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Analysing the Main Standards for Climate-Induced Mechanical Risk in Heritage Wooden Structures: The Case of the Ringebu and Heddal Stave Churches (Norway)

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Abstract: Studying, controlling and extrapolating the indoor microclimate of historical buildings have always been at the forefront among numerous preventive conservation strategies, especially in case of buildings made of organic hygroscopic materials, e.g., wood. The variations and fluctuations of the microclimatic variables, namely temperature (T) and relative humidity (RH), could have a detrimental effect on the mechanical properties of wooden objects, works of art and structures. For this reason, through the years, several guidelines have been provided by standards and protocols about the optimal microclimatic conditions that should be ensured to avoid the decay and the eventual catastrophic failure of heritage objects and buildings. In this work, two historical buildings entirely made of Scots pine wood have been analysed: the Ringebu and Heddal stave churches (Norway). These churches store several wooden medieval statues and paintings that are also susceptible to the effects of the microclimate. For this reason, the timeseries of the indoor relative humidity of the two churches have been analysed, in the framework of the indications provided by the standards. The criticalities of the existing protocols have been pointed out, emphasizing the need for systematically and periodically updated specifications, tailorable to a given case study of concern, without forgetting the ever-present needs of energy- and money-saving approaches.

Keywords: wood; cultural heritage; climate-induced risk; relative humidity; standards; stave churches

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1. Introduction

Heritage structures made by organic hygroscopic materials are highly susceptible to the microclimate that surrounds them. For the conservation and preservation of such structures, it is mandatory to assess the impact that the microclimate has on the decay of the constituent materials, preferably following internationally recognized guidelines and protocols. The existing standards are guides that provide indications to limit the climate-induced physical damage of hygroscopic, organic materials, kept in long-term storage or exhibition in indoor environments (such as museums, galleries, storage areas, archives, libraries, churches and modern or historical buildings). As already performed for historic libraries [1], a brief overview on the existing protocols about the wooden objects' conservation is described and summarised in Table 1. The Italian Legislative Decree D. Lgs. 122/98 (art. 150, par. 6) [2] delineates the main guidelines to ensure optimal conditions for the conservation of artefacts made by different materials; for wooden manufacts, the RH is recommended to range between 40% and 65%, while the T is recommended to range between 19 °C and 24 °C. The UNI10829:1999 [3] defines that, for wooden furniture, wooden sculptures, and panel paintings, the allowable RH should be confined between 50% and 60%, while the T should be around 19–24 °C. The European Standard EN15757:2010 [4] defines that, for organic hygroscopic materials, it is preferable to avoid RH extremes. To do so, the priority is keeping a stable RH or, at least, keeping the RH within a specific target range, limiting its fluctuation. The episodes in which the RH falls outside the target range are dangerous for the conservation of the studied objects as they represent extreme and severe variations. On the other hand, no indication is provided on the temperature profile. The EN16893:2018 [5], in the Annex C, defines that, for organic hygroscopic unconstrained materials, in order to maintain mechanical stability and avoid damage, the RH should range between 30% and 65%. Similarly, the Standard ISO 19815:2018 [6] defines tables on the risk of damage due to T and RH; in addition, it is underlined that it is difficult to set fixed thresholds for RH as the permissible limits depend on the RH level at which the item is equilibrated. The ASHRAE handbook [7] describes climate classes with given specifications on T and RH for the building envelopes that may contain movable cultural heritage, such as, for example, museums hosting collections in modern/recent structures. ASHRAE provides guidance on the allowable T/RH ranges that minimize several types of climate-induced decay (biological, chemical and mechanical) on different types of collection materials. However, despite ASHRAE not being strictly designed for historic buildings, the recommendations for museums, galleries, etc.—needing to reduce stress on their building envelopes—can be cautiously adapted to historical buildings. In particular, since historical buildings are typically subjected to limited artificial climatic control, control class B can be considered. According to Chapter 24 in [7], for this control class, the allowable RH range is between 30% and 70%.

Table 1. International guidelines on the preservation of wooden cultural heritage.

Document	Year	Type	Indications	Active (Yes/No)	Reference
D. Lgs. 112/98, art. 150, par. 6	1998	Legislative Decree	For wooden manufacts RH = 40% ÷ 65%, T = 19°C ÷ 24 °C	N	[2]
UNI 10829	1999	Standard	For wooden furniture and sculptures RH = 50% ÷ 60%, T = 19°C ÷ 24 °C	Y	[3]
EN 15757	2010	Standard	RH = limited within safe bands, T = no limits	Y	[4]
EN 16893	2018	Standard	For organic hygroscopic materials RH = 30% ÷ 65%	Y	[5]
ISO 19815	2018	Standard	For organic hygroscopic materials RH = 30% ÷ 65%	Y	[6]
ASHRAE Handbook (Chapter 24)	2019	Guidelines	For historical buildings, the *B* climate class is recommended: RH = 30% ÷ 70%	Y	[7]

