An approach to assess future climate change effects on indoor climate of a historic stone church

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SUMMARY:
Man made climate change on earth is a fact widely agreed on. The changing exterior conditions are not only affecting the buildings exterior surface, but also the resulting climate on the inside of the building. Especially in case of sensitive interior, like in cultural heritage buildings, this may lead to new challenges in the future. This paper presents an exemplary approach to assess the influence of changing exterior climate on the inner climate and thus on the interior of the building. A weather data set containing modelled values from 1960-2100 is compared to measured climate data within the same region. A methodology using descriptive statistics for the comparison of the modelled and the measured climate data is developed. After calibrating the modelled climate data the whole modelled weather dataset is processed as input for hygrothermal building simulation. A simple stone church in the region of interest is modelled. The hygrothermal building model is calibrated with past measured interior climate data. The successfully calibrated building model is then combined with the long-time climate file to predict interior climate conditions under the influence of climate change. Hygrothermal building simulation allows not only to assess the changes in building energy use but also in comfort conditions (which is, besides for people, "comfortable" for the valuable interior).

1. Introduction

Man made climate change on earth is a fact widely agreed on. Changing exterior conditions do affect the durability of buildings and the building energy use. But furthermore the interior climate conditions, strongly dependent on the exterior conditions, are likely to change. Especially in case of sensitive interior, like in cultural heritage buildings, this may lead to new challenges in the future. This paper summarizes the necessary steps for a well-founded assessment of climate change impact on hygrothermal conditions inside the building. The calibration of the modelled exterior climate with long term measured meteorological data is a first step. As example building an unconditioned stone church was selected. This church is located close to a weather station, which allowed the calibration of the modelled climate date. In a second step the building model itself is calibrated. Measurements of the temperature and relative humidity inside the chapel are compared to simulation results by hygrothermal whole building simulation. The calibrated building model allows applying long term climate data as boundary conditions. These results allow an assessment of critical changes in e.g. temperature or humidity levels or short time fluctuations. In the following, the modelled chapel and actual occurring problems are described. The paper will show how the interior conditions may change over time.

1.1 The chapel of ease St. Margaretha in Roggersdorf

After a complete renovation of the chapel of ease St. Margaretha (see Figure 1) in September 2004, the churchwarden noticed moisture damages on the walls. A subsequent climate measurement showed that those were a matter of condensation damage that occurs mainly in the transitional period during spring-time. At that time the building is still cold because of the winter. If warm, humid air enters the building due to natural air flow or uncontrolled ventilation inside, it condenses on the cold wall surfaces. But even in the summer and fall warm humid weather conditions can cause problems due to condensation. From December 2004 to August 2006 the temperature and relative humidity were measured inside and outside the church. Outer climate data are available from the Fraunhofer IBP outdoor testing facility at Holzkirchen, only 5 km away from Roggersdorf. During the measured period the climate inside the church shows a high average humidity with values over 75% relative humidity for more than half of the time of the year. During winter time the church also freezes with temperatures below 0°C for more than six weeks in a row [Kilian 2007]. Subsequently, the church starts with very low wall temperatures into spring time and the warm season. Another problem was the uncontrolled opening of windows and doors during that time, trying to reduce the moisture by ventilating at the supposed right times. In summer 2005 "ventilation traffic lights", showing the times when the water content of the outdoor air was lower than indoors, were used to give advice to the guardian of the church. This increased the daily fluctuations of relative humidity significantly, in spring and summer 2005 the fluctuations were above 15% relative humidity on more than 30 days. Daily changes above 15% relative humidity are thought to be critical to works of art [Holmberg 2001], as the risk of structural damages due to swelling and shrinking of materials increases with the range of relative humidity change per day.

