# INFLUENCE OF SPECIAL REPORT ON EMISSIONS SCENARIOS AND THE REPRESENTATIVE CONCENTRATION PATHWAYS SCENARIOS ON THE PRESERVATION OF CHURCHES WITH A DEFICIENT MICROCLIMATE

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**Abstract:**

Climate change will significantly impact all over the world. Many studies related to architecture have quantified its impact on energy consumption and thermal comfort, among others. However, there are few studies related to heritage preservation that analyse its impact. Given the relation between indoor and outdoor microclimate, this work analyses the influence of climate change on the variation of indoor relative humidity and temperature levels to preserve heritage elements. For this purpose, the changes caused by both the Special Report on Emissions Scenarios (SRES) and the Representative Concentration Pathways (RCP) scenarios in the preservation level of a church with a deficient microclimate in the Mediterranean region were analysed. Monitorings were conducted with an interval of hourly acquisition for a year and neural networks were used to predict future time series (for the years 2050 and 2100). The results showed the significant impact of climate change, particularly with the RCP 8.5 scenario. The zones of high temperatures and relative humidity obtained the greatest percentage of hours in the current scenario. In this sense, 57.45% of the annual hours in the current scenario were grouped in these zones. However, the climate change scenarios obtained the following values in 2100: 67.16% in B1, 75.29% in A1B, 76.48% in A2, 58.93% in RCP 2.6, 68.53% in RCP 4.5 and 81.10% in RCP 8.5. Thus, these results imply not only a greater degradation of heritage elements, but also a change in conservation strategies aimed at optimizing interior microclimates.

**Keywords:**

Climate change, indoor microclimate, prediction, SRES and RCP scenarios, preservation, heritage elements

**Highlights:**

- Analysis of the indoor microclimate of a church in the Mediterranean region
- Impact of climate change on the interior microclimate
- Greater negative impact with the RCP 8.5 scenario
- Prediction of the time series through neural networks

## 1. Introduction

Historic buildings are an essential part of mankind's cultural heritage [1]. Their immense value comes from the architectural characteristics, the designs and materials of structures or envelopes, as well as from the heritage elements in them which are part of the tangible cultural heritage and could disappear if appropriate preservation strategies are not adopted. The literature provides a wide background on studies about preventive conservation and restoration monitoring of religious heritage buildings throughout fuzzy logic [2] and offer guidelines for preventive measurements of artworks in relation with the indoor microclimate [3], [4]. In this sense, previous studies evaluate risk indices based on temperature (T) and relative humidity (RH) conditions (e.g. the performance Index, the biological Risk Index, the equivalent Lifetime Multiplier to evaluate the chemical risk, the Daily Span Index and Spatial Homogeneity Index) that allow the identification of the most probable types of deterioration that could occur to artworks due to inadequate indoor microclimate (i.e. mechanical, biological and chemical damage) [5], [6]. Other work also evaluate the Heritage Microclimate Risk index (HMR) and the Predicted Risk of Damage (PRD) index by analysing the microclimate parameters T and RH [7].

As previously mentioned, one of the main aspects that could influence the preservation of these artworks is the indoor microclimate of buildings [3], with temperature and indoor relative humidity variations being the main factors influencing tangible heritage [4]. Thus, controlling these environmental variables could guarantee appropriate conditions to preserve materials. In this regard, most of the existing heritage elements in historic buildings have been preserved until today without adopting measures in most cases. However, the changes caused by the activity carried out in these buildings in the last century have significantly modified some aspects, such as the high occupancy in these spaces [8], [9], the use of HVAC systems [10], [11], and defects in the envelope [12], which could damage indoor microclimate. The use of HVAC systems could be the most important aspect as they are widely used to guarantee users' thermal comfort and certain values that ensure the artefacts conservation [13], [14]. However, a regulated microclimate to guarantee users' thermal comfort does not imply appropriate conditions to preserve the materials inside buildings. Nevertheless, HVAC systems are very likely to be used as a preservation measure for heritage elements, an aspect included in standards such as EN 15759-1 [15]. Given the high variability showed by the microclimate of the historic built environment in the last century, several studies have analysed the state of various case studies and have established improvement strategies [16]–[18]. These studies vary in terms of monitoring techniques and analysis methodologies, revealing that monitoring techniques allow to determine the state of the indoor microclimate and are appropriate to establish improvement strategies in order to preserve exposed heritage elements.

However, the difficulties to know accurately the indoor microclimate of a building during a long period usually force to conduct short monitoring. Long-term monitoring studies are less common in the literature but it is possible even conduct an indoor microclimate study over 20 years, as it is was demonstrated by Bonacina et al. in the case of the Scrovegni Chapel in Italy [19]. Afterwards, the aspects that should be dealt with by using HVAC systems were determined to keep the indoor microclimate under appropriate conditions. However, the time required to conduct this kind of monitoring makes the analysis of all the built environment of historic buildings something of a challenge. Thus, most studies are based on short monitoring [12] (those that record measures without completing 2/3 annual periods [3] – or estimate environmental conditions through simulations using computational models that are calibrated against measured indoor conditions [16]–[18].

These techniques have allowed improvement strategies to be established not just with HVAC systems. In this regard, several studies have analysed change effectiveness in building envelopes. Cardinale et al. [20] analysed the most appropriate improvements to be made on the Cathedral of Matera (Italy) by combining a floor radiant heating system with the restoration of the cathedral. The results showed that this combination of improvements led to appropriate conditions for both the preservation of historical elements and users' thermal comfort. These improvement strategies could not just be based on effective technologies or designs, since modifying operational patterns could sometimes improve preservation conditions significantly. This aspect was showed by Camuffo et al. [21], who analysed the variations in the microclimate during the religious masses in the church of Rocca Pietore. In this case, the heating system used was switched on only during the liturgical services and generated rapid temperature and humidity changes. The temperature stratification meant a hot and dry air in the upper levels that implied the condensation of the moisture on the cold walls and dangerous crystallization cycles.

Most studies are based on ecclesiastical buildings, but other types of buildings have also been analysed. The works by Torres-González et al. [22], [23] in the Royal Alcázar of Seville (Spain) determined the existing hygrothermal conditions to preserve the plasterwork of the fills in the courtyards. Likewise, some libraries have also been analysed because of the preservation characteristics of paper: the work by Diulio et al. [24], which analysed 11 libraries in La Plata (Argentina), is worth stressing. This work analysed the most important parameters to preserve the elements of these libraries, stressing the importance of both thermal insulation and conditions of adjacent rooms. Andretta et al. [25] assessed the microclimate of the Classense Library of Ravenna in Italy. For this purpose, monitoring was conducted in winter and summer to determine the existing weaknesses to preserve old books in indoor spaces. Likewise, museums containing a great variety of pieces with heritage value have been analysed, such as the works by García-Diego et al. [26], who analysed the Sorolla room of the Pio V Museum of Valencia (Spain) or Sciurpi et al. [27], who analysed the "La Specola" Museum of Florence (Italy). Museum objects, which are pieces with great historical-artistic value, should be under environmental conditions that preserve them throughout the time. For this reason, criteria have been established to regulate lighting, the impact of ultraviolet rays, the ventilation of exhibition spaces, and optimal environmental temperature and relative humidity conditions to preserve the various materials at an European, national and regional level [28]–[30].

All these studies concluded that a remote-control system [31], management [32], [33], and the classification system of the microclimate [34] are essential to achieve users' thermal comfort and to preserve heritage elements. Nevertheless, the impact of climate change on the indoor microclimate has not been widely studied. This is a remarkable aspect because this impact could be very significant in the future to preserve architectural and heritage elements [35] due to the combination of temperature rise, extreme phenomena, and moisture variability [36]. Some studies have analysed extreme phenomena, such as typhoons [37] and sea level rise [38], [39]. Likewise, the impact of climate change on the functional useful life of Chilean buildings was analysed by Prieto et al. [40], [41], who were based on the fuzzy logic methodology to determine how future conditions in cold climates could benefit building useful life. However, the behaviour is expected to be different in warm zones [42], [43].

Recently, Bienvenido-Huertas et al. [44] analysed the variability of the indoor microclimate of buildings located in warm zones considering climate change action. The results showed a progressive degradation. However, the study was limited to one of the first scenarios (A2) developed by the Intergovernmental Panel on Climate Change (IPCC) and included in the Special Report on Emissions Scenarios (SRES) [45]. Likewise, other scenarios were included in the SRES, and then a new group of scenarios was developed through the Representative Concentration Pathways (RCP) [46]. Thus, this variability of scenarios could modify the effects expected by climate change on the indoor microclimate of historic buildings located in warm zones. This variability could be more significant in buildings with a deficient indoor microclimate (i.e., buildings that have inappropriate temperature and relative humidity values in the current scenario to preserve heritage elements). Aspects such as defects in the envelope or bad maintenance imply that the indoor microclimate is very influenced by the variations of the outdoor climate [12]. For this reason, this study analysed the effects expected by the SRES and RCP climate change scenarios on a building with a deficient indoor microclimate in warm region.

The Student's Chapel of the University of Seville (Fig. 1), built in the mid-18th century, was chosen as the case study as its heritage elements present a degradation tendency from the last quarter of the 20th century to nowadays. Some of its main assets of cultural interest have been restored, such as the sculpture of the Christ of the Good Death, which has been restored 4 times in the last 40 years. Likewise, it is a chapel that alternates its use with periods of inactivity. The church is used every day for masses and for tourist visits. These activities take place in the morning and in the afternoon. The use of the air conditioning system is limited to the summer months. Indoor units are only located in the nave of the chapel (central area of the chapel and transepts). Thus, this chapel is appropriate to analyse the effect expected by climate change on the indoor microclimate, considering three SRES scenario levels (B1 [low], A1B [medium], and A2 [high]) and three RCP scenarios (RCP 2.6 [low], RCP 4.5 [medium], and RCP 8.5 [high]). As for the climate of Seville, the city is in the B4 climatic zone according to the classification of the Spanish Building Technical Code [47]. Thus, this area is characterized by mild winters and low rainfall. Summer seasons correspond to the severest climatic typology in Seville, reaching temperature values greater than 40°C, together with low RH, even less than 60%. Additionally, according to the data retrieved from the State Meteorological Agency (AEMET in Spanish), thanks to meteorological station situated in Lat: 37° 25' 0'' N; Lon: 5° 52' 45'' W; Alt.: 34m, from 1970 to 2020. The monthly average of RH% varies ± 20% RH, although there is an annual trend that indicates a slight decrease in relative humidity in the last 20 years. Additionally, the monthly average of minimum and maximum temperatures varies ±5°C and indicates an average increase of 1°C during the last 20 years, regardless of the season of the year. These climate characteristics are an interesting basis scenario to analyse the future impact of climate change on the conditions of the indoor microclimate.