Based on these main protocols in Table 1, several strategies, approaches, risk-based analyses and simulations have been proposed. Huijbregts et al. [8] assessed the indoor conditions of museums with both the ASHRAE guidelines and an in-house method, based on comparing the relative humidity around a wooden object with its bulk relative humidity. Later on, Camuffo et al. [9] proposed a preventive conservation methodology for wooden collections and objects; the main idea consisted of reconstructing the outdoor climate and simulating the indoor one by calculating the transfer function represented by a building, in compliance with the European Standard EN 15757:2010. Similar studies were conducted by Bertolin et al. [10] on reconstructing the historic climate for heritage buildings, in order to obtain information about the target RH level that can be considered suitable for conservation. The hygrothermal behaviour of historic buildings has been studied by Silva and Henriques [11,12] as well, carrying out risk-based analyses of the natural climate limited by the targets defined by the standards [4]; it was concluded that detailed analyses are needed to assess the sustainable conservation of collections and buildings, taking into account that more demanding environments require a strong use of HVAC systems and, therefore, significant energy consumption. Several additional studies [13–16] have been conducted on the microclimates of historic churches and museums, based on extensive field surveys. They highlight that, in some cases, the indoor environmental conditions do not meet the requirements established by the standards and they are, therefore, not suitable for the preservation of movable heritage; for this reason, passive and/or active techniques need to be implemented to resolve the hygrothermal deficiencies. Moreover, a way of evaluating the indoor environment in historical buildings may be based on calculating the indoor environmental quality (IEQ) index [17]. The IEQ index ranges from 100 to 0 and it is calculated based on the already known thresholds defined for T, RH, ultra-violet light and carbon-dioxide concentration [18,19]: the lower the IEQ index, the greater the risk of damage. The acceptable ranges for these quantities, defined by ASHRAE and Thomson Standards [19], are fixed and do not follow the climate variability, unlike the thresholds defined by EN15757. As a matter of fact, as visible in Table 1, most of the existing standards on the conservation of wooden objects and buildings establish fixed and constant safety thresholds for the microclimatic variables. This means that the thresholds remain as they are, even if extreme climatic conditions are experienced. For this reason, several studies have been carried out to propose new strategies and approaches that could be more flexible and adjustable to the variability of climate, often resorting to the use of HVAC systems. Bertolin et al. [20] and Califano et al. [21] recently proposed novel empirical ad machine learning tools to assess the risk of climate-induced mechanical decay in wooden structures, based on experimental evidence; the obtained results lay the foundation for establishing novel hygromechanical damage functions for wooden items. Kompatscher et al. [22] proposed a model to investigate dynamic setpoint conditions when intermittent heating/conditioning is in use in environments such as library archives; they simulated four different microclimatic scenarios (reference, with short-term fluctuations, with intermittent conditioning, with dynamic setpoint control) to try to combine both the objective of conservation and the objective of energy saving, usually in contrast with each other. Limiting the energy consumption is one of the main issues that have been recently brought to the attention of researchers, especially in the light of the current critical geopolitical events. If, on the one hand, there is the need to protect and preserve historic heritage from the natural climatic variations by mitigating them artificially, then, on the other hand, there is the need to save energy and limit its consumption (i.e., eventually to return to a "more natural" climate). Simulations and risk assessments on the evolution of energy consumption and costs for historical buildings and buildings that house artefacts have been carried out in the framework of global climate change [23], ensuring that the indoor climate is compliant with the ASHRAE [18], Thomson [19] and FCT-UNL guidelines [24]. Thus, not only has the evolution of energy consumption/cost due to the climate change been simulated, but the possible future risk for artworks has been evaluated as well [25]. In this framework, the current work aimed to investigate the main standards in matter of conservation of the wooden cultural heritage subjected to climate-induced risks. In particular, the standards are discussed in relation to two heritage case studies: Ringebu and Heddal stave churches (Norway). The timeseries and the fluctuations of the indoor relative humidity of the two churches have been analysed with respect to the indications provided by the international guidelines, and the criticalities of the existing protocols have been pointed out, emphasizing the need for up-to-date specifications. The two case studies are presented in Section 2 together with general information about the in-the-field monitoring campaign; the general assessments on the two churches' microclimates, their compliance to the standards in force, and the main results are discussed in Section 3; the concluding remarks are highlighted in Section 4.

2. Materials and Methods

The two case studies investigated in the current work are two medieval wooden churches located in Norway: the Ringebu and Heddal stave churches (see Figure 1). The words "stave church" refer to the way the church was built. As a matter of fact, stave construction is a building method based on the use of wooden posts (the staves) as load-bearing elements. They are usually arranged in a frame consisting of vertical and horizontal elements that rest on stone foundations. Both Ringebu and Heddal buildings are almost completely made of Scots pine wood and store many wooden artefacts, such as panel paintings and statues (Figure A1). The two churches are objects of the research projects Symbol (n. 274749) and Spara Och Bevara (n. 50049-1); in particular, they belong to long, in-the-field climatic monitoring campaigns that started in March 2019 and are ongoing. Microclimatic data (indoor and outdoor temperature, indoor and outdoor relative humidity see Figure 1) collected inside and outside Ringebu church during the first two years of the monitoring campaign have been shown for the first time in [21], while the same data collected inside and outside Heddal church are reported for the first time in Figure A2 in the Appendix A of this work.

