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# Fluctuations in the indoor environment in Spanish rural churches and their effects on heritage conservation: Hygro-thermal and $CO_2$ conditions monitoring

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ABSTRACT

The indoor environment and its natural dynamics in small Spanish historical churches such as the studied here depend on the variations of outdoor climate and the moisture dynamics of walls, built with different materials. Such indoor environments are impacted by local factors, which may put at risk the conservation of a church's cultural assets. Natural ventilation in spring, the presence of people and especially the wintertime use of ageing heating system induce substantial fluctuations in indoor environments primarily affecting the stability of relative humidity (RH). RH is the physical parameter that can induce efflorescence as well as plaster blistering and detachment in its inside walls, drying and cracking in the timber and efflorescence and disgregation in the carved dolostone. Where the RH inside building is not high, as in the present case, natural and induced fluctuations may lower it considerably (<25%), which is detrimental to conservation and human well-being both. Human presence partially counters the steep declines in RH attributable to heating in winter and warm, dry summer weather, although the trade-off is a rise in $CO_2$ levels inside the church. Heating induces substantial changes in the *T* and RH on the high altar and in the upper areas of the nave, while natural ventilation affects the RH at the base of the church and favours the elimination of $CO_2$. The results obtained have allowed us to develop a series of recommendations that might be useful for the preventive conservation of such historic buildings, without compromising human comfort.



## 1. Introduction

The natural indoor environment or historic indoor climate is defined as the hygro-thermal conditions (RH-*T*) prevailing inside a building throughout a representative period of its history [1–5]. The indoor environment tends to be more stable than the outdoor climate and to fluctuate less and more slowly. Under these temperature and humidity conditions, the materials comprising both the indoor elements (such as stone ashlars, clay-based materials, timber coffered ceilings, stuccos, deck slabs) and the works of art they enclose (sculptures, paintings, frescoes) adapt and become acclimated, and thus endure the passage of time [5–8].

The indoor environment depends primarily on the outdoor climate, building structure and dimensions, construction materials used and the hydrogeology of the underlying soil [9]. Interference is nonetheless inevitable, and may even generate artificial or induced microclimates with steep temperature (*T*) and humidity (RH) fluctuations that may destabilise the fragile balance between indoor climate and conservation of the artistic and architectural heritage [1,4,5,7,10,11]. Material surfaces are known to be affected by abrupt changes in environmental temperature and humidity, for these two parameters govern the most common types of decay, such as wet-dry cycles [1,4,12], thermal shock [10] and surface or under-surface salt dissolution-crystallisation [13–15]. The ultimate consequence, known as material stress or fatigue, induces cracking, blistering, scaling, disaggregation and detachment in wall surfaces

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[10,12]. Moisture condensation may contribute to dissolving alkaline surfaces when the water vapour comes into contact with $CO_2$ flowing into the church through open doors or generated by human metabolism, use of certain heating systems or lit candles or incense [12,16,17]. Carbonate (lime mortars or limestone) and sulfate (gypsum or cement mortars) dissolution releases anions and cations that are carried inward where they precipitate as salts [14,15]. Another result of surface condensation and damp (in the presence of high humidity and moderate temperatures) is biological colonisation by fungi, bacteria or even insects that may cause biodeterioration in certain areas of the building [5,12,16].

The indoor conditions in historic buildings may be characterised by temperature and relative humidity values that run counter to human comfort [12,18,19]. Consequently, the main fluctuations in the indoor environment are can be attributed to human users, whose mere presence alters the existing conditions and whose thermal comfort requires the use of environmental control systems [6–8,12,18,20–22].

Many historical buildings (museums, theatres, palaces) have been studied in recent decades to establish requisites and strategies that would guarantee the protection and conservation of their indoor cultural assets, the well-being of their inhabitants, their energy efficiency and their economic sustainability. All those studies take as their point of departure a detailed understanding of the natural indoor environment and its variations in connection with any severe periodic alteration [3,7,11,19–26]. These authors also showed that each building has its own specific indoor environment that depends on a host of local factors, precluding any possible generalisation in such studies.