**Fig. 1.** Case study analysed in this research work. A) Exterior view of the church main entrance and B) interior views of the church where it is possible to see different valuable sculptures

## 2. Methodology

The proposed methodology is defined in the following subsections and is included in Fig. 2. The steps given in the study are explained in the next subsections.

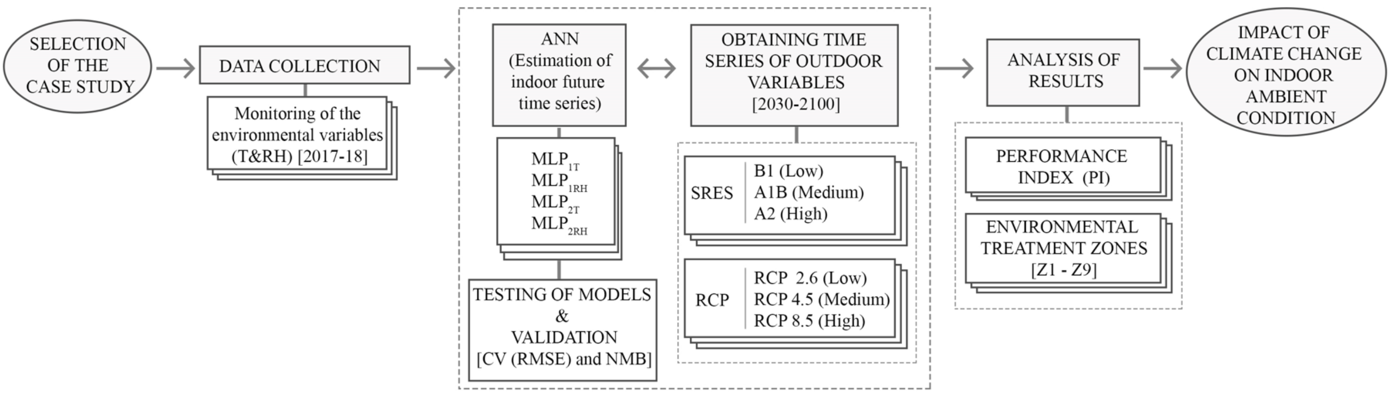


**Fig. 2.** Flowchart that represents the method

*2.1. Monitoring indoor microclimate*

The impact of climate change scenarios was analysed by using artificial neural network models (described in Subsection 2.3.). For this purpose, the indoor microclimate of the chapel was monitored to develop predictive models. Based on previous tests, two points with different characteristics were detected: P1, which corresponds to both the altar and the sculpture of the Christ of the Good Death, at a height of 1.90 m above the floor; and P2, which corresponds to the nave of the chapel (central area of the chapel and transepts), at a height of 2.60 m above the floor. These two points were monitored (Fig. 3) with HOBO U12-012 data loggers (Table 1) from 1 August 2017 to 24 July 2018, with a data acquisition interval of 1 hour. Likewise, hourly records of the outdoor climate were compiled during the same monitoring period by using a VAISALA HMP45D equipment of the Spanish Meteorological Agency (Table 1). In Fig. 4 the daily average values are shown, as well as the fluctuations of the measurements.

**Table 1.** Technical specifications of the equipment used.

| Equipment/probe* | Variable | Measurement range | Accuracy |
|---|---|---|---|
| VAISALA HMP45D | Temperature | [-20-60 °C] | ±0.2 °C |
| | Relative humidity | [0.8-100%] | ±1 % |
| HOBO U12-012 | Temperature | [-20- 70 °C] | ±0.35 °C |
| | Relative humidity | [5-95%] | ±2.5 % |

*Both equipment fulfil the conditions established by EN 16242 [48] and by EN 15758 [49].