2. Methods

2.1 Exterior climate modelling and data

For the simulation a modelled climate dataset was used. This was modelled with the Regional Model - REMO. The REMO-UBA simulations were commissioned by the German Federal Environmental Agency (UBA) and have been performed at the Max Planck Institute for Meteorology using the regional climate model REMO [Jacob 2005]. The REMO runs on 10 km horizontal resolution (0.088 deg.) for the time period of 1950 to 2100 for Germany, Austria and Switzerland. The simulations have been driven by results from the coupled ocean atmosphere model ECHAM5-MPIOM. Data for the geographical location of Holzkirchen was exported from 1960 to 2100. The climate change scenario used was the A1B IPCC scenario, which is a balanced sources assumption. This paper uses two datasets for modelled climate; 1995 to 2010 and 1985 to 2100, every data-set with a resolution of one hour time steps. The first is used to compare modelled with measured climate conditions, the second to compare past with future climate conditions. The measured climate data was recorded at the meteorological station at the Fraunhofer-Institute for Building Physics in Holzkirchen. Here also the dataset from 1995 to 2010 with one hour time steps is used for the comparisons. All exterior climate data sets were combined in a way to provide climate data useable by hygrothermal building simulation tools.

2.2 Interior climate modelling

For the simulation of the hygrothermal building behaviour the software tool WUFI Plus was used [Holm et al. 2003]. In the following the general conditions, the assumed building geometry and materials as well as the heating, ventilation and air conditioning are described. The time of calculation for the calibration of the model lasted from January, 1st to December, 31st of the year 2005. The simulation was carried out in time steps of one hour. The location of the church is in Roggersdorf near Holzkirchen. Therefore meteorological data of Holzkirchen of the year 2005 was used for the calibration simulation. A weather file was created which consisted of one hour values of exterior temperature, relative humidity, global and diffuse radiation, rain, wind and barometric pressure. Inner loads were not taken into account for the base case, assuming that there is no church service.

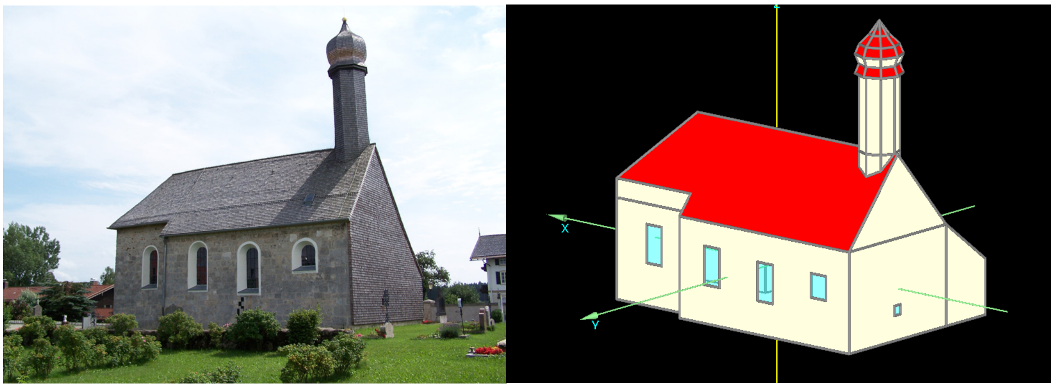

Figure 1: Picture and screenshot of the computer model of the exemplary church.

A detailed model of the chapel's geometry was created in WUFI Plus (Fig. 2). For the simulation the main body was divided into three zones. In the nave, the finally assessed zone, an infiltration air change with outside air of 0.5 1/h was assumed. The tower as well as the entrance area were treated as attached unheated zones with assumed exterior temperature and relative humidity in the zones. The outer walls of the chapel are built from sandstone. At the inner surfaces there is a layer of lime plaster. The base plate exists of a layer with loose material which is mainly covered by natural stone plates. Under the benches at the north and south side of the church there are panels out of hard wood instead. The ceiling to the attic, the third zone, consists of softwood, an air layer, mineral wool and again softwood. The chapel's roof and its covering are mainly built with softwood and shingles on the outside. The windows have a single glazing with an overall thermal transmission value of 3.7 W/m²K.

