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Climate Change Impacts on Indoor Cultural Heritage and Collections in Greece †

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Abstract: The preservation of historical buildings, as well as museum exhibition facilities, is critical under the changing environmental conditions. Since the potential outdoor climate changes may affect the recommended environmental conditions within the museum microenvironment, there is an urgent need for further research into the relationship between the outdoor and indoor climate and how future changes could affect it. This study investigated the relationship between the indoor and outdoor climate conditions in museums and historical buildings located in Greece. The main goal of this work was to assess the suitability of the indoor microclimate by applying the heritage microclimate risk (HMR) and the predicted risk of damage (PRD) indices. In order to achieve a detailed assessment of the present temperature and relative humidity (RH) outdoor conditions over the specific case studies, data from three different sources were incorporated in the study (observed, reanalysis, and model data). The model data were derived from the regional climate model RegCM4 with a fine spatial resolution of 10 × 10 km. The indoor environmental parameters were collected both from the museums and the historical buildings in the two case studies. In cases where indoor environmental data were not available, monitoring sensors were installed. The findings indicate that in cases where there is no control over climate conditions, the indoor climate is predominantly influenced by the outdoor climate. As a result, these spaces exhibit a heightened sensitivity to potential future temperature increases.

Keywords: climate change; cultural heritage; outdoor environment; indoor environment; present simulations

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1. Introduction

Museums serve as important cultural institutions that help to preserve and share our collective heritage and knowledge. One of the primary functions of museums is to collect and preserve objects and materials of cultural significance [1]. However, historical buildings and museum antiquities are indeed vulnerable to the indoor microclimate. The temperature, relative humidity, and air quality conditions within a building or museum can directly impact the preservation of cultural artifacts. The interiors of objects and collections held in historical buildings and museums are susceptible to decay caused by fluctuations in temperature and humidity, which can result in mechanical, chemical, and biological damage [2].

There are several factors that can influence the indoor climatic conditions of a building [3]. Therefore, climate change is expected to pose new challenges to the internal climate of museums. Rising temperatures and changing humidity levels associated with climate change can also affect the stability of collections and accelerate the rate of the outdoor climate, building dimensions and structure, construction materials, and promote hydrogeology of the soil beneath the building of degradation, as well as create ideal conditions for

mold insect growth [4]. Thus, it is important for museums to develop adaptation strategies and implement measures to mitigate these impacts.

Greece is well known for its rich cultural heritage and for its large number of museums, many of which are dedicated to preserving and showcasing Greece's cultural and historical artifacts. However, Greece is facing new threats from climate change. Recent projections for the region of Greece using a regional climate model under the RCP4.5 scenario reveal an increase in temperature of 3.6 °C by the end of the 21st century [5]. Based on the above "moderate" scenario, Tringa and Tolika, in their previous study on the impacts of the outdoor microclimate on Greek cultural heritage, showed that monuments will be exposed to a 'moderate-maximum' risk more frequently in the future [6].

Since the cultural heritage preserved in museums or historical buildings is exposed to the risk of damage and deterioration, due to the microclimatic conditions characteristic of the environment that houses it, this study focused on analyzing the indoor environments of specific historical buildings and museums in Greece. The main goal of this work was to evaluate the suitability of indoor microclimates and to assess the damage risk by applying two new indices.

2. Materials and Methods

2.1. Case Studies

The Archaeological Museum of Thessaloniki, the Church of Acheiropoietos in Thessaloniki, and the Archaeological Museum of Delphi in Delphi were selected for the study of their indoor climate. The Archaeological Museum of Thessaloniki and the Archaeological Museum of Delphi are two modern museums where their microclimate is typically maintained using heating, ventilation, and air conditioning (HVAC) systems. On the contrary, the Church of Acheiropoietos is primarily constructed with heavy stone and brick masonry, and it does not have HVAC systems to control the climate parameters. Instead, the church relies on heating devices, which are likely used to provide localized heating during colder periods.