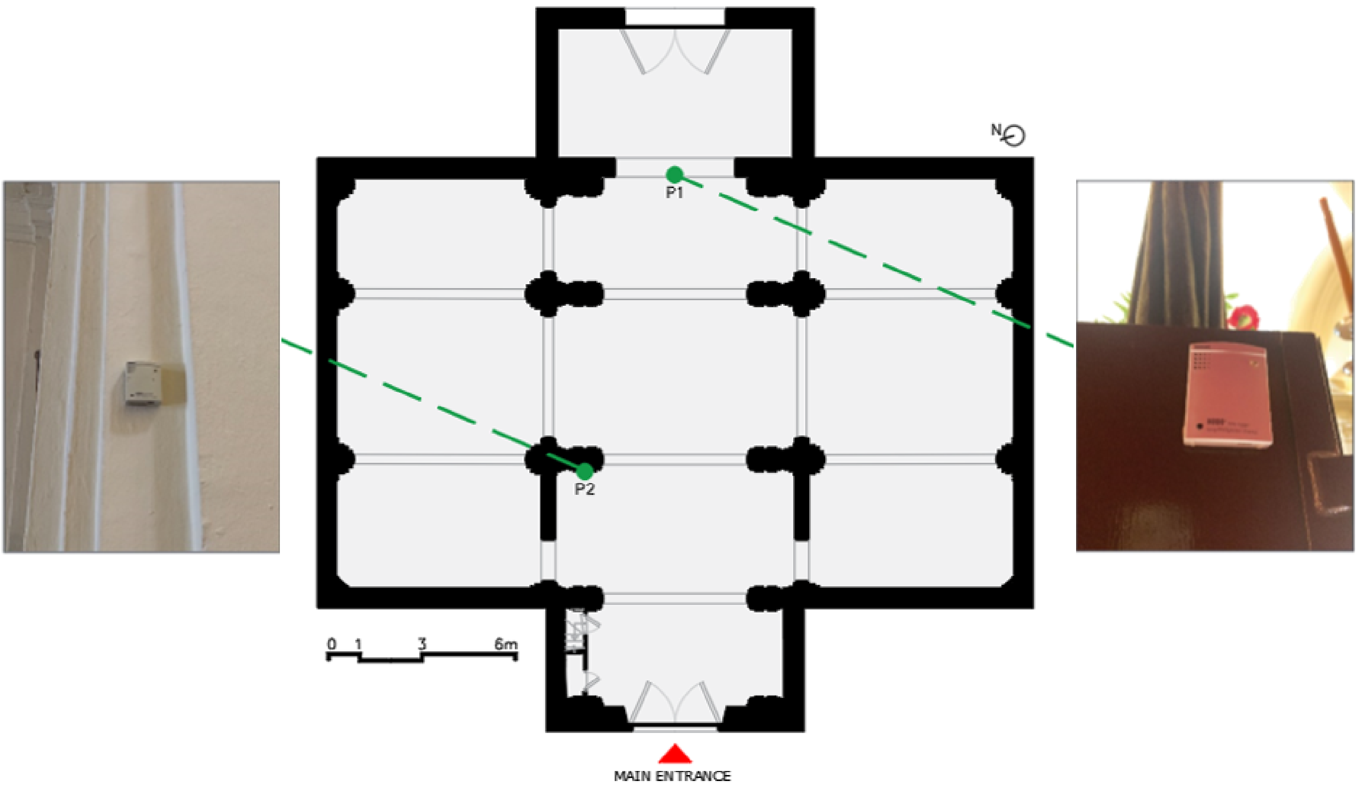


**Fig. 3.** Layout of the chapel and location of the measurement points.

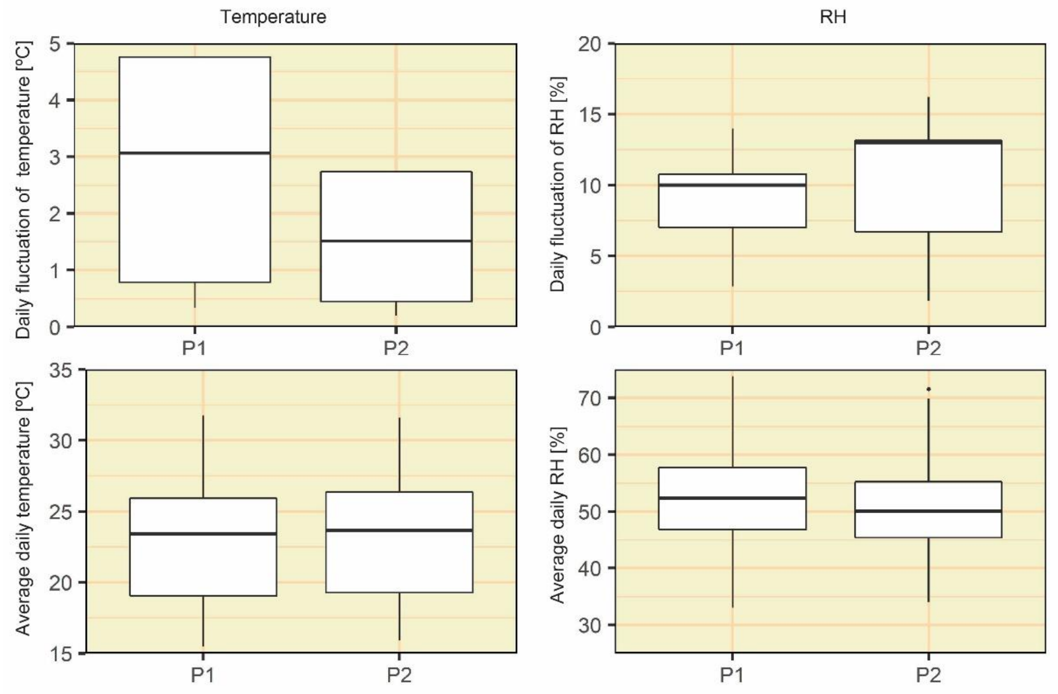


**Fig. 4. Fluctuations and daily average values of the measured points.**

*2.2. Analysing indoor microclimate*

The indoor microclimate was analysed by using a procedure followed deviates from what is provided in [50]. For this purpose, the materials of the heritage elements inside the church were identified (Table 2, and Figs. 5 and 6). All these elements can be grouped in two types of material: canvas or wood. Thus, the limit temperature and relative humidity values established in UNI 10829 regarding these two materials could be determined (Table 3). The preservation level obtained was analysed through the performance index (PI), which was proposed by Corgnati et al. [51] and has been widely used [12], [24], [52]–[54]. PI determines the percentage of monitored records that are within the preservation thresholds (Eq. (1)). This value can be used to determine whether the preservation level is appropriate, with the lower limit being 80%, thus indicating that the microclimate is deficient with values lower than 80%. Nonetheless, it is possible that the reality of the indoor microclimate is not shown by the unique assessment of PI as the records outside the preservation thresholds are not analysed. For this reason, this study also included the approach used in a previous study [44]. This approach allowed all the records monitored to be analysed by using 9 environmental treatment zones (Fig. 7). These zones join all the possible combinations of cases that can be obtained in the indoor climate, with the zone Z-5 corresponding to the preservation thresholds of UNI 10829. For this purpose, the methodology of the environmental treatment zones was complemented with the determination of the Euclidean distances with the closest preservation values. Table 4 shows the distances considered for each zone (varying according to the closest preservation point). Thus, whereas in Z-6 the closest preservation point is the upper threshold of relative humidity, in Z-7 the closest preservation point is both the lower threshold of relative humidity and the upper threshold of temperature.

$$PI = 100\frac{n}{N} \tag{1}$$

Where $n$ is the number of records located among the preservation thresholds, and N is the total number of records.

**Table 2.** Heritage elements inside the case study.

| Name | Typology | Material | Author | Chronology |
|---|---|---|---|---|
| Adoration of the Shepherds | Painting | Canvas | Diego Bejarano | 1760-1765 |
| Angel's lamp | Sculpture | Wood | Juan de Espinal and Benito de Hita y Castillo | 1763 |
| Annunciation | Painting | Canvas | Bernardo Lorente Germán | 1741 |
| Storm door | Furniture | Wood | Unknown | 1775-1799 |
| Crucified Christ | Painting | Canvas | Unknown | 1600-1640 |
| Crucified Christ | Painting | Canvas | Unknown | 1600-1650 |
| Christ of the Good Death | Sculpture | Wood | Juan de Mesa | 1620 |
| Flagellation of Saint Cosmas and Saint Damian | Painting | Canvas | Unknown | 1657 |
| Miracle of Saints Cosmas and Damian | Painting | Canvas | Unknown | 1657 |
| Altarpiece of the Virgin with the child | Altarpiece | Wood | Unknown | 1700-1750 |
| Altarpiece of the Virgin of Anguish | Altarpiece | Wood | Manuel Guzmán Bejarano | 1998 |
| Altarpiece of the Virgin of Remedies | Altarpiece | Wood | Julián Jiménez | 1762 |
| Saint Augustine | Painting | Canvas | Unknown | 1620-1650 |
| Saint Ambrose | Painting | Canvas | Unknown | 1620-1650 |
| Saint Anthony of Padua | Sculpture | Wood | Unknown | 1700-1750 |
| Saint Charles Borromeo | Sculpture | Wood | Benito de Hita y Castillo | 1762 |
| Saint Cosmas and Saint Damian with Angel | Painting | Canvas | Unknown | 1657 |
| Saint Francis Xavier | Sculpture | Wood | Unknown | 1700-1750 |
| Saint Gregory the Great | Painting | Canvas | Unknown | 1620-1650 |
| Saint Hieronymite | Painting | Canvas | Unknown | 1620-1650 |
| Saint Joachim | Sculpture | Wood | Unknown | 1700-1799 |
| Saint Joseph | Sculpture | Wood | Benito de Hita y Castillo | 1762 |
| Saint Anna | Sculpture | Wood | Unknown | 1700-1799 |
| Virgin with the Child | Painting | Canvas | Unknown | 1750-1799 |
| Virgin of Remedies | Sculpture | Wood | Benito de Hita y Castillo | 1762 |
| Virgin of Belem | Sculpture | Wood | Juan de Astorga | 1817 |

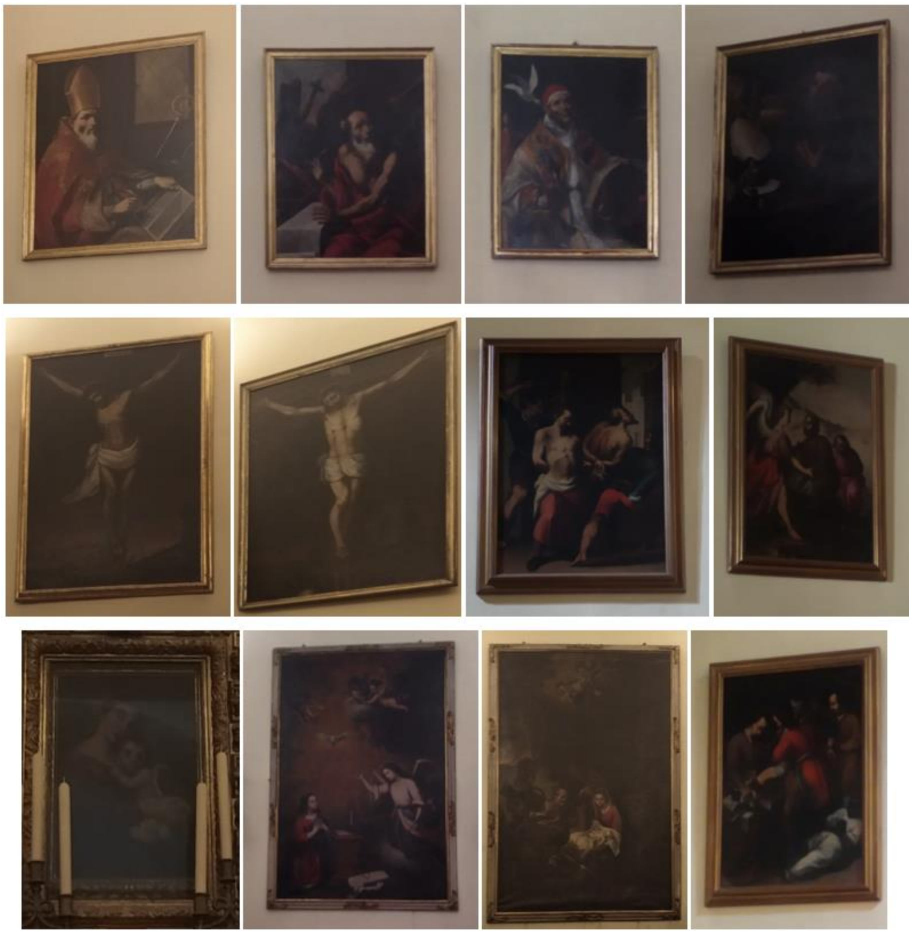

**Fig. 5.** Paintings exhibited in the church. 1st row: Saint Augustine; Saint Ambrose; Saint Gregory the Great; Saint Hieronymite; 2nd row: Crucified Christ (x2); Flagellation of Saint Cosmas and Saint Damian; Saint Cosmas and Saint Damian with Angel; 3rd row: Virgin with the Child; Annunciation; Adoration of the Shepherds; Miracle of Saints Cosmas and Damian;