2.3 Statistical Methods

To show the applicability of the modelled exterior climate data a comparison with real measured data is required. There are several statistical approaches and methods in the literature for comparing simulated climate data with measured ones. The challenge is the large amount of the data which mostly consists of hourly weather data for different parameters for the whole prediction period. Togrul and Togrul [Togrul 2002] as well as Bashahu [Bashahu 2003] compared simulated with measured climate data using simple descriptive methods to check the climate prediction models. Root mean square error (RMSE) and mean bias error (MBE) show the linear correlation between the records, in each case, a low value is expected. These approaches are unreliable on their own. In order to obtain reliable results on the quality of the model, the authors recommend an additional test by a t-test. Nik [Nik 2010] describes both, parametric and nonparametric methods, for the assessment of simulated climate data. As a non-parametric method he uses box plots. This allows a first overview of the extensive datasets. For more detailed studies, he refers to the "Ferro-hypotheses". Ferro's [Ferro 2005] goal in the comparison of climate datasets is to represent the differences in the probability distributions. For all expected influences on the climate data hypotheses are established. Their influence on the simulated climate data is then represented by quantile-quantile plots. In this project, the focus concentrates initially on the use of boxplots to get a first overview of the data. A liftchart shows more clearly the compliance of modelled with measured climate data. The application of the "Ferro-hypotheses" is the last method to run.

With a boxplot, the distribution of data is displayed graphically. The box is limited by upper and lower quartiles which represent the 25% and the 75% borders. Thus, the box contains the middle 50% of the data and shows the interquartile range. The line in the box shows the median of the data. The whiskers indicate the values outside of the interquartile range. The length of the whiskers is limited at 1.5 times the interquartile range. Data that exceed this limit are shown as outliers. The boxplots used in this paper contain all hourly values for the described periods. The liftplot is also a graphical method for the comparison of measured and predicted data sets. Prediction and measurement values are arranged in ascending order of the simulated values. These so-ordered values are then divided into equal-sized classes. The number of classes should be chosen in a way that an adequate number of classes, each with an appropriate count of values, is generated. On each of the classes the mean of the corresponding measured values is formed. These mean values are then plotted in the liftchart. A strictly monotone slope of measured data is desired as it shows the quality of the simulation model. In addition, the means of the divided simulated values can be plotted in the liftchart. They should approximately match the measured means. Ferro et al. want to investigate the differences in the probability distribution of two data sets. They use quantiles to detect the reason for discrepancies. The differences can be in location or in the scale. Of course a combination of both is possible. This results in four hypotheses which represent: H1 = no difference in scale and location; H2 = differences only in scale; H3 = differences only in location; H4 = differences in scale and location. The equalities are according to Ferro et al the quantiles for the distribution obtained by adjusting one distribution to have, respectively, the same scale, location, and location and scale as the other distribution. The data sets are compared in quantile-quantile-plots. The values are arranged ascending and plotted in pairs of values. By comparing the quantile-quantile plots of data sets, respectively adjusted, the cause for differences can be investigated.

3. Results

The methods described in chapter 2 are applied to the datasets. Most of the statistical methods can be applied to all, exterior climate assessment, model calibration and interior climate assessment. The use of the methods will be exemplarily shown.

3.1 Exterior Climate Assessment

In a first step it is to determine, if the modelled climate data set represents the climate conditions on the given location. Local circumstances, e.g. nearby mountains, or other uncertainties in the climate modelling that influence the micro climate may cause that the modelled climate can not be applied for a detailed assessment of a particular building.