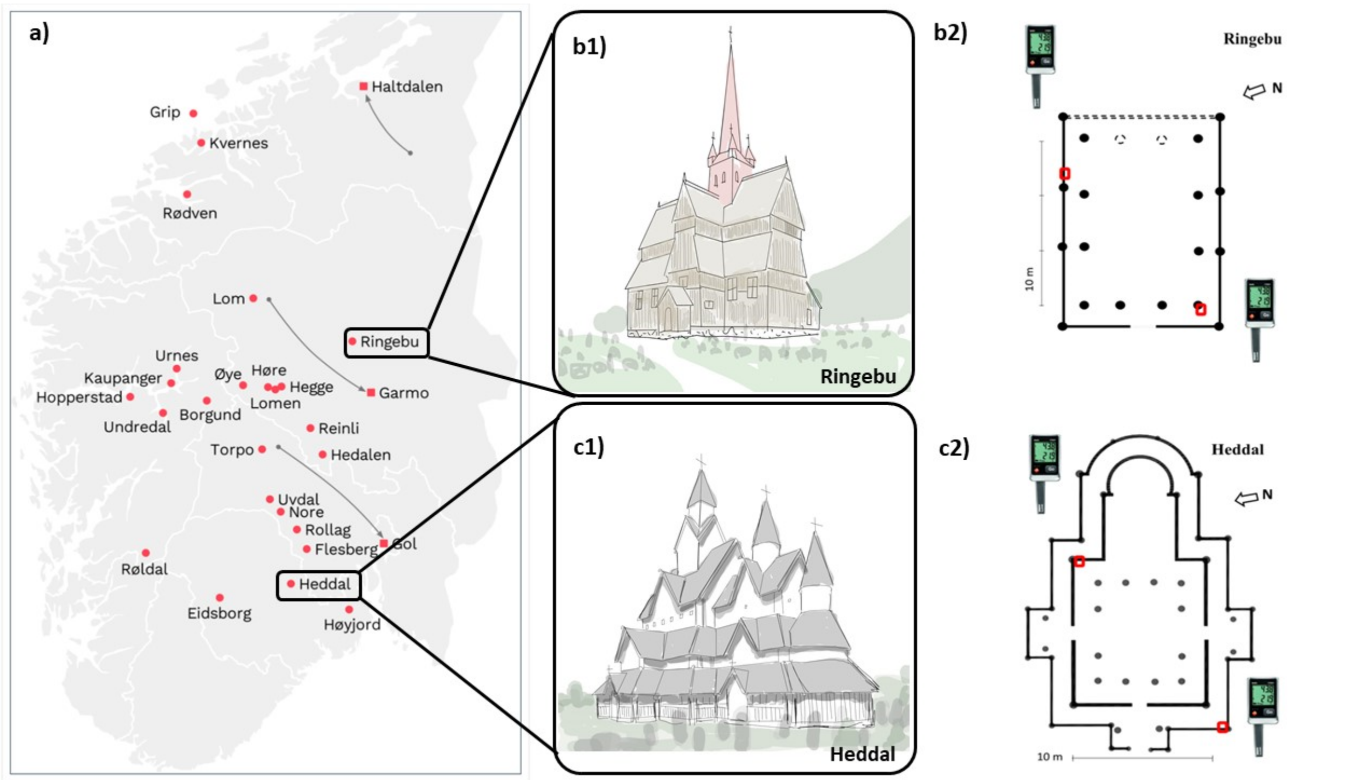

Figure 1. (**a**) Map of southern Norway with highlighted the locations of the still existing 28 Stave churches (red dots) after preserved stave churches in Norway by Store norske leksikon (https://snl.no/ accessed on 11 May 2022). (**b1**) Map and Hand drawn sketch of Ringebu Stave church adapted by [21]. (**b2**) Horizontal plan with scale unit, northern direction and locations of the indoors dataloggers installed indoors in Ringebu. (**c1**) Hand drawn sketch of Heddal Stave church. (**c2**) Horizontal plan with scale unit, northern direction and locations of the indoors dataloggers installed indoors in Heddal. Subplots (**b1**) and (**c1**) have been drawn by Elena Sesana.

The microclimatic data were collected by means of Testo 175H1 dataloggers, characterized by a precision of 0.4 °C and 1% RH and a resolution of 0.1 °C and 0.1% RH. The sensors were positioned at a height of 2.2 m to avoid the interference with people and their locations are visible in the floor plans of the two churches in Figure 1. The selection and positioning of the dataloggers followed the suggestions achieved after the monitoring of few other stave churches that are being studied in the framework a wider project, the MOV—environmental monitoring of the impact of climate change on protected buildings—funded by the Riksantikvaren, the Norwegian Directorate for Cultural Heritage, that started in 2017 and is still ongoing. In the framework of this project, the case studies are monitored to evaluate the impact that the climate change may have on them in a long-term perspective. To this end, the case studies have been equipped with low-impact instrumentation: with a few (two or three) battery sensors (to avoid the use of electricity and, so, the risk of fire) located in diametrically opposite positions. In this contribution, the collected T and RH data are useful to characterize the microclimate of the two case studies and to highlight its impact on both the wooden structures and wooden works of art stored within the churches themselves. In both churches, traditional radiators are installed and are usually switched on in cold periods of the year to guarantee indoor thermal comfort. Ringebu church is sporadically heated from mid-September to mid-April, only in cases of scheduled events (weddings, services, funerals, etc.); for this reason, this heating strategy is referred to as sporadic intermittent heating (SIH). Heddal church is continuously heated from October to May, to keep a constant indoor temperature of at least 5 °C; in addition, in case of scheduled events, from time to time, the heating is further turned up. Differently from Ringebu's, Heddal's heating strategy is named continuous mild heating (CMH). A summary is reported in Table 2.

Table 2. Use of heating in Ringebu and Heddal stave churches.

Church	Type of Heating	Heated Period
Ringebu	Sporadic (only in case of events)—SIH	Mid-September–Mid-April
Heddal	Continuous (≈5 °C) and sporadic (in case of events)—CMH	October–May

3. Results and Discussion

3.1. General Assessments on Microclimate

Analysing the monitoring data, preliminary information and assessment on the microclimate of the two stave churches can be easily performed. The indoor RH vs. indoor T ellipse is reported in Figure 2a for Ringebu Church and Figure 2b for Heddal Church. The two plots show scatters of hourly data collected in the two churches from March 2019 to March 2021. The different colours represent the four seasons of the typical calendar year: orange for spring, red for summer, green for autumn and blue for winter. The main difference between the two adopted heating strategies is easily appreciable from the two plots. In Figure 2a, the effect of SIH (representative of the microclimate conditions in Ringebu) is clearly visible: during winter, when the heating is not on, the scatters reach a minimum T value of about −10°C and a maximum RH value of about 90%, due to the wet and cold natural Norwegian climate; on the other hand, when there are scheduled events in winter and, so, the artificial heating is sporadically used, the blue scatters are shifted towards high T values (averaged around 15 °C) and low RH values (averaged around 30%), due to the contemporary heating and drying of the indoor environment. This behaviour is visible even in spring and in autumn, when SIH is used (Table 2). In Figure 2b the effect of CMH (representative of the microclimate conditions in Heddal) is clearly visible as well: during winter, the scatters are confined in a very limited area, due to the fact that a target T level (≈5 °C) is set. On the other hand, the mid-seasons (spring and autumn) are characterized by a highly fluctuating microclimate, while the summer season is characterized by less fluctuating (natural) climatic conditions.

Another way for assessing the microclimate of the two case studies is based on defining the daily ranges of T and RH evaluated over the two years of the monitoring campaign. For the generic microclimatic variable, X, its range on the i-th day, DX_i, is defined as follows:

$$DX_i = X_{max,\ i} - X_{min,i}\ i = 1, \ldots, N_{tot} \quad (1)$$

where $X_{max,i}$ is the maximum value for the X during day i, and $X_{min,i}$ is the minimum value for the X during day i, while N_{tot} is the total number of days in the considered period. Bar plots of daily RH range (DRH) and the daily T range (DT), computed according to Equation (1) for each season, are reported in Figure 3a,b for Ringebu church and in

Figure 3c,d for Heddal church, respectively. The height of each bar represents the mean value of the daily range for the considered season, while the black lines represent its standard deviation. In addition, a map of *DRH* vs. *DT* is reported for Ringebu (Figure 4a) and Heddal (Figure 4b) church. As in Figure 2, different colours have been used to identify the different seasons. Analysing Figures 3 and 4, the effects of the different heating strategies adopted in the two churches are easily understandable. The use of CMH in Heddal allows limited daily variations in both T and RH, while the use of SIH determines a high scatter and variability of the microclimate, especially in autumn and in winter.