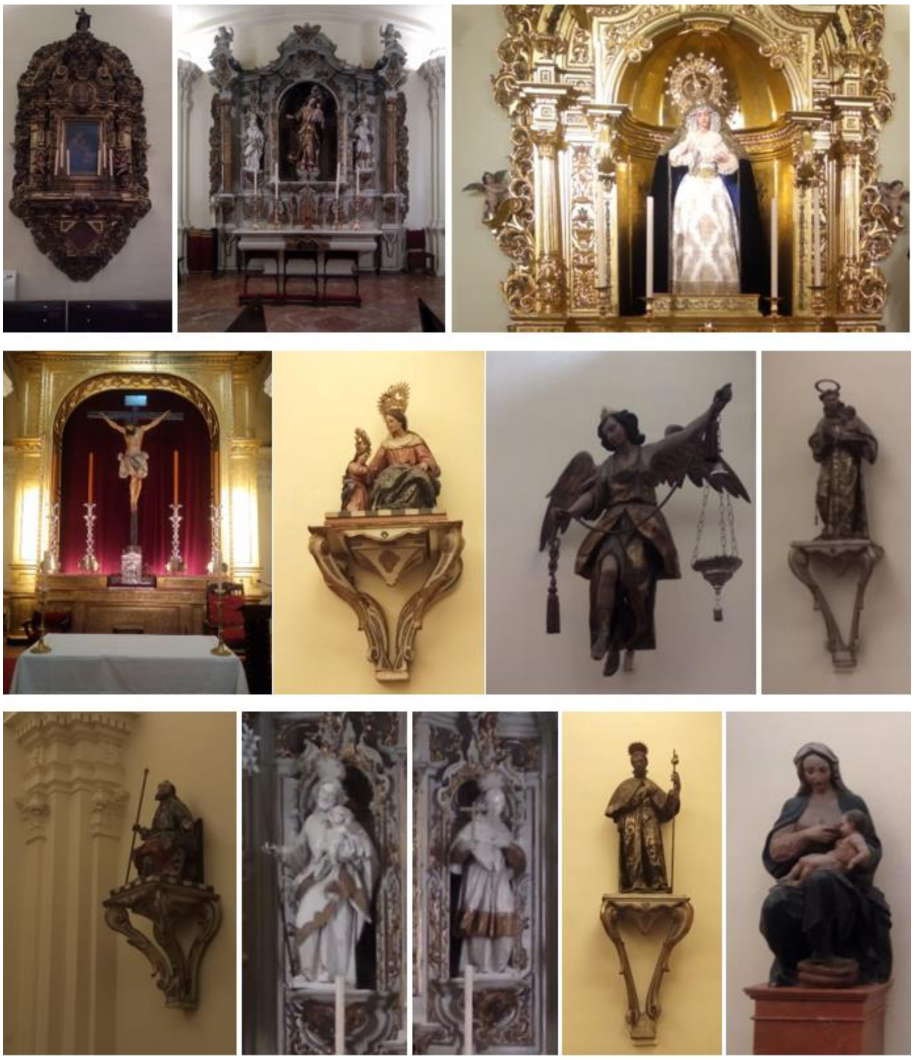

**Fig. 6.** Altarpieces and sculptures exhibited in the church. 1st row: Altarpiece of the Virgin with the child; Virgin of Remedies; Altarpiece of the Virgin of Anguish; 2nd row: Christ of the Good Death; Saint Anna; Angel's lamp; 3rd row: Saint Anthony of Padua; Saint Joachim; Saint Joseph; Saint Charles Borromeo; Saint Francis Xavier; Virgin of Belem.

**Table 3.** Range of appropriate environmental values to preserve the heritage objects of the church according to UNI 10829 [50].

| Artwork | Temperature [ºC] | Relative humidity [%] |
|---|---|---|
| Wooden objects | [19, 24] | [50, 60] |
| Canvas | [19, 24] | [45, 55] |

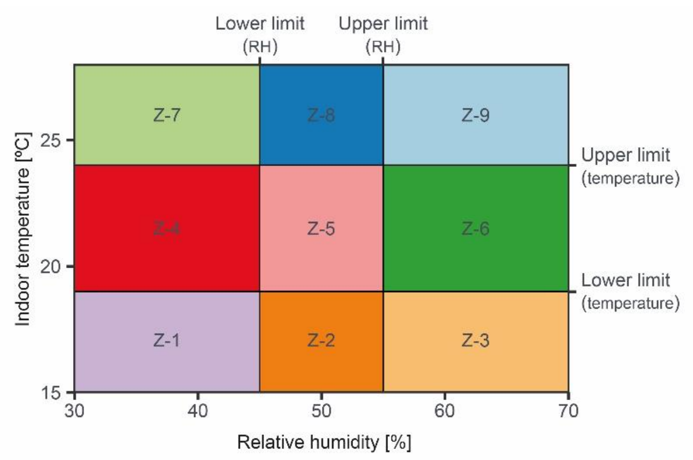


**Fig. 7.** Matrix with the environmental treatment zones divided according to the relative humidity and temperature limit values.

**Table 4.** Description of the environmental treatment zones according to temperature and humidity.

| Treatment zones | Description | Euclidean distance | |
|---|---|---|---|
| Z-1 | Temperature and relative humidity below lower thresholds | $d_i = \sqrt{(T_{low,limit} - T_i)^2 + (RH_{low,limit} - RH_i)^2}$ | (2) |
| Z-2 | Temperature below the lower threshold and relative humidity among the limits | $d_i = \lvert T_{low,limit} - T_i \rvert$ | (3) |
| Z-3 | Temperature below the lower threshold and relative humidity above the upper threshold | $d_i = \sqrt{(T_{low,limit} - T_i)^2 + (RH_{up,limit} - RH_i)^2}$ | (4) |
| Z-4 | Temperature among the thresholds recommended, but relative humidity below the lower threshold | $d_i = \lvert RH_{low,limit} - RH_i \rvert$ | (5) |
| Z-5 | Temperature and relative humidity within preservation thresholds | | |
| Z-6 | Temperature among the thresholds recommended, but relative humidity above the upper threshold | $d_i = \lvert RH_{up,limit} - RH_i \rvert$ | (6) |
| Z-7 | Temperature above the upper threshold and relative humidity below the lower threshold | $d_i = \sqrt{(T_{up,limit} - T_i)^2 + (RH_{low,limit} - RH_i)^2}$ | (7) |
| Z-8 | Temperature above the upper threshold and relative humidity among the limits | $d_i = \lvert T_{up,limit} - T_i \rvert$ | (8) |
| Z-9 | Temperature and relative humidity above upper thresholds | $d_i = \sqrt{(T_{up,limit} - T_i)^2 + (RH_{up,limit} - RH_i)^2}$ | (9) |

*2.3. Estimating future scenarios by using artificial neural networks*

The artificial neural networks (ANN) were used to estimate future time series as they are able to address predictive approaches [55], [56], mainly to estimate numeric data [57]–[59]. The ANN models estimated the hourly values of the two environmental variables (temperature and relative humidity) in the two points inside the chapel. In particular, multilayer perceptrons (MLPs) were used in this study due to their universal approximation capacity [60]–[62]. All the MLPs were designed with sigmoidal activation functions, and training was conducted by backpropagation [63].

As for the input variables of the models, those related to the outdoor climate (obtained through the data from the weather station) were used to estimate the indoor climate with the future estimates of the climate of the zone. Thus, the input variables were outdoor climate variables (outdoor temperature ($T_{ext}$), outdoor relative humidity ($RH_{ext}$), and outdoor dew temperature ($T_{dp-ext}$)), together with the hour and the month of the year. This design of input variables is an interesting option to characterize indoor microclimate as climate data from the weather agencies are used [64]. The output variables were temperature and indoor relative humidity. Likewise, a particular MLP was designed for each output variable and location (Table 5). Thus, the MLPs used in this study only estimated an output variable in each location. A total of 4 MLPs were used. The output variables were logarithmically transformed to obtain better performance in the MLPs.

**Table 5**. Input and output variables considered in the MLPs.

| Point | MLP | Input variables | Output variables |
|---|---|---|---|
| P1 | P1-Ti | $T_{ext}$, $RH_{ext}$, $T_{dp-ext}$, month, hour | $\log_{10} T_{int}$ |
| | P1-RH | $T_{ext}$, $RH_{ext}$, $T_{dp-ext}$, month, hour | $\log_{10} RH_{int}$ |
| P2 | P2-Ti | $T_{ext}$, $RH_{ext}$, $T_{dp-ext}$, month, hour | $\log_{10} T_{int}$ |
| | P2-RH | $T_{ext}$, $RH_{ext}$, $T_{dp-ext}$, month, hour | $\log_{10} RH_{int}$ |

The records obtained in the monitoring described in Subsection 2.1 were used to generate the dataset and to develop the MLPs (each hourly value corresponded to an observation of the dataset): 75% of the data monitored were used for the training, and the remaining 25% for the testing. To reduce the bias and variance in the results, the training used a 10-fold cross validation [65]. Likewise, the optimal architecture was analysed by varying the number of the hidden layers and the neurons in those layers (the architecture of the MLPs ranged between 1 and 2 hidden layers, analysing a combination of neurons ranging between 2 and 10 in each layer). The process was carried out with the R programming environment. For this purpose, the performance of the MLPs was assessed. In this regard, and given the similarity of the process with building energy simulations, the validation statistical parameters of ASHRAE Guideline 14-2014 [66] were used: the Normalised Mean Bias Error (NMBE) (Eq. (2)) and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) (Eq. (3)). The limit values related to each parameter were obtained according to ASHRAE Guideline 14-2014: between -10% and 10% in NMBE, and lower than 30% in CV(RMSE) [66], [67].

$$NMBE = \frac{1}{\bar{m}} \cdot \frac{\sum_{i=1}^{n}(m_i - s_i)}{n-p} \quad (2)$$

$$CV(RMSE) = 100 \cdot \frac{1}{\bar{m}} \cdot \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n-p}} \quad (3)$$

The optimization process determined that the architecture with 2 layers, with six neurons in the first layer and four in the second layer, achieved the best performance, thus obtaining appropriate values in the statistical parameters. The point clouds between the estimated and actual values are shown in Fig. 8, and the statistical parameters are included in Fig. 9. In this regard, the greatest value of NMBE was -2.74% and the greatest value of CV(RMSE) was 8.67%, which are far from the limit values of -10% and 30%, respectively, established by ASHRAE Guideline-14 [66]. Thus, the MLPs designed were valid to estimate future time series.