2.2. Data

In order to determine the relationship between the indoor and outdoor temperature and relative humidity (RH) data, data from three different sources were incorporated [observed, reanalysis (ERA5-Land), and model data]. The model data were derived from the regional climate model RegCM4 with a fine spatial resolution of 10 × 10 km. The indoor environment data were monitored using data logger sensors programmed to automatically record values every hour. Environmental monitoring sensors located within the Archaeological Museum of Thessaloniki provided the data for this study for the period 1 January 2019 till 31 January 2021. In the case of the Archaeological Museums of Delphi and the Church of Acheiropoietos, we installed our own sensors and initiated a new data monitoring campaign which is still ongoing. The sensors were installed inside the buildings in June 2022 and are still recording today. However, the first two months of data were discarded due to the errors caused by certain factors, such as sensor stabilization and equilibration. The study period for the case of the Archaeological Museum of Thessaloniki and for the Church of Acheiropoietos was the period 1 August 2022 till 31 December 2022.

2.3. Methodology

The heritage microclimate risk (HMR) index and the predicted risk of damage (PRD) index were utilized to evaluate the suitability of the indoor microclimate and to assess the damage risk. The HMR index depends on the indoor microclimate, and it allows for the assessment of the risk to which cultural heritage is exposed within a room caused by the indoor microclimate. In this study, the historical HMR index (HMR_{hs}) was applied, and the thresholds for this index were determined based on the indoor data series, excluding any "scattered values". More information on index equations is available in the study by Fabbri

and Bonora [7]. The PRD index depends on the HMR and the material type (inorganic, organic, paintings etc.).

$$HMR_{hs} = \left(\frac{HMR_{env}^{hs} + HMR_{osc}^{hs}}{2} \right)$$

$$PRD = 1 - 0.95 \times e^{(-a \times HMR^4 - b \times HMR^2)}$$

3. Results

3.1. Temporal Analysis of the Indoor and Outdoor Thermo-Hygrometric Conditions

In order to gain a complete understanding of a building's hygrothermal behavior, it is important to comprehend not only its indoor microclimate, but also its relationship with the outdoor environment. For this reason, the hourly variations of both the internal and outdoor temperatures were studied for the Archaeological Museums of Thessaloniki and Delphi as well as for the Church of Acheiropoietos. Although this study was carried out for all three buildings, Figure 1 displays the results for the Archaeological Museum of Thessaloniki and the Church of Acheiropoietos. In general, it was found that the indoor temperature trend of all three buildings follows the outdoor temperature trend. The internal temperature of the Archaeological Museums of Thessaloniki and Delphi and the Church of Acheiropoietos fluctuated 6.0 °C, 5.8 °C, and 3.6 °C on average, respectively, higher than the outdoor temperature. This indicates that the average temperature of the church is relatively closer to the outside temperature compared to the other two buildings, as it lacks an HVAC system. Additionally, despite the church having a greater temperature range with more extreme values, there were no significant differences observed in the hourly fluctuations when compared to the other two museums. In contrast to the Church of Acheiropoietos, the indoor RH trend in the Archaeological Museums of Thessaloniki and Delphi did not exhibit any similarity to the trend of the outdoor RH. In addition, the average indoor RH levels of the Archaeological Museums of Thessaloniki and Delphi and the Church of Acheiropoietos fluctuated 17.2%, 21.1%, and 8.4%, respectively, lower than the outdoor RH. Finally, no significant differences were observed in the hourly RH fluctuations among the three buildings under study.