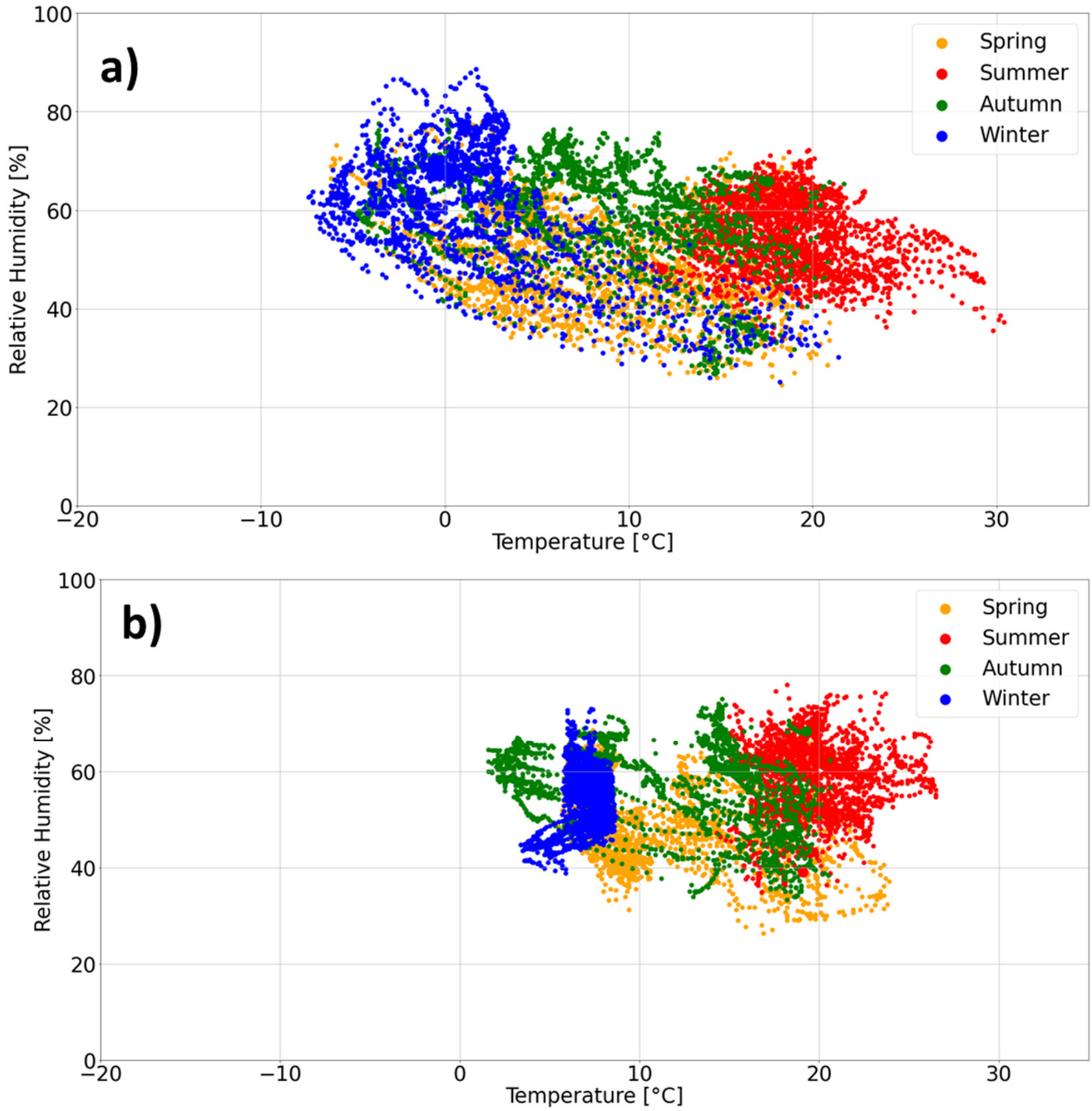

Figure 2. RH vs. T ellipses of data collected in Ringebu church (**a**) and Heddal church (**b**) from March 2019 to March 2021. The different colours represent the different seasons of the calendar year, according to the legend.

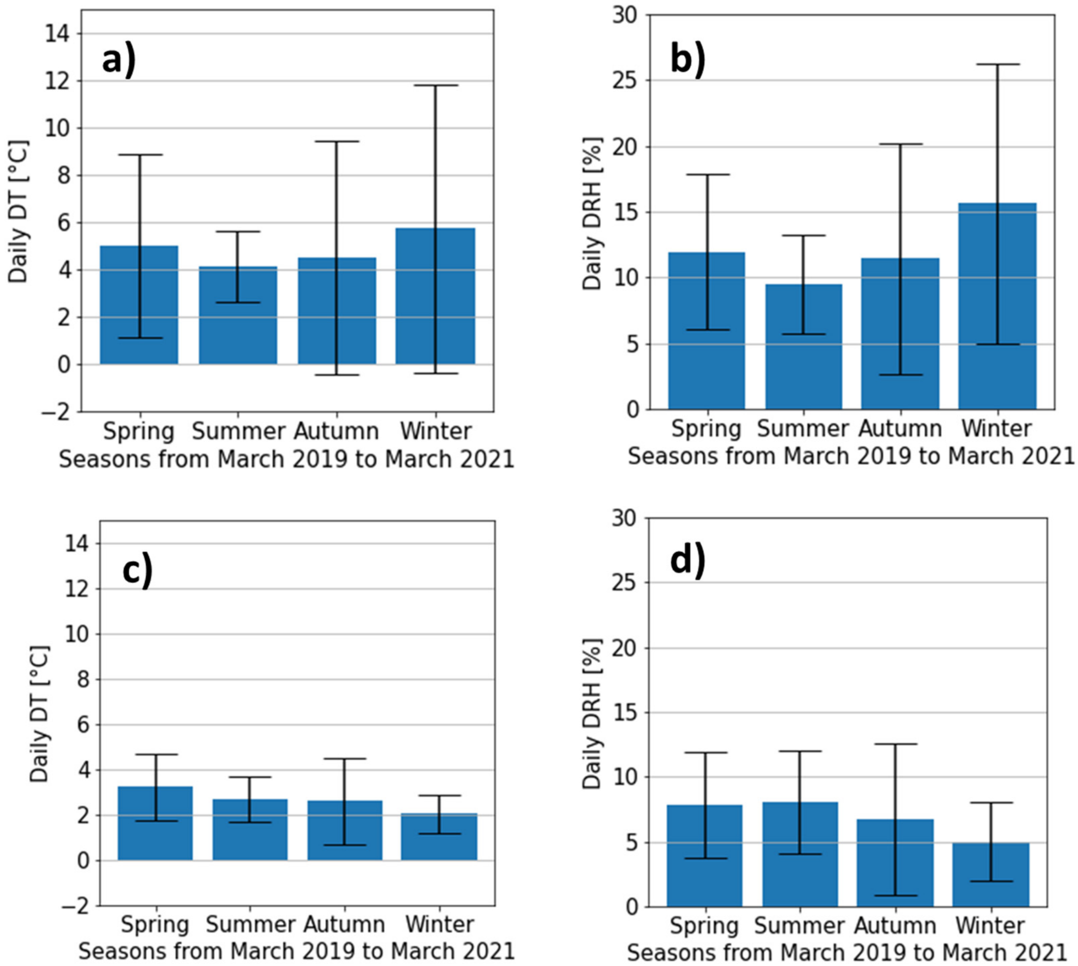

Figure 3. Bar plots of daily RH range and daily T for Ringebu church (**a**,**b**) and for Heddal church (**c**,**d**). The height of the bars is the average value for the considered daily range during one of the four seasons, while the black line is the standard deviation.