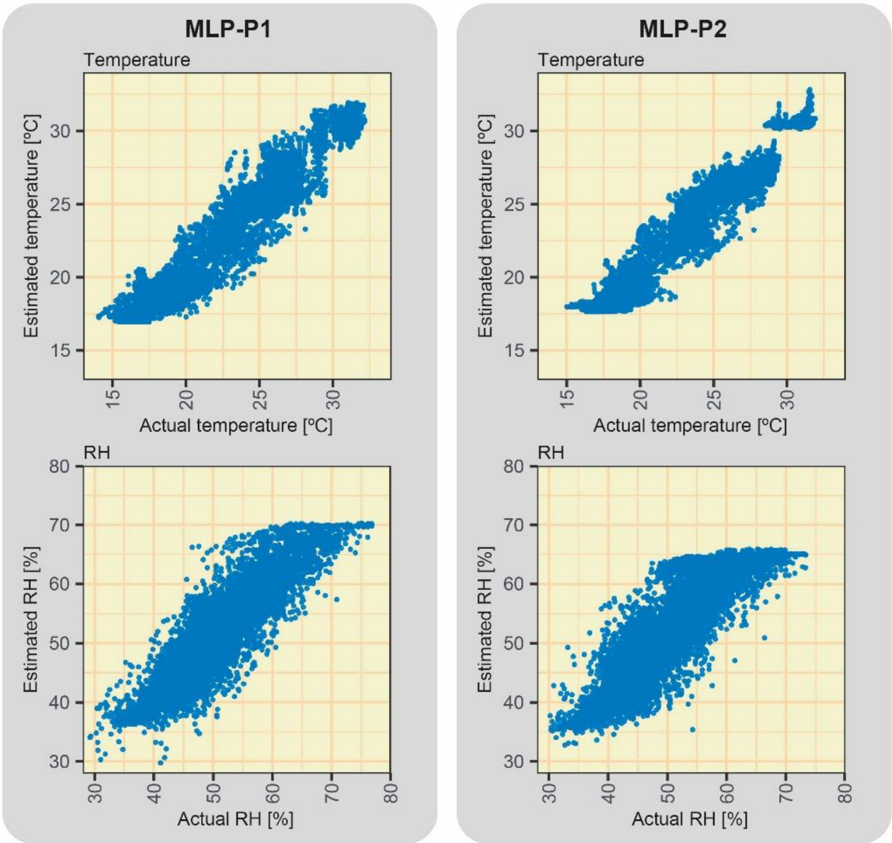


**Fig. 8.** Clouds of points with the real values and those estimated by the MLPs.

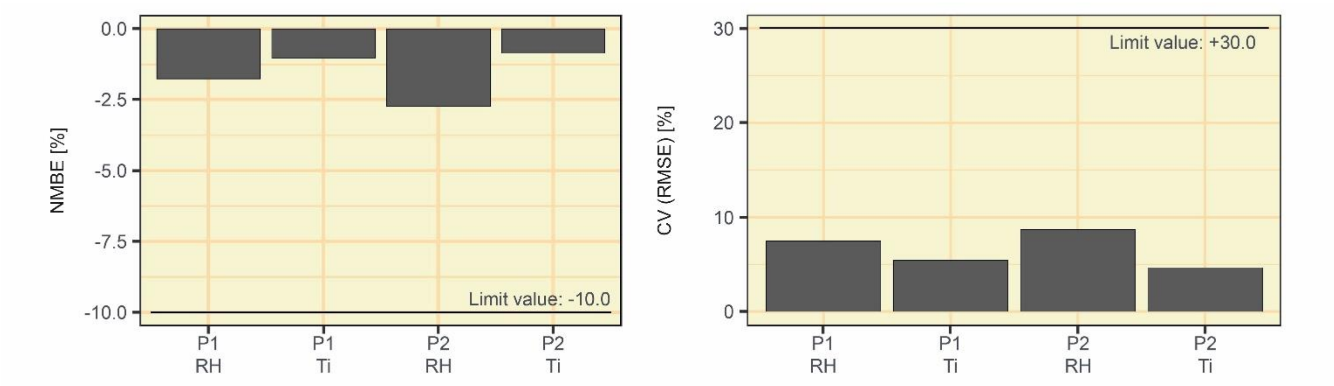


**Fig. 9.** The values obtained in the statistical indicators to assess the hourly estimates of the multilayer perceptrons. The limit values represented correspond to those established in ASHRAE Guideline 14 for hourly values.

*2.4. Future scenarios*

As for the future scenario, the SRES and RCP scenarios were used. On the one hand, SRES define the various climate change scenarios included in the 2007 Report of the IPCC [45]. The scenarios considered in this study were B1, A1B and A2 due to the variability of the severity level considered by each scenario, with B1 being a weak incidence scenario of climate change, and A2 being among the most unfavourable scenarios. The hourly data of each scenario in Seville were obtained through METEONORM 8 [68]. For this purpose, METEONORM uses an average of 18 climate models included in the 2007 Report of the IPCC. The models used are averaged for the years 2011-2030, 2046-2065, and 2080-2099. Through linear interpolations, METEONORM obtains values of each decade of the 21st century. Thus, each scenario (B1, A1B, and A2) obtained the climate data corresponding to the decades of the 21st century following the decade in which this study was conducted (i.e., 2030, 2040, 2050, 2060, 2070, 2080, 2090, and 2100).

On the other hand, the RCP scenarios showed various evolution tendencies of the greenhouse gas emissions included in the 2014 Report of the IPCC [69]. Thus, 3 scenarios with a different severity level of climate change were used: RCP 2.6 (low), RCP 4.5 (medium), and RCP 8.5 (high). The characteristics of these scenarios show the possible variability throughout the 21st century. Thus, the RCP 2.6 scenario is the closest one to the goal established by the Paris Agreement [70], whereas the RCP 8.5 scenario is the most unfavourable, with high temperature rise and serious effects on the habitat [69]. METEONORM contains the RCP 2.6, 4.5 and 8.5 scenarios of 10 global climate models based on the average of a selection of the Coupled Model Intercomparison Project 5 (CMIP5) [71]. This study therefore compared both the SRES A1B, A2 and B1 scenarios, and the RCP 2.6, 4.5 and RCP 8.5 scenarios, all corresponding to each decade of the 21st century.

## 3. Results and discussion

The MLPs allowed the time series of both the temperature and relative humidity of the indoor microclimate to be obtained in each scenario. These MLPs were used to characterize the behaviour in the two main locations of the indoor microclimate (P1 and P2). Figs. 10 and 11 show the point clouds of the hourly values obtained in each scenario-decade combination, as well as the temperature and relative humidity thresholds for wood and paintings. These results also showed the unfavourable behaviour of the indoor microclimate to preserve heritage elements. Thus, most hourly records throughout the year were out of the preservation limits in the current scenario. In this regard, the PI in the current scenario oscillated between 12 and 18%, values which are far from the minimum considered by Corgnati et al. [51], i.e., 80%. Climate change clearly influences the indoor microclimate, thus moving the point clouds towards the zones with the greatest temperature and relative humidity values, thus reducing the percentage of hours within the preservation limits in all the scenarios analysed. Nonetheless, the decrease varied in each scenario: in the SRES scenarios, B1 obtained decreases between 3.68 and 6.34%, A1B between 7.97 and 10.40%, and A2 between 8.74 and 11.19%. These decrease values were like those obtained in the RCP scenarios. However, there were three clear decrease levels in the RCP scenarios: RCP 2.6 obtained decreases between 0.27 and 1.52%, RCP 4.5 between 3.53 and 4.73%, and RCP 8.5 between 9.85 and 11.88%. Thus, climate change will progressively reduce the percentage of hours within the preservation thresholds.

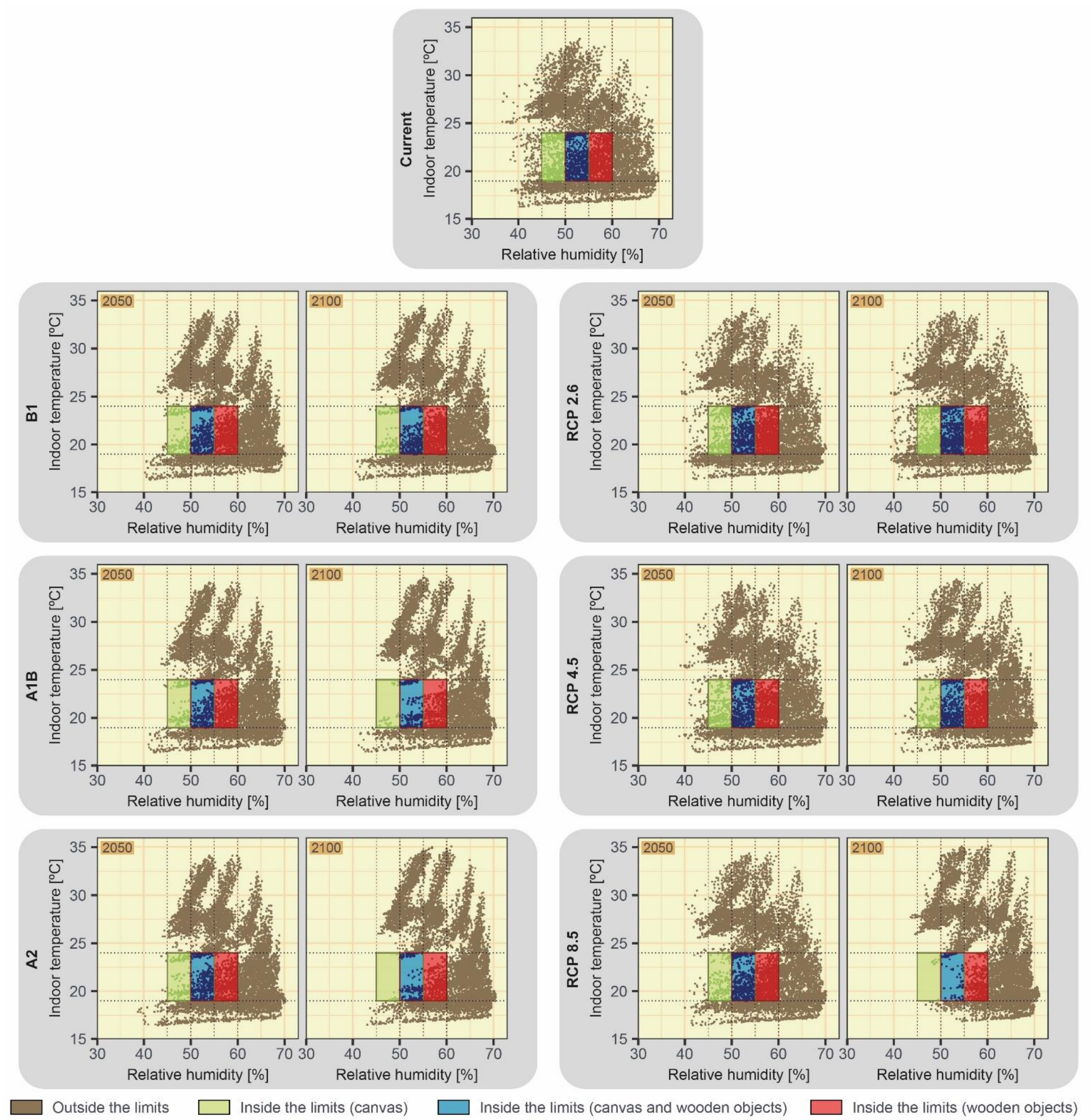


**Fig. 10.** The hourly values obtained in P1 of the indoor environmental variables and delimitation of the optimal preservation zones for each scenario.