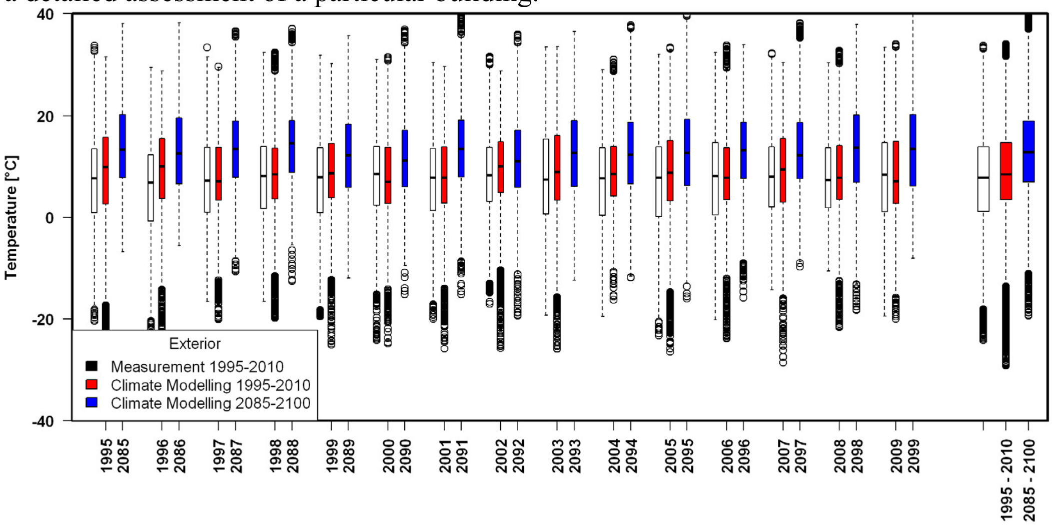

Figure 2: Boxplots of exterior temperature conditions

Three different exterior climate data sets are compared. Measured and modelled climate from 1995 to 2010 as well as modelled climate from 2085 to 2100. An “exact” comparison of the values does of course not make sense, as the modelled climate conditions are not a real weather prediction but much more a statistical climate prediction. Figure 2 shows a comparison of boxplots for all hourly values of the exterior temperature for each year of the chosen period. A direct comparison of measured and modelled temperatures between 1995 and 2010 shows annual differences in location and scale. The boxplots for the whole period on the right-hand side show that the differences in the distribution are not too big, with a mean temperature measured of 7.7 °C (IQR = 12.8 °C) and a mean temperature modelled of 8.7 °C (IQR = 11.3 °C).

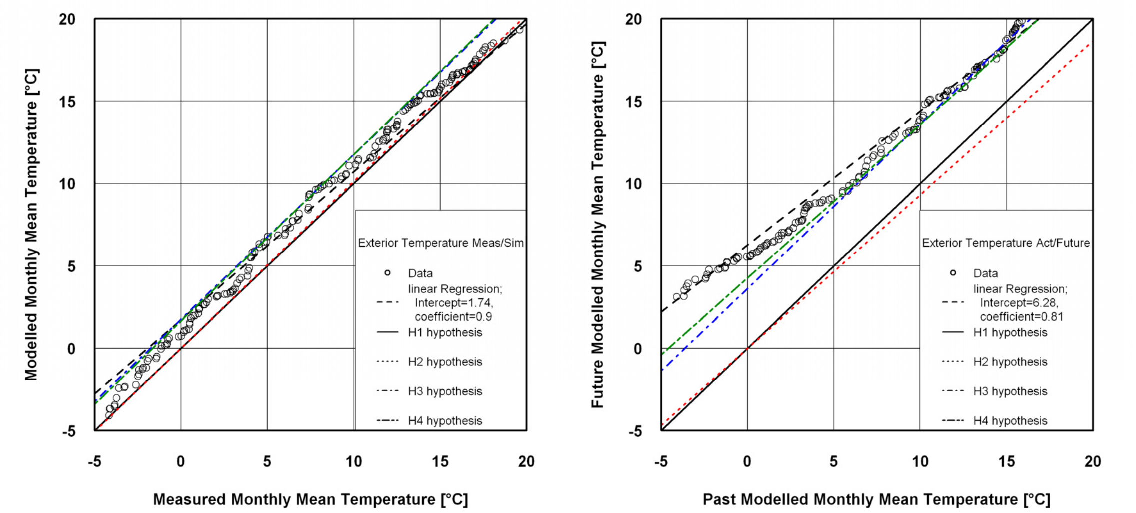

Figure 3: Graphical representation of the Ferro hypothesis for exterior temperature measured/modelled (left) and modelled past/modelled future (right)