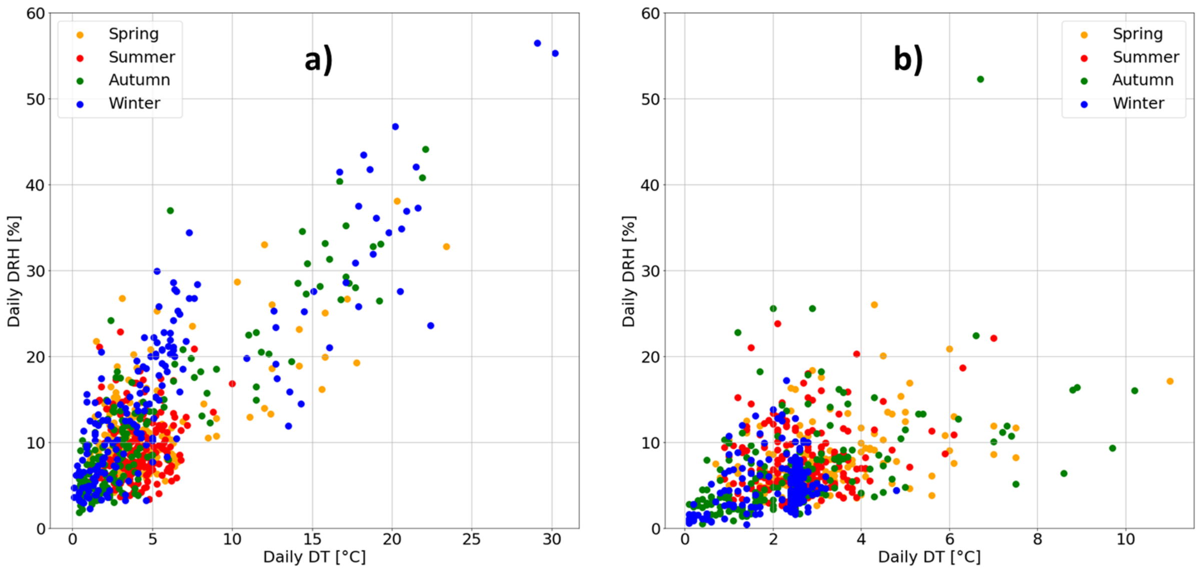

Figure 4. Scatter map of daily range of RH vs. daily range of T for Ringebu church (**a**) and Heddal church (**b**). The different colours stand for the different seasons of the calendar year, according to the legend.

These preliminary and general assessments about the indoor microclimate in Ringebu and Heddal stave churches highlight that these two historical wooden buildings undergo periods of heating/de-heating, which can cause severe fluctuations in RH. The wide variability of the RH, due to the artificially conditioned microclimate, can have detrimental effects on the wooden artefacts and structures, possibly causing deformations and failures. For this reason, the compliance of the indoor RH and its fluctuations to the existing protocols (Table 1), in matter of conservation of wooden structures subjected to climate-induced risks, is assessed in the following section.

In addition, in the light of the cited standards, the median of data (MoD) strategy, presented and described in detail for the first time in [20], is used in the following subsection. According to this strategy, by scanning entire RH timeseries and computing the median of data on short time windows, it is possible to catch the variations of RH and to evaluate their entity both in terms of amplitude and duration.

3.2. Implementation of the Standards

As summarized in Table 1, the existing standards and protocols provide precise indications about the thresholds that RH should not exceed to ensure the conservation of the wooden cultural heritage. The indoor RH in Ringebu and Heddal churches is reported in Figure 5a,b, respectively, with the thresholds defined in Table 1. It can be appreciated how the safety thresholds are exceeded, especially in Ringebu church (Figure 5a), due to the use of SIH (from September 2019 to April 2020 and from September 2020 to March 2021). On the other hand, the use of CMH in Heddal church (Figure 5b) makes the RH more stable over time and, therefore, the safety thresholds are less often exceeded.

The D. Lgs. 122 (art.150, par. 6) and the UNI 10829 are the oldest ones and defines very strict indications (black dashed lines and orange dashed lines, in Figure 5): the allowable RH should be confined in a 25%- or 10%-wide range, respectively. Going on with the years, the indications have become less strict: the EN 16893 and the ISO 19815 define a 35%-wide range for the allowable RH (red dashed lines in Figure 5), while the ASHRAE Handbook defines a 40%-wide range for the allowable RH (green dotted lines in Figure 5). The progressive enlargement of the allowable region has probably been driven by the fact that too strict measures impose a severe and extended use of heating, ventilation and air conditioning (HVAC) systems. Imposing less strict thresholds is, therefore, reflected in a reduction in energy and money consumption. However, fixing a wide allowable range for RH can be misleading for the actual needs of conservation of the cultural heritage. In particular, this can cause the neglection or underestimation of noteworthy climatic conditions; as a matter of fact, it could happen that steep and rapid increases/decreases in RH may occur even if still in the safe allowable range defined by the protocols. In addition, a further issue stands in the fact that fixed thresholds do not follow the evolution of the actual microclimatic timeseries and are applied to any case study without adjustments. A further step has been made by introducing the EN 15757, which defines the upper and lower bounds (purple curves in Figure 5) of the safe RH band, based on the historic microclimate. As visible in Figure 5, the bounds defined by this last standard follow the evolution of the RH timeseries and can adapt to the considered case study. This means that with the EN 15757 the "one size fits all" policy of the previous protocols has been translated into the newest "tailored to the case study" policy. However, as discussed in [21], the EN 15757 could be misleading in some cases as it neglects those severe fluctuations that may occur in the safe band as well. For this reason, following the median of data (MoD) strategy proposed in [21], the main fluctuations of RH due to the use of artificial heating (i.e., RH drops) in the two stave churches have been identified in the two years timeseries. All the collected RH drops, identified in terms of RH_{start} (RH value from which the drop starts) and RH_{min} (minimum RH value encountered during the drop), are reported in Figure 6 for Ringebu church and in Figure 7 for Heddal Church, together with the thresholds defined in Table 1.