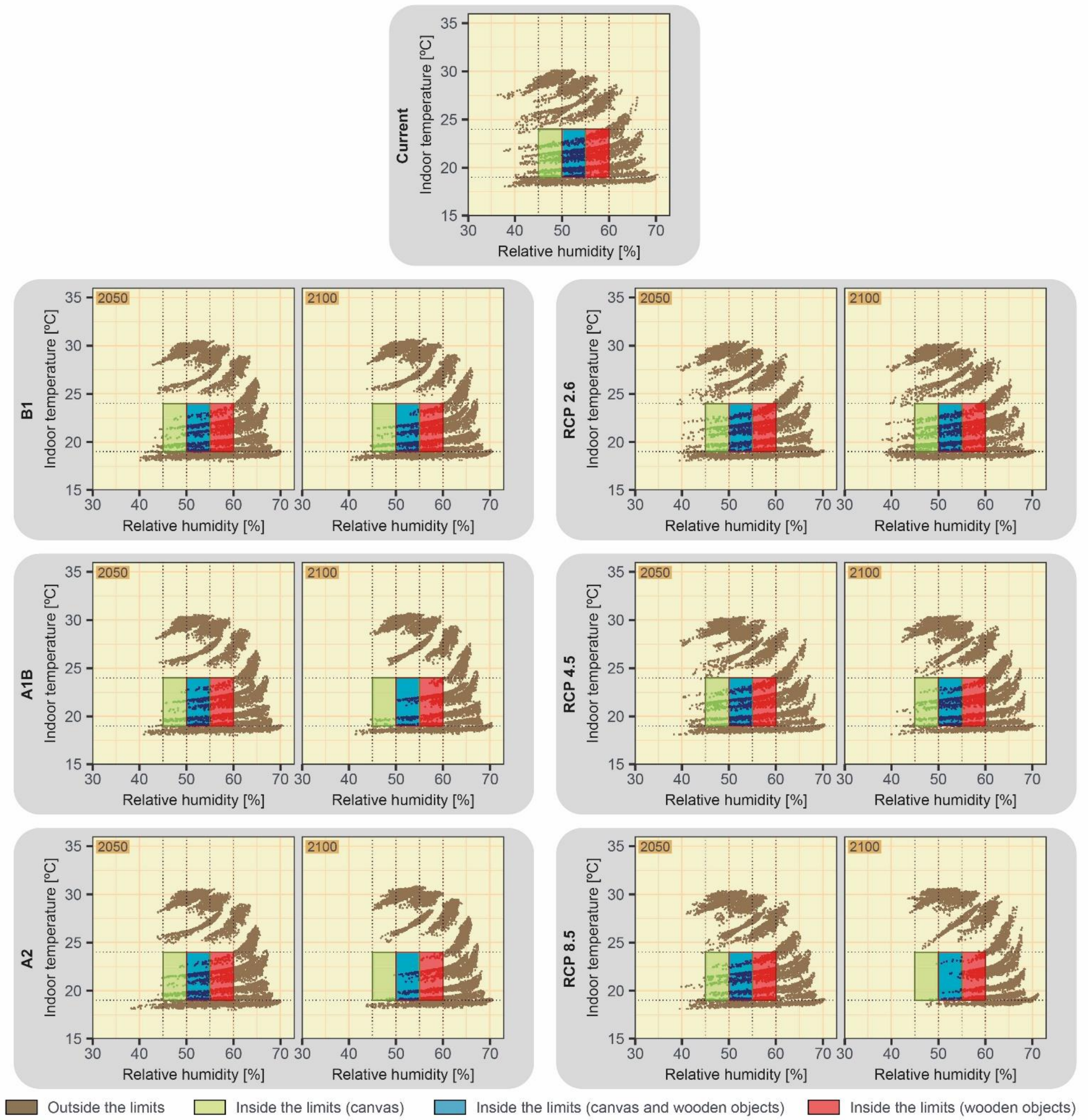


**Fig. 11.** The hourly values obtained in P2 of the environmental variables of the interior and delimitation of the optimal preservation zones for each scenario.

However, this aspect becomes important when the behaviour of the hours that are outside of the preservation thresholds are analysed. The reason is the possible variation of the preservation strategies by changing the location of the annual hours in the environmental treatment zones (i.e., the zones suggested in this study in comparison with the preservation limits). To analyse this aspect, Figs. 12 and 13 show the percentage of hours located in each environmental treatment zone. Climate change scenarios varied the percentage of hours in the preservation thresholds. In this regard, the scenarios had a different behaviour, although generally there was the same tendency in each environmental treatment zone: Z-1, Z-2, Z-4, and Z-7 obtained progressive percentage decreases (with values between 0.04 and 1.41%), whereas the remaining zones presented a progressive increase (with values between 0.07 and 1.67%). Nevertheless, percentage variations were different in each scenario, with the scenarios with a less significant change being those obtaining lower values in the percentage variations. This aspect can be seen in the RCP 2.6 scenario, in which the decarbonisation measures all over the world were effective. In this scenario, the percentage variations oscillated between -0.3 and 0.26% in all the environmental treatment zones. However, in the other RCP scenarios, variations were more significant: RCP 4.5 between -0.66 and 0.88%, and RCP 8.5 between -1.073 and 2.08%. As for the SRES scenarios, percentage variations were similar: between -1.16 and 0.835% in B1, between -1.38 and 1.64% in A1B, and between -1.41 and 1.67% in A2. Thus, these results showed the maximum percentage decrease values in the 3 scenarios considered, whereas the maximum increase values (coincident with the increase of the hours located in Z-9) were greater in the most unfavourable SRES scenarios (A1B and A2). Nonetheless, the scenario with the greatest increase of hours was the RCP 8.5 scenario, with a maximum increase value of 2.08%, thus showing the great variation of the indoor microclimate by developing the various scenarios predicted. However, some scenarios were favourable and tended to keep the current behaviour of the indoor microclimate, such as the RCP 2.6 scenario and B1. In this regard, whereas the RCP had three tendency variations (low, medium, and high), in the SRES scenario there were two variation levels as the changes obtained with A1B and A2 were very similar. This aspect showed the great richness of using RCP scenarios to analyse climate change, since scenarios with clear different behaviours are considered.

The zones Z-6, Z-7, Z-8, and Z-9 obtained the greatest percentage of hours in the current scenario. In this regard, 57.45% of the annual hours in the current scenario were grouped in these zones. However, the climate change scenarios obtained the following values in 2100: 67.16% in B1, 75.29% in A1B, 76.48% in A2, 58.93% in RCP 2.6, 68.53% in RCP 4.5, and 81.10% in RCP 8.5. The percentage obtained in 2100 had the same tendency that the percentage variations mentioned above. Thus, the RCP scenarios provided the analysis with greater richness as there were three clear variation levels, with the RCP 2.6 scenario obtaining a situation like that obtained in the current scenario, whereas the RCP 8.5 scenario included more than 80% of the hours of the year. On the other hand, the SRES scenarios did not provide the analysis with that variability due to the similarities between A1B and A2. In addition, the SRES scenarios did not consider a scenario so unfavourable. In this regard, the RCP 8.5 scenario obtained a percentage greater than 4.61% in comparison to the most unfavourable situation obtained with the SRES scenarios.