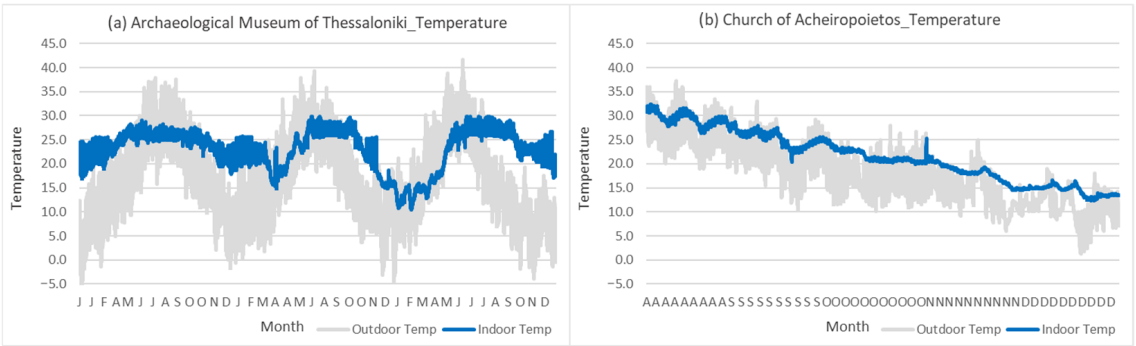

Figure 1. Hourly fluctuations (**a**) for the indoor and outdoor temperatures for the Archaeological Museum of Thessaloniki (for the period 1 January 2019 till 31 January 2021) and (**b**) for the Church of Acheiropoietos (for the period 1 August 2022 till 31 December 2022.).

Figure 2 presents the scatter plots between the indoor and outdoor temperature for the Archaeological Museum of Thessaloniki and for the Church of Acheiropoietos. The scatterplot on the left has an R-value of 0.197, indicating a weak positive correlation between the indoor and outdoor temperatures. This suggests that there is a tendency for the indoor temperature to increase when the outdoor temperature increases, but the relationship is not strong. On the other hand, the scatter plot on the right, with an R-value of 0.7199, indicates a strong positive correlation between the indoor and outdoor temperatures. This means

that in the case of the Church of Acheiropoietos, there is a significant tendency for the indoor temperature to increase when the outdoor temperature increases.

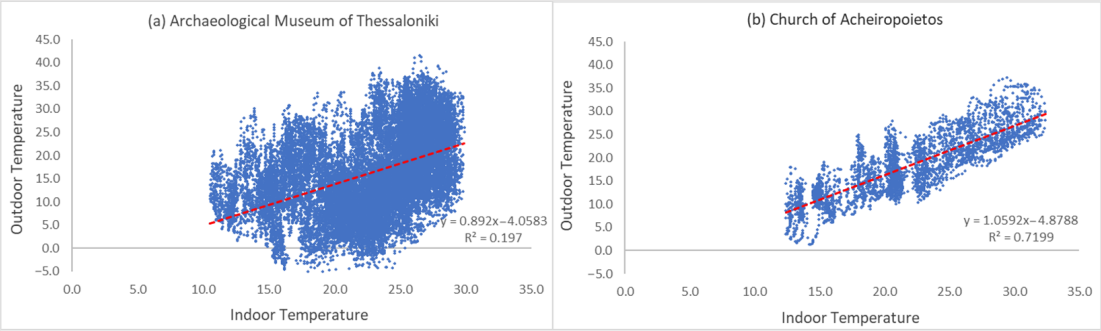

Figure 2. Scatter plots between the indoor and outdoor temperatures (**a**) for the Archaeological Museum of Thessaloniki (for the period 1 January 2019 till 31 January 2021 and (**b**) for the Church of Acheiropoietos for the period 1 August 2022 till 31 December 2022. The red lines represent the general trend.

Regarding the RH, the R-values for the Archaeological Museums of Thessaloniki and Delphi, as well as for the Church of Acheiropoietos, are 0.0075, 0.0105, and 0.4051, respectively. In the case of the museums, the data points exhibit a scattered and random pattern, indicating a very weak correlation between the indoor and outdoor RH. However, the higher R-value for the Church of Acheiropoietos reveals a moderately positive correlation between the indoor and outdoor temperature, suggesting that there is some degree of responsiveness to the outdoor RH; however, this correlation is not particularly strong.