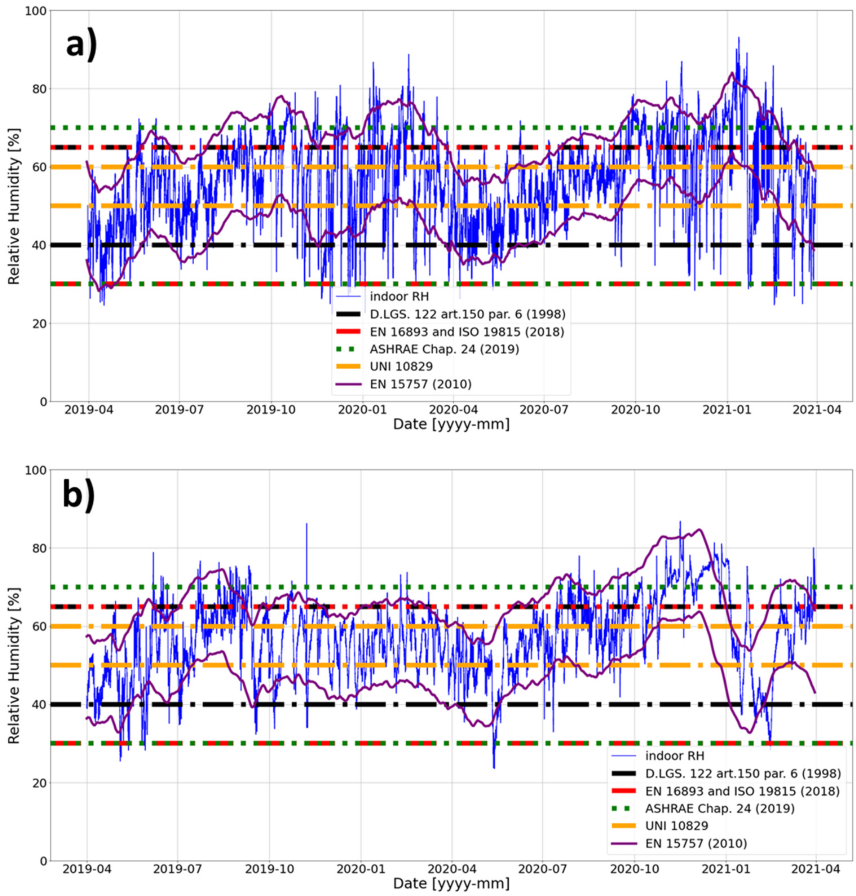

Figure 5. Indoor RH timeseries in Ringebu (**a**) and Heddal (**b**) church, together with the thresholds defined by the standards: D. Lgs. 122 art. 150 par. 6 (black dashed line), UNI 10829 (orange dashed lines), EN 16893 and ISO 19815 (red dashed lines), ASHRAE Chap. 24 (green dotted lines), EN 15757 (purple curves).

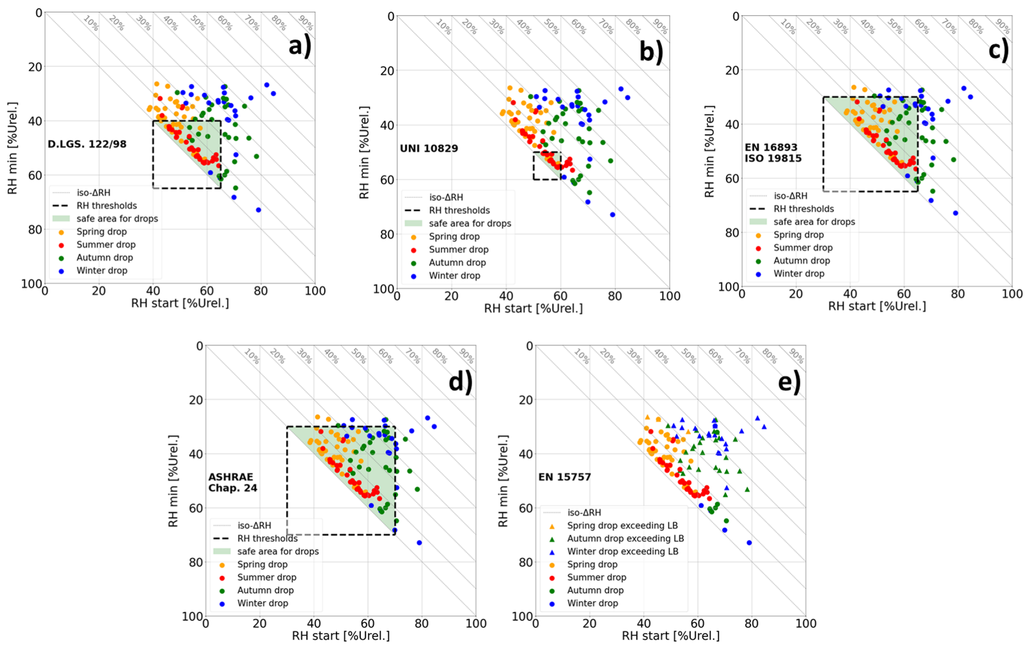

Figure 6. Scatterplots of the drops of RH identified in Ringebu church through the MoD strategy as originally explained in [20], together with the thresholds defined by the standards: D. Lgs. 122 art. 150 par. 6 (**a**), UNI 10829 (**b**), EN 16893 and ISO 19815 (**c**), ASHRAE Chap. 24 (**d**), EN 15757 (**e**).