Churches are among the most recent buildings to be addressed in this regard, since in countries with very cold and humid climates, the uncontrolled installation and use of heating systems beginning in the twentieth century have been shown to induce the deterioration of building interiors by adversely affecting their historic climates [4,9,10,12,20,27,28].

In Spain's cultural heritage, ninth-to nineteenth-century churches constitute a very numerous group of listed “historic-artistic monuments”. In most cases, they are architectural gems of considerable historic and artistic worth. They are spread across the entire country, and are mainly found in rural areas. Throughout their history, these buildings have been reconstructed and rehabilitated in ways that have modified not only their appearance but also their indoor climate. In addition, heating began to be installed in many of these churches in the mid-twentieth century. The preference was for warm-air, intermittent systems, favoured for their low cost and speedy response, providing a comfortable indoor environment in short periods of time. In the absence of any regulation for this practice in such buildings until December 2012 (Spanish and European standard UNE-EN 15759-1) [29], heating systems were chosen in pursuit of users' thermal comfort, with no regard for the sustainable conservation of indoor church environments or their artistic assets [12].

San Juan Bautista Church (thirteenth-sixteenth centuries) at Talamanca de Jarama, a town 45 km N-NE of Madrid, Spain is a representative example of such historic buildings. It has been a listed monument since 1931. While this church can seat up to 300 seated people, it is scantly occupied most of the year (50–150 people), with a full congregation normally only for services on significant religious holidays (Christmas, Easter, local festivities and so on). Normal mass hours consist of one service each on Friday and Saturday evenings and two on Sunday mornings. The low efficiency of its centralised and intermittent warm-air heating system installed in 1972 [30,31] has led to its mere occasional use for 1–2 h four to five times a week (Friday through Sunday; ~5–6 h/week) from November through April. In recent years considerable moisture has been detected in its lower walls, with the concomitant rise in environmental humidity. As a result, the church is ventilated by opening its doors an average 10 h daily.

The objectives pursued in the present study were, consequently: a) to characterise the type of natural environment prevailing inside a Spanish rural church, and its relationship to the outdoor climate and the associated conservation issues; b) to establish how natural ventilation, human presence and heating interfere with the natural dynamics of the indoor environment; and c) to determine whether the resulting alterations affect the decay of its inner walls and the deterioration of its artistic assets. Those data could be used to establish a series of recommendations for future action to control indoor hygro-thermal and $CO_2$ conditions with a view to conserving the indoor heritage in small churches.

## 2. Description of the church, the local climate and the heating system

San Juan Bautista Church was built in the twelfth-thirteenth centuries (Romanesque style) with dolostone ashlars. It was reconstructed in the sixteenth century (Renaissance style) with rubble stone and mortar, brick and an earth fill (Fig. 1). The apse and presbytery (high altar) are all that remain of the original church. The main body or nave, enlarged in the sixteenth century, has a rectangular floor plan (27 × 12.5 m) and is divided into three aisles with variable heights: 10.5 m in the middle aisle and 9 m in the two side aisles. The floor is 90 cm below the base of the high altar. The church lies at 30–50 cm below street level. The walls are 50 cm thick in the main body and 60 cm in the high altar. In 1885, when the church was in ruins, the south wall and bell tower were rebuilt, and a new choir was added over the west entrance. The present structure consequently has a 393 $m^2$ footprint and contains 3952 $m^3$ of air.

The church's most valuable indoor heritage elements include a Mudejar-style timber coffered ceiling, Romanesque ornamental dolostone carvings, primarily on the high altar, and a number of eighteenth century polychrome sculptures. These elements are highly sensitive to abrupt changes in humidity (wet–dry cycles) and the concomitant salt mobilisation and crystallisation.

The predominant stone, a yellow dolostone from nearby quarries [32], is found in ashlars, rough ashlars and ornaments of high altar (indoor and outdoor apse and presbytery), columns and arcades of main body and outdoor portals of south and west wall dados. This soft (105.2 ± 6.7 Mpa), porous (10–16%), high water

**Fig. 1.** San Juan Bautista Church (twelfth-sixteenth centuries), Talamanca de Jarama, Madrid, Spain.