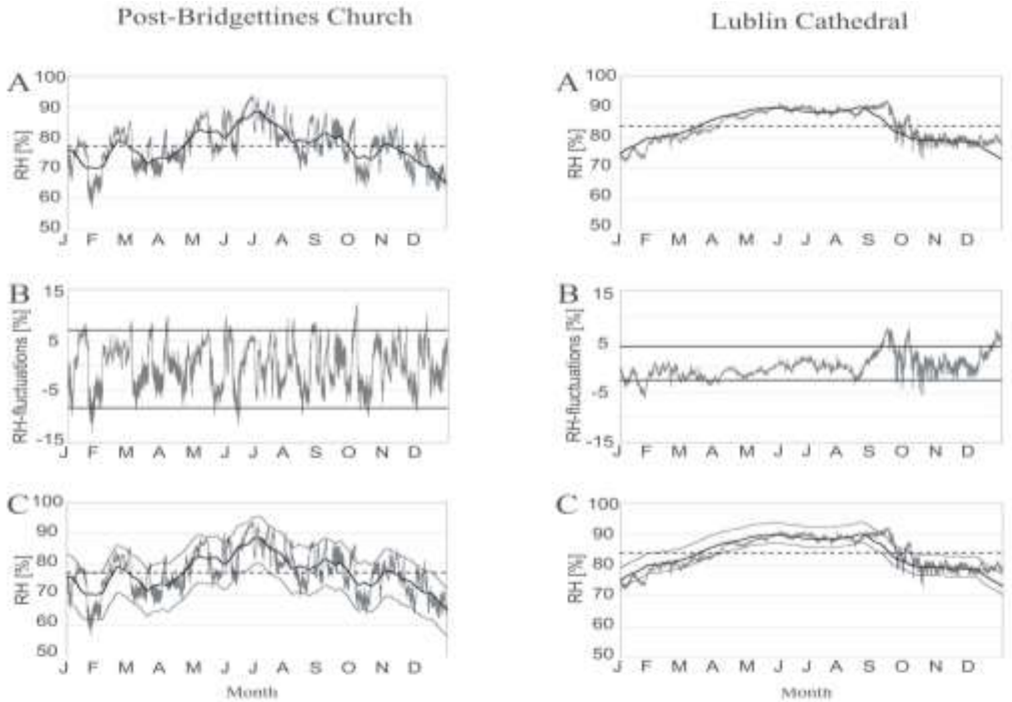

Fig. 8. A: Indoor 10-minute RH (grey line), seasonal cycle (black line) and annual average (horizontal black dashed line) in the crypts in 2016; B: Short-term fluctuations of RH around the seasonal cycle with lower and upper limits as 7th and 93rd percentiles (black lines); C: Target RH level and range (black dotted lines)

Therefore, there is no need to introduce any major restrictions in them. The crypts in the Cathedral, with an area twice as large and located under a larger building, far from the main entrance, are less exposed to the influx of air from outside, and the fluctuations in temperature and humidity in them are much smaller. This narrows the range of optimum values.

Conclusions

Analysis of the microclimate conditions of the two historic churches in Lublin based on measurements made in 2016 indicates that limits of acceptable temperature and humidity established in the process of conservation of cultural heritage for a given climate zone are not appropriate for every building. Due to differences in construction, the number of people inside, and the activity and type of heating system, each historic building should be considered individually. The buildings analysed in this study are located in the temperate climate zone, and therefore, on the basis of the literature and the ASHRAE Handbook, the optimal values adopted were air temperature between 15 and 25°C and relative humidity between 40% and 70%. In the case of the Lublin Cathedral, nearly all readings were within the acceptable range, but in the Post-Bridgettines Church such cases accounted for only slightly more than half, primarily due to excessive humidity. The historical climate of each church, reflecting the conditions to which the building is acclimated, was determined according to European standard EN 15757:2010. In the Lublin Cathedral, the acceptable values based on the historical climate closely overlapped with the optimal values for the climate zone, especially in the case of air temperature, amounting to 13.9–25.1°C and 33–68% RH. In the Post-Bridgettines Church, the maximum target ranges were 11.3–23.3°C and 60.4–83.5% RH. The historical climate indicates that the Post-Bridgettines Church is adapted to much higher relative humidity than that suggested by the limits based on the literature and the ASHRAE Handbook, while the Lublin Cathedral is adapted to much lower values than the previously determined optimal values. As these conditions have prevailed in the two churches for many years, maintaining them at a similar level should not pose a threat to their interiors.

An important factor which may also cause damage to historic elements is high hour-to-hour variations in air temperature (above 0.5°C or 1.5°C) and relative humidity (above 5%). In the locations by the altars in the churches analysed in this study, such variation occurred only occasionally, accounting for less than 3% of cases in the Post-Bridgettines Church. Such situations barely occurred at all in the crypts of either building, and only in the case of changes in temperature.

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