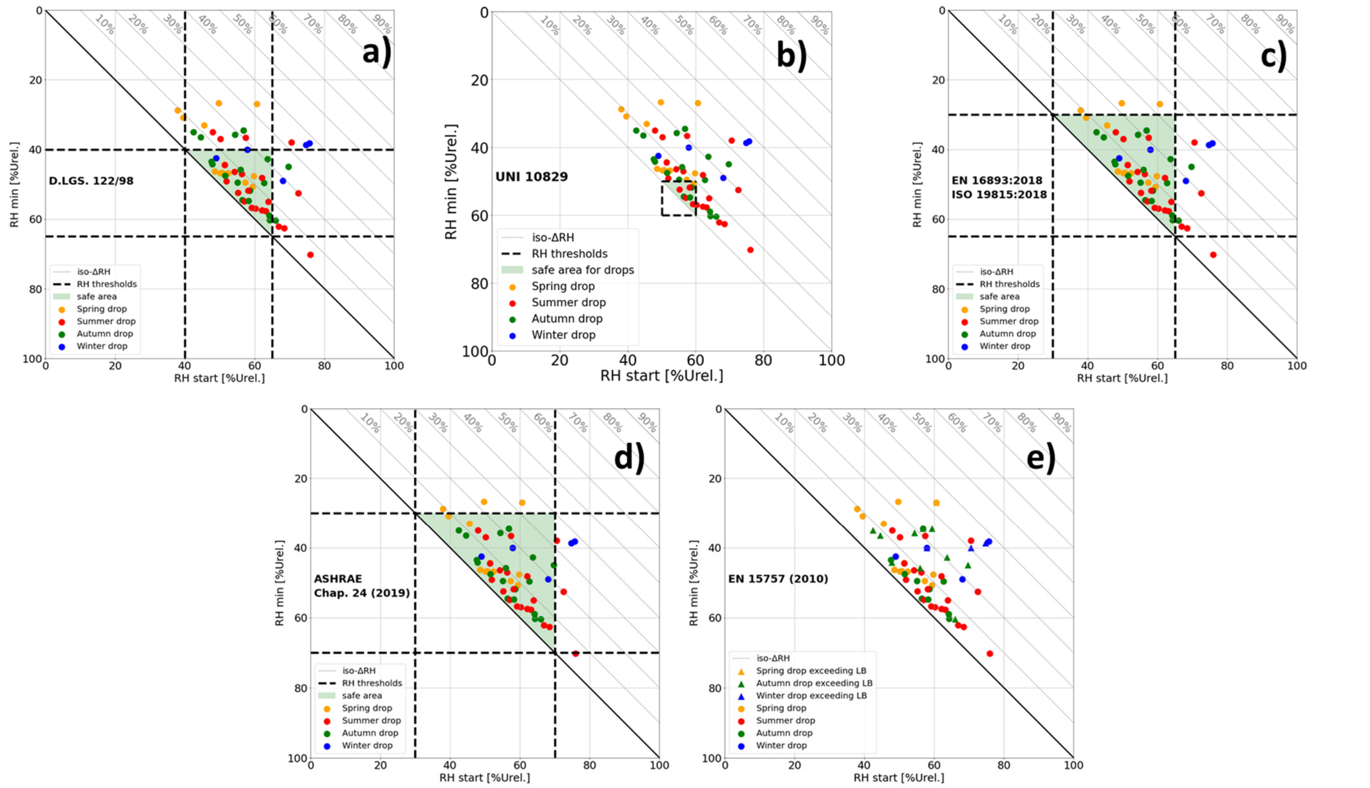

Figure 7. Scatterplots of the drops of RH identified in Heddal church through the MoD strategy as originally explained in [20], together with the thresholds defined by the standards: D. Lgs. 122 art. 150 par. 6 (**a**), UNI 10829 (**b**), EN 16893 and ISO 19815 (**c**), ASHRAE Chap. 24 (**d**), EN 15757 (**e**).

Each subplot of Figures 6 and 7 reports the RH_{min} vs. the RH_{start} for each of the identified RH drops. In addition, the light-grey, tilted lines are iso-drop lines, while the scatters are represented with different colours according to the season, as in the previous figures. The thick black dashed lines in the subplots (a–d) of Figures 6 and 7 are the RH thresholds defined by the standards in Table 1 and highlight the allowable area for RH drops (light green). In subplot (e) of Figures 6 and 7, as the EN 15757 does not provide fixed RH thresholds, different shapes have been used for the scatters to indicate if the RH drops exceed (triangles) or not (circles) the lower bound (LB) of safe band, due to the heating (and drying) of the environment. From Figures 6 and 7, as already discussed for Figure 5, it can be seen how the allowable RH area was enlarged through the years, mainly for saving money and energy.

However, loosening the measures in terms of RH thresholds is surely preferable under the economically and energy-based points of view as it is linked to limiting the use of HVAC systems; on the contrary, it is not recommendable for conservation purposes because the larger the safe area, the fewer the RH drops that are classified as risky. According to this logic, only a few RH combinations are considered damaging (i.e., the ones falling outside the green triangle in Figures 6d and 7d). After all, some RH drops that belong to the safe green area defined by the recent ASHRAE Handbook (Figures 6d and 7d) simultaneously exceed the lower bound defined by EN 15757 (triangles in Figures 6e and 7e). This underlines that the adoption of large thresholds is not preferable for the cultural heritage conservation, despite being more conservative in terms of energy consumption. In addition, applying fixed thresholds to the same family of materials, regardless to the actual conditions and features in play, can be counterproductive. In this framework, the EN 15757 appears to be the most reliable standard produced so far; nevertheless, its points of weakness are undeniable as it defines as risky RH fluctuations just the ones that exceed the moving thresholds, while it has been seen that severe RH fluctuations occur in the safe band as well [21]. For this reason, a systematic reorganization of standardization is surely needed in the field. First of all, the absence of regulated procedures for the microclimatic monitoring and data analysis hinders the development of reliable and universally recognized pathways for conservation studies. Moreover, the standards in force only provide general guidelines to be followed to avoid risky conditions for heritage buildings and works of art, irrespective of the case study under concern. As a matter of fact, up to now, the "one size fits all" policy has been mainly preferred but, nowadays, it can be considered outdated for two main reasons:

(i). The "tailored to the case study" policies have been introduced through the EN 15757 and have shown to be quite reliable in the first analysis, even if improvable;
(ii). Each museum/gallery/historic building has its own budget to rely on and its proper source of energy support, depending on the country it is in and on the national politics in matters of conservation and energy sources. This means that the implementation of generalized guidelines does not reflect the actual possibilities and needs anymore.

Finally, the main issue is that the standards are not periodically updated or modified, even though continuous and quick climatic and environmental changes occur. For the above reasons, establishing sustainable and reliable new policies that are tailored to a given case study, in order to both avoid the climate-induced mechanical decay and limit the energy consumption, is fundamental. This last aspect is quite contemporary, especially in the framework of the 2020s European geopolitical situation, which is drastically modifying the energy market and pressing international authorities to look for different energy sources and strategies. The severe impact that the international circumstances could possibly have on the field of heritage science and conservation concerns the reduction in the—already limited—funds and energy provision; this would dramatically affect the health state of those historical buildings (as the stave churches, for example) that can rely only on the use of non-sophisticated (and, in some cases, obsolete) HVAC systems for mitigating the climate-induced effects. As a matter of fact, due to construction reasons and aged state of the constituent materials, some heritage buildings cannot be radically restored to improve their energy efficiency. Based on the considerations made so far, in the case of Ringebu and Heddal stave churches, the most immediate and least intrusive conservation measures that could be adopted are the following:

(i). Limiting the use of artificial heating from November to February as much as possible. The limit needs to be set not only on the duration of the heated periods (in Heddal, the heated period lasts several months and is extremely energy-consuming) but particularly on their entity (in Ringebu, the indoor environment sometimes reaches a T of 20 °C, while the natural outdoor T is −10 °C).
(ii). Limiting the number of waivable events in cold periods of the year or shifting them to temperate months, thus avoiding a severe use of artificial heating and implementing a mild artificial microclimate policy exclusively during the mid-seasons.