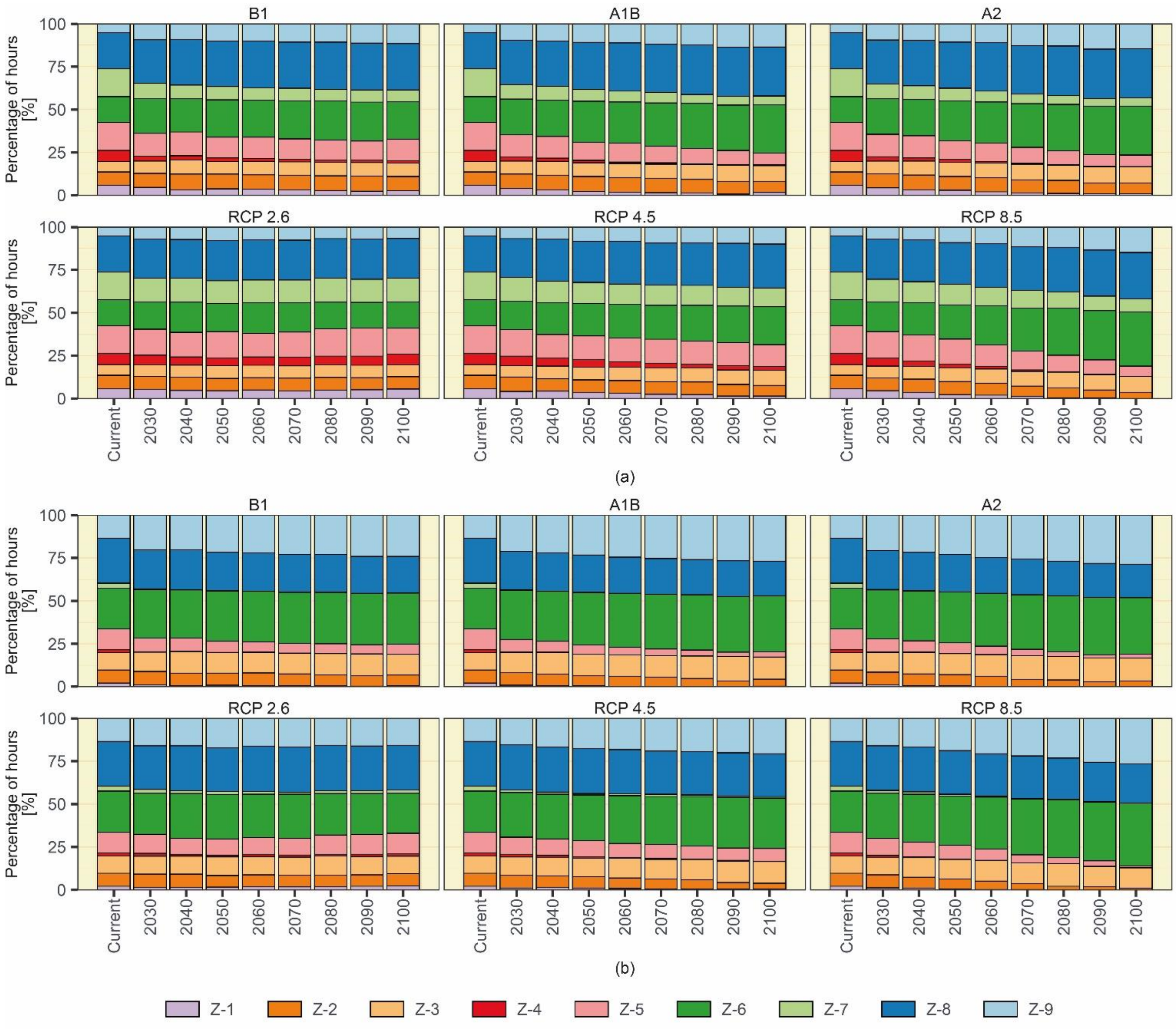


**Fig. 12.** Percentage of hours of the year located in the various preservation zones in P1, (a) for wooden objects, and (b) for paintings.

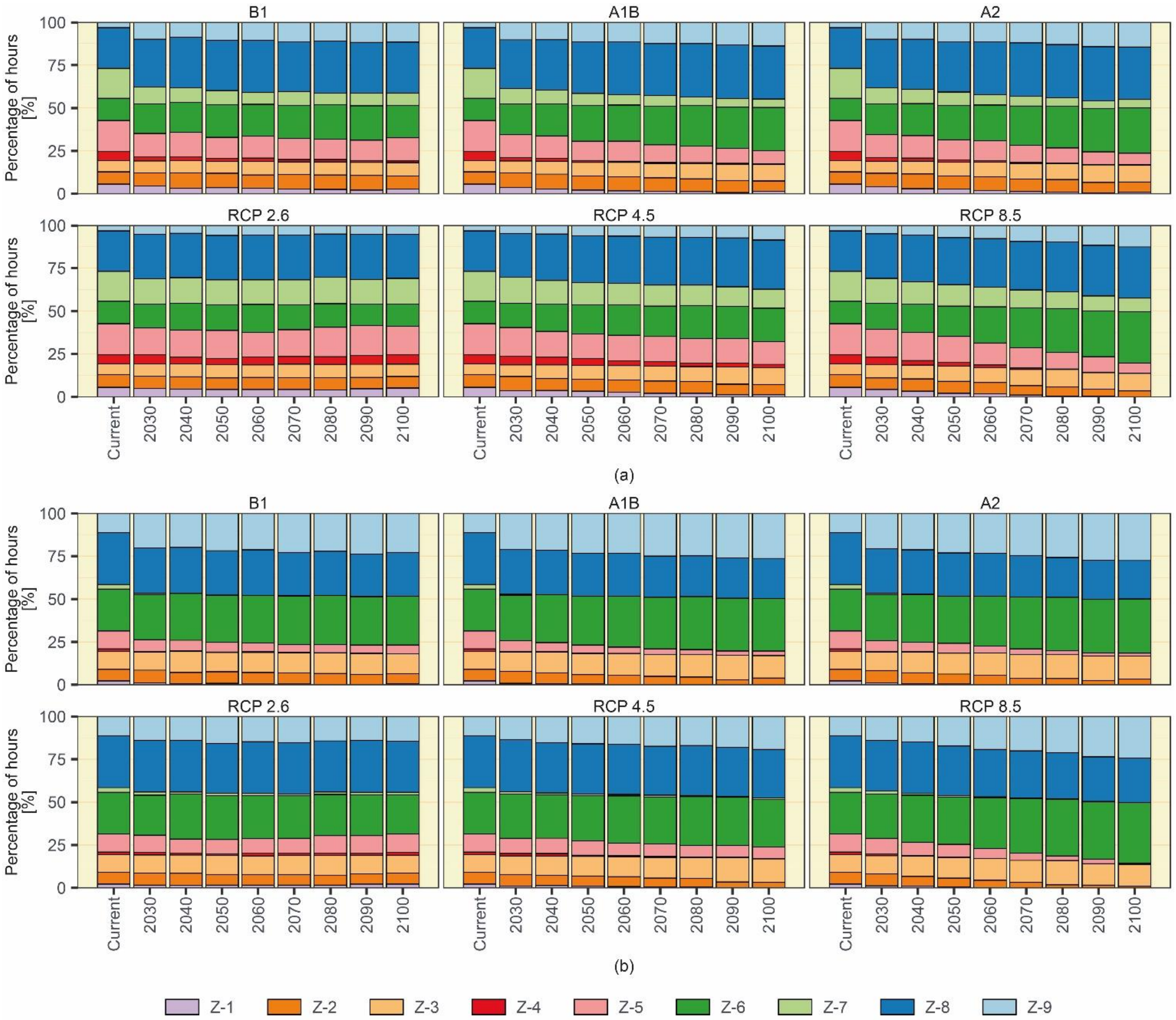


**Fig. 13.** Percentage of hours of the year located in the various preservation zones in P2, (a) for wooden objects, and (b) for paintings.

The variation of the percentage of hours was complemented with the analysis of the distance of the hours with the closest preservation threshold values. The distance was analysed, so the severity level of the zones outside the preservation limits was obtained. Thus, the greater the distance to the closest preservation thresholds, the more difficulties to achieve an appropriate indoor microclimate. Figs. 14 and 15 show the boxplots of the distance distributions in each environmental treatment zone in the current scenario and in the years 2050 and 2100. Climate change tended to increase the distance in the zones with the greatest temperature and/or relative humidity relationship (i.e., Z-6, Z-7, Z-8, and Z-9), whereas in the remaining zones the distance tended to decrease, thus reflecting the less severity that cold periods will present in the preservation of heritage elements. In this regard, the variation of the distances had the same tendency detected with the 3 RCP scenarios. As for the RCP 2.6 scenario, the distributions presented similar tendencies throughout the 21st century, although with slight variations. Thus, from the current scenario to the years 2050 and 2100, the distribution quartiles varied between -1.04 and 1.15. In the RCP 4.5 and 8.5 scenarios, distances significantly varied. This variation was characterized by the increase of the distances in Z-6, Z-8, and Z-9, where quartiles presented increases between 2100 and 2050 that oscillated between 0 and 0.57 in RCP 4.5 and between 0.44 and 1.51 in RCP 8.5. In addition, the maximum values increased in both scenarios, with an increase of 2.33 in Z-9 with RCP 8.5. As for the most favourable environmental treatment zones to use heating systems (Z-1 and Z-4), there was a decrease between 2100 and 2050 of up to -7.06 in the distance values. This showed the almost loss of usefulness of the use of heating to preserve with the RCP scenarios, in particular with RCP 8.5. As for the SRES scenarios, there were similar tendencies (effectiveness loss of heating and increase of the distances in the zones with greater temperature and/or relative humidity), although there were not three clear different variation levels as with the RCP scenarios. Thus, B1 obtained a small variation in comparison with the current scenario, with quartile values oscillating between -1.51 and 1.77, whereas A1B and A2 obtained values between -2,00 and 1.98, and between -2.32 and 1.98, respectively. Likewise, the maximum increase detected in zones with high temperature and relative humidity (e.g., Z-9) did not reach the values obtained with the RCP 8.5 scenario. Thus, whereas the change from 2050 to 2100 increased the maximum values up to 2.33, with the SRES scenarios there was an increase of 1.22 with A2 and of 0.71 with A1B. Thus, the use of the SRES would not assess more unfavourable situations that could be considered with the RCP 8.5 scenario. These results showed the variability of the distributions of the hourly values obtained. The results of this study therefore showed the high impact expected due to climate change in the indoor microclimate of the historic buildings located in the Mediterranean region. Except in the RCP 2.6 scenario, the conditions of the indoor microclimate significantly changed in the remaining scenarios. Although this aspect did not vary the percentage of hours within the preservation thresholds (due to the deficient state of the church), climate change varied the behaviour of the indoor microclimate outside the preservation thresholds, with a greater prevalence of high temperature and relative humidity values, as well as the increase of the distance in comparison with closer preservation thresholds (thus making the use of strategies something of a challenge to obtain a greater percentage of hours within the preservation threshold). Moreover, there were variations presented by the SRES and RCP scenarios. In this regard, the RCP scenarios allow levels of scenarios to be clearer presented than the SRES scenarios as climate can be maintained throughout the 21st century, as well as the most unfavourable scenario. The most unfavourable estimates in the SRES scenarios could be very low in comparison with the RCP 8.5 scenario, thus implying that architects and engineers based on estimates of SRES scenarios know that their preservation strategies loss effectiveness throughout the 21st century. According to the results obtained, the use of measures based on cooling and dehumidification could be the most appropriate action framework to adapt the indoor microclimate to preserve heritage elements.