3.2. The HMR_{hs} and PRD Indices

In order to evaluate the suitability of the microclimates and to assess the risk of damage the heritage microclimate risk and the predicted risk of damage index were used. Regular checks were conducted on both the assets and values housed in the Archaeological Museum of Thessaloniki and the Delphi Museum, as well as the conservation conditions of the buildings themselves. So far, no signs of deterioration have been found in either museum. For the Church of Acheiropoietos, we considered that the assets of values and the paintings have adapted to the microclimatic conditions of their environment. For the reasons mentioned above, both $HMR^{hs}_{e.low}$ and $HMR^{hs}_{e.high}$ were computed from data series collected from the environmental monitoring sensors in the museums rather than from standard reports [7].

Figure 3 shows the results of the HMR_{hs} and PRD indices for both the Archaeological Museum of Thessaloniki and for the Church of Acheiropoietos. These indices were applied for inorganic, organic, mixed, and paintings materials/objects. The HMR_{hs} index value for the temperature parameter in the Archaeological Museum of Thessaloniki is +0.09, indicating a minimum microclimate risk and a reduced probability of damage. More specifically, the probability risk of damage (PRD) is 5.4%, 5.8%, 6.2%, and 6.5% for inorganic, organic, mixed, and paintings materials/objects, respectively. Similarly, the HMR_{hs} index value for RH is +0.04, corresponding to a probability of damage under 10% for all materials under study (5.2%, 5.1%, 5.2%, and 5.3%, respectively). The risk of the microclimate (HMR_{hs}) due to temperature in the Archaeological Museum of Delphi (not shown) was found to be equally low (+0.13), while the value of the HMR_{hs} index for RH was almost zero (+0.004). Overall, the indoor microclimate of the under study halls of the Archaeological Museums of Thessaloniki and Delphi can guarantee the preventive conservation of the antiquities hosted there. Regarding the indoor climate of the Church of Acheiropoietos, the results revealed that the HMR_{hs} index for temperature was +0.06 and for RH +0.11. The slightly higher HMR_{hs} index resulting from the RH in the Church of Acheiropoietos appears to primarily impact the mixed materials and the paintings that adorn the church's surroundings.