It is clear that these are only general recommendable indications, but future works will surely deal with the construction of a complete and reliable logic in matter of preventive conservation actions to be taken, hopefully relying on adjustable and up-to-date guidelines.

4. Conclusions

In this work, the microclimate inside two historical wooden buildings (Ringebu and Heddal stave churches–Norway) has been analysed, based on data collected during a long in-the-field monitoring campaign, carried out for two years, since March 2019. The use of HVAC systems in both churches during cold months, for ensuring acceptable levels of thermal comfort, causes severe fluctuations of temperature and relative humidity that can have a detrimental effect on the mechanical properties of wooden objects, works of art and structures. For this reason, the indoor RH timeseries and fluctuations have been investigated, according to the indications provided by the existing standards (D. Lgs. 122 art. 150 par. 6, UNI 10829, EN 16893, ISO 19815, ASHRAE Chap. 24, EN 15757) for the conservation of wooden cultural heritage. Due to the remoteness of the stave churches' sites and to their vulnerability, it has always been difficult to set up long monitoring campaigns. Therefore, in the field of conservation of the stave churches, the evaluations and considerations of the current work are innovative and have never been carried out before. From the above investigations, the following main points have been highlighted:

(i). A critical discussion on the optimal climatic thresholds defined by the protocols allowed to delineate the points of weakness of the protocols themselves, in relation to the actual data collected through the monitoring campaign;
(ii). Standards based on fixed thresholds (UNI 10829, D. Lgs. 122 art. 150 par. 6, EN 16893, ISO 19815, ASHRAE Chap. 24) have been based on enlarging the allowable range for RH over time, due to economic and energetic reasons. This is translated in a possible underestimation of the actual climate-induced mechanical risk on assets and artefacts made of wood;
(iii). The only standard based on moving thresholds is the EN15757, which defines the allowable range for RH following the actual trend of the climatic timeseries;
(iv). Applying the standards' (fixed and moving) thresholds to real microclimatic data has brought to light that severe variations of RH occur even in the areas that are considered safe by the protocols (Figure 5).

For the above reasons, it can be concluded that the regulations in force have many weakness points; therefore, future studies should move in the direction of periodically updating the protocols and making them tailorable to the case study at hand, without forgetting the ever-present needs in terms of energy- and money-saving approaches. To this end, timeseries manipulation strategies showed to be helpful and could possibly support the standardization process by defining adaptable ways of analysing the case studies, one by one.

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Appendix A

Figure A1. Indoor of Ringebu (**B**) and Heddal (**D**) stave churches: wooden building assets and altars are visible. The sensors positioned in Ringebu (**A**) and Heddal (**C**) are shown as well.

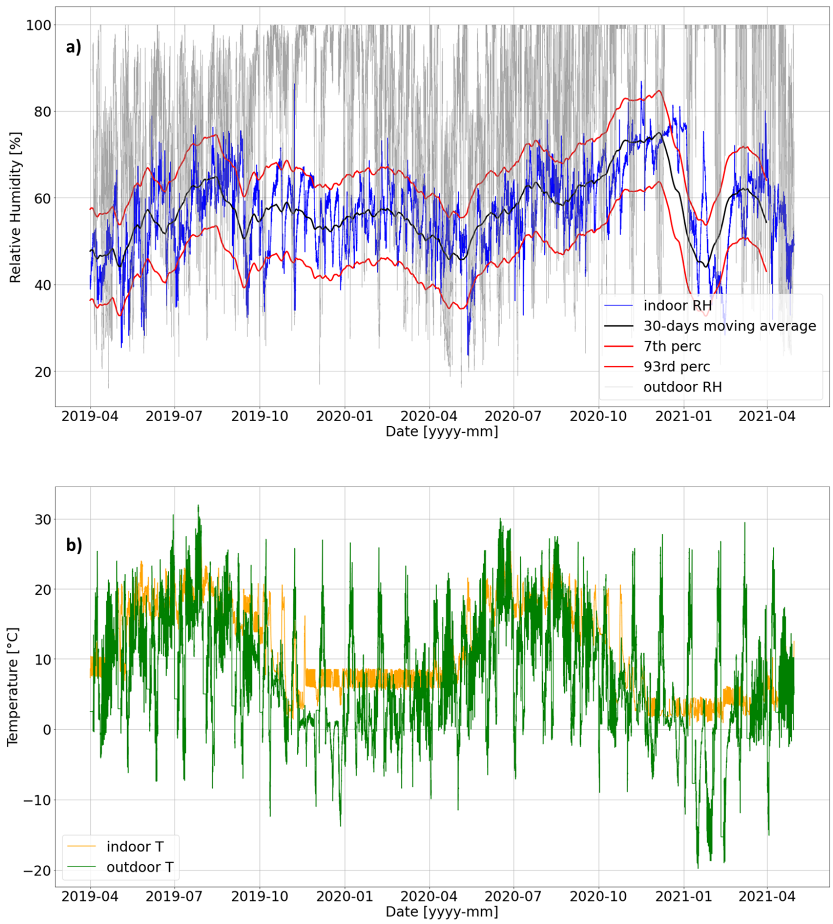

Figure A2. Microclimatic timeseries collected inside and outside Heddal church from the end of March 2019 to the end of April 2021: (**a**) outdoor RH (grey), indoor RH (blue), moving average of RH (black) and percentiles (red) of RH fluctuations computed according to [4]; (**b**) outdoor T (green) and indoor T (orange).

Figure A2a shows the measured indoor RH (blue curve), its moving average (MA) calculated over 30 days (black curve) and the 7th (bottom red curve) and 93rd (top red curve) percentiles of the RH fluctuations for Heddal church, calculated according to [3], over two years of observation (from 30 March 2019 to 30 April 2021). In addition, the outdoor RH is plotted with a light-grey curve. Figure A2b shows the indoor T (orange curve) and the outdoor T (green curve) in Heddal.

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