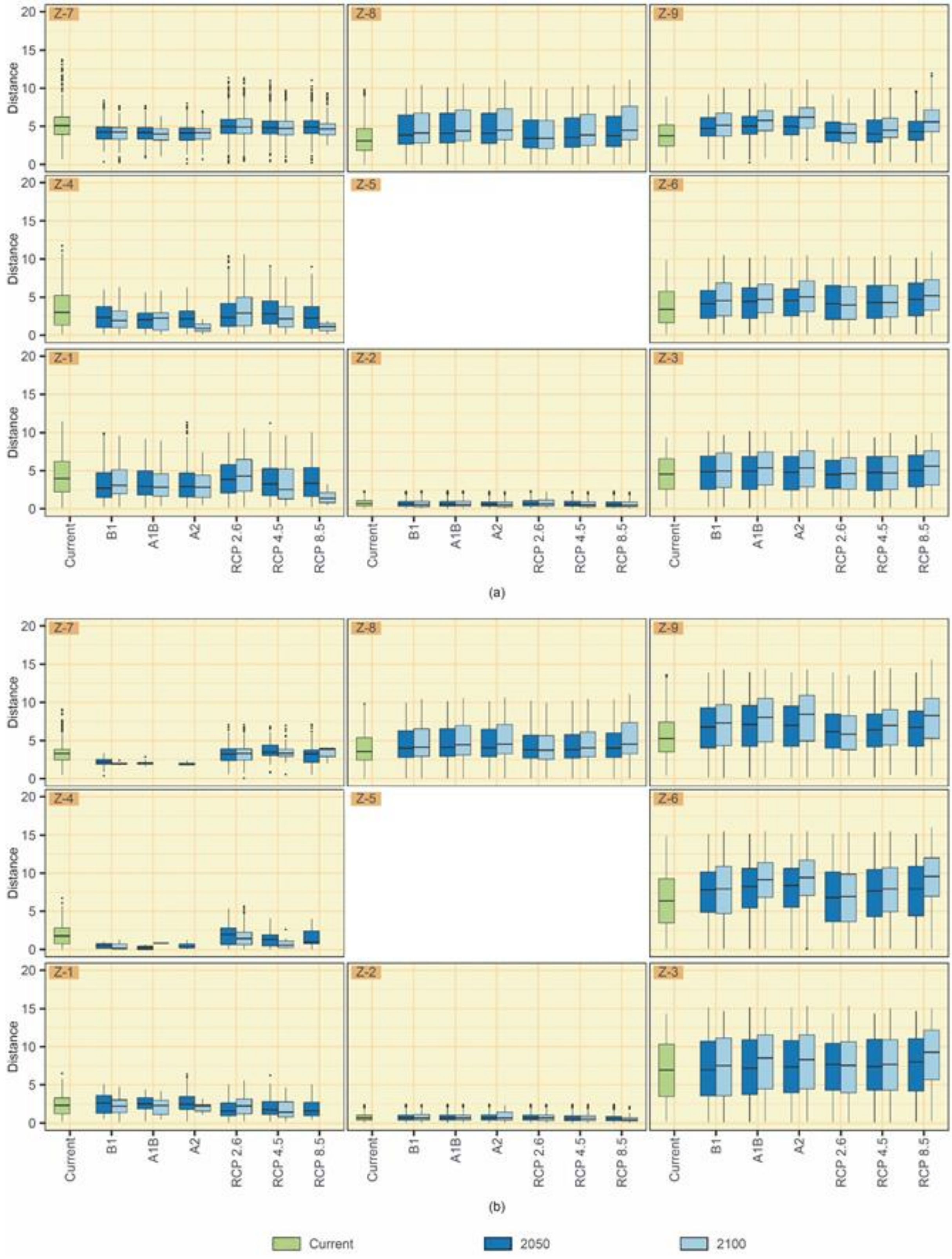


**Fig. 14.** Boxplots with the distance distributions obtained in P1 by each scenario: (a) for wooden objects, and (b) for paintings.

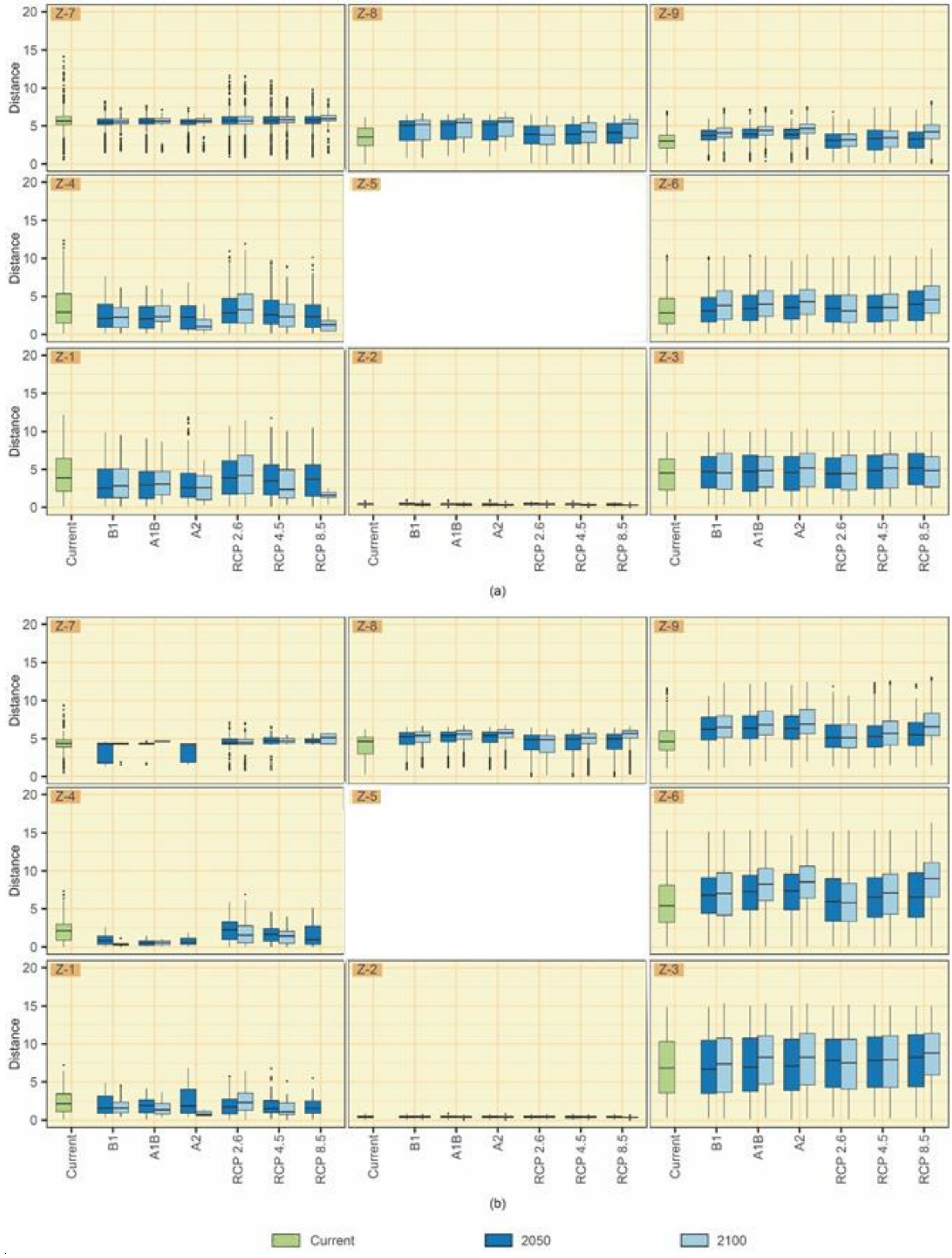


**Fig. 15.** Boxplots with the distance distributions obtained in P2 by each scenario: (a) for wooden objects, and (b) for paintings.

## 4. Conclusions

Preserving the heritage elements of historic buildings is among the main challenges of today's society. Climate change could play an important role as the conditions of the indoor microclimate could significantly vary. This aspect could be more significant in the case of buildings located in warm regions with a current deficient state. For this purpose, this study assessed the impact expected due to climate change on the indoor microclimate of a church in the three scenarios proposed by SRES (B1, A1B and A2) and in the three scenarios proposed by RCP (RCP 2.6, 4.5 and 8.5), and the following conclusions were obtained:

- Artificial neural networks were used to estimate the time series of future scenarios, thus showing that the indoor microclimate is altered in all the assumptions.
- The type of scenario considered could significantly vary future estimates of the indoor microclimate. In this regard, whereas the RCP scenarios showed three clear levels of changes in the indoor microclimate, the SRES scenarios only showed two levels (one for B1 and another for both A1B and A2). Thus, the RCP scenarios are provided with greater richness by considering three clear variation levels of the indoor microclimate.
- The variations of the most unfavourable RCP scenario (RCP 8.5) were not reached by the SRES scenarios. In this case, the SRES scenarios obtained estimates of the indoor microclimate like those obtained by the RCP 4.5 scenario.
- In the medium and high variation levels, the indoor microclimate was characterized by decreasing the percentage of hours in the environmental treatment zones with low temperatures and/or relative humidity and by significantly increasing the percentage of hours in the zones with the greatest temperature and/or relative humidity. Thus, cooling and dehumidification strategies should be used in the indoor microclimate. This aspect became important in the RCP 8.5 scenario, in which the distance values were high in comparison with the closest preservation thresholds.

It is worth stressing the importance of both climate change and governmental measures that could be adopted to mitigate greenhouse gas emissions. These policies have been always related to issues such as sustainability and life quality improvement of future generations. However, this study proves the clear differences that could take place by using effective policies throughout the 21st century (reflected in the RCP 2.6 scenario), in comparison with no using effective policies (the RCP 8.5 scenario). Thus, decarbonisation policies could also improve the preservation of heritage elements as their current state is not significantly varied. Thus, new measures would not be used for the existing heritage elements, limiting the needs for technological innovation in the sector (an aspect that would be required in medium and high scenarios as both the percentage of hours and the distance to the preservation thresholds are increased in environmental treatment zones with high temperature and relative humidity).

Further studies should focus on the design of effective strategies to achieve the preservation of heritage elements, thermal comfort and low energy consumption to have an appropriate performance methodology. Likewise, future works should analyse the impact of climate change on the indoor microclimate by including a greater variety of climate zones and with or without treatment in the current scenario. This aspect would provide greater knowledge on the impacts of climate change on the existing indoor microclimate.

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