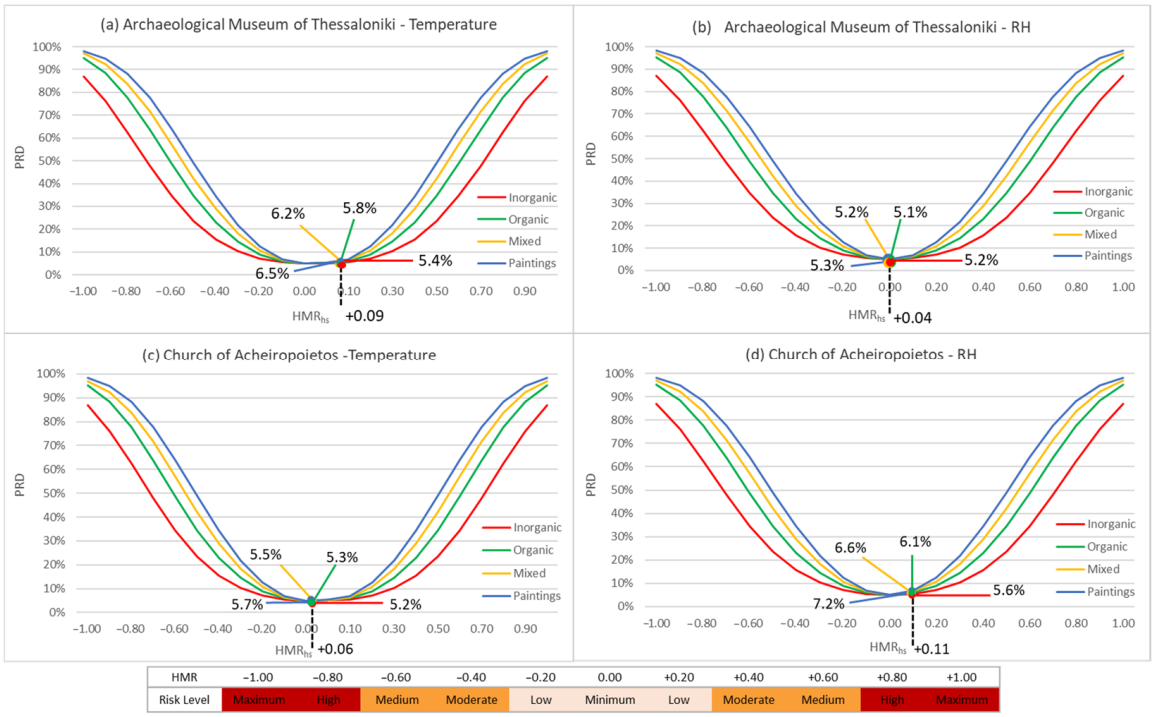

Figure 3. The HMR_{hs} and PRD indices for temperature (left) and RH (right) for the indoor environment of the Archaeological Museum of Thessaloniki (up) (for the period 1 January 2012 till 31 January 2021) and for the Church of Acheiropoietos (down) (for the period 1 August 2022 till 31 December 2023).

4. Conclusions

In this work, the impacts of climate change on indoor cultural heritage and collections in Greece were studied. This study aimed to comprehensively understand the relationship between indoor and outdoor climate variables (namely temperature and RH), and subsequently assess the risk of heritage microclimate risk and the predicted risk of damage. The findings indicate that the indoor temperature trends of all three buildings align with the outdoor temperature trends. The scatter plots provided further confirmation of these findings, demonstrating that all three buildings exhibit a certain level of responsiveness to changes in the outdoor temperature, with the Church of Acheiropoietos showing a stronger correlation between the indoor and outdoor temperature. In addition, a moderate correlation between the indoor and outdoor RH was revealed in the case of the church in contrast to the other two museums. The absence of climate control systems within the church's interior undeniably plays a significant role in influencing this relationship [8]. However, it is important to acknowledge that the existing literature suggests the involvement of other factors that may contribute to this phenomenon. Architectural design, building materials, thermal inertia, natural ventilation, location, the climate, and the use of the building are among the potential factors that can influence the thermo-hygrometric dynamics in a building [9,10]. Despite the church's larger temperature range compared to the other two modern museums, no significant differences were observed in the hourly temperature and RH variations. Moreover, heavy constructions succeeded in stabilizing the indoor temperatures and reducing the demand for cooling [8]. Potentially, the construction materials and architectural design of the Church of Acheiropoietos contributed to a larger thermal mass in comparison to the other two museums [11]. The ultimate goal of this study was to evaluate the potential risk to the microclimate within each of the under study buildings, as well as to assess the probability of damage to the cultural objects housed within them. The results of the HMR_{hs} and PRD indices showed that the environments of all three buildings are characterized by a minimum microclimate risk for both temperature and RH, leading to a reduced probability of damage for all the materials

studied (inorganic, organic, mixed, and paintings). Nonetheless, the slightly higher HMR_{hs} index resulting from the RH in the Church of Acheiropoietos appears to primarily impact the mixed materials and the paintings that adorn the church's surroundings. Therefore, it would be useful to give greater emphasis to the microclimatic conditions of the Church of Acheiropoietos due to the presence of more sensitive materials.

Overall, it is evident that the indoor temperature of all three buildings is influenced by the temperature of the outdoor environment. However, it turned out that this influence is reduced in cases where HVAC systems are installed. Therefore, without implementing the appropriate measures, it is possible that the hygrothermal conditions of museums and historical buildings may undergo changes in the future as a result of climate change [12]. This could potentially lead to visitors' discomfort or even damage to the artifacts or structure within the church if the temperature and RH becomes too high [13]. Finally, we intend to focus further on the future thermo-hygrometric conditions of museums and historic buildings and provide useful information for the potential heritage microclimate risk in the future.

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Data Availability Statement: The ERA5 dataset is available online at https://cds.climate.copernicus.eu/ (accessed on 2 February 2023). The dataset is derived from Aristotle University of Thessaloniki (AUTH) and the indoor environment of museums is available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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