Comparing past measured or modelled data with future exterior temperatures changes the picture. The level of the temperature is higher in all years, whereas the annual bandwidth seems not to change (mean = 13.4 °C, IQR = 12.0 °C). These assumptions can be graphically displayed and checked by plotting the monthly mean values and compare them to the graphs according to the Ferro hypothesis. Due to the mentioned adjustment both distributions are equal and thus the H1 hypothesis forms a line through the origin. The other lines present the other hypotheses which differ in slope (H2) intercept (H3) or both (H4).

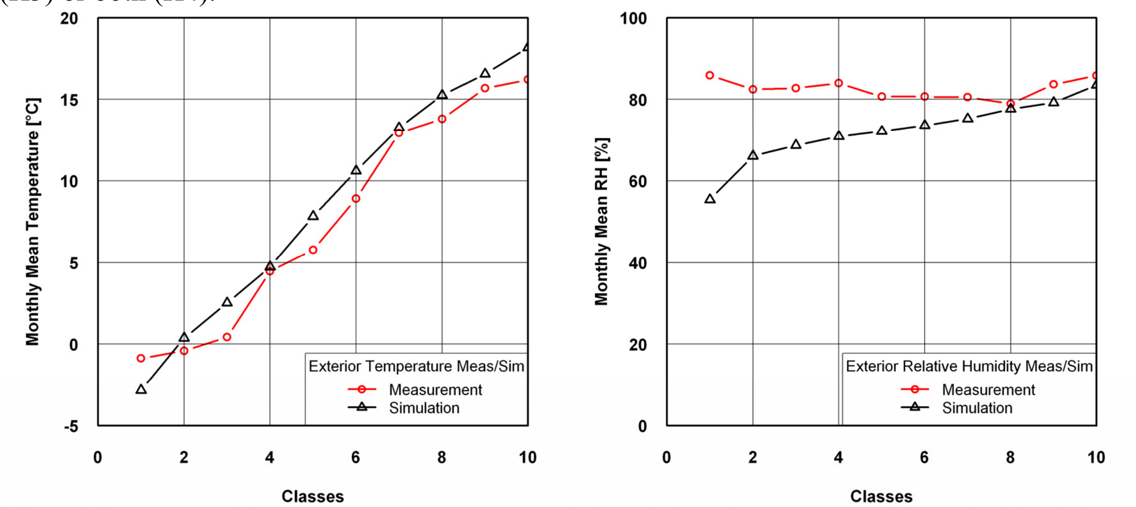

Figure 4: Lift plot for exterior temperature and relative humidity

Figure 3 left shows the modelled monthly mean temperature over the measured monthly mean data. All hypotheses are close to each other and the H2 hypothesis is quite exactly the H1 hypotheses. The quantiles are represented in lower temperatures by the H3/H4 hypothesis which means a difference in location and location and scale. In higher temperatures they are described by the H1/H2 hypothesis and thus by a change in scale. Figure 3 right shows the modelled past over the modelled future temperature and so shows a change in climate. Slope and intercept of the quantiles are best described by the H4 hypothesis and thus by a change in location and scale. The simulation values in the lift plot in Figure 4 show an increase for both, temperature and relative humidity, as these were the sorting values. The measured temperature values follow the simulation values in a similar slope and thus the inclination shows the quality of the model to predict the measured values. In the case of the relative humidity the measured values show no slope, and hence no spreading. The modeled data are not derived well by the model. Overall the methods show that simulated temperatures are well predicted by the model. The liftplot shows slight deviation and the hypothesis plot allows a broad assessment of the cause. Both methods are therefore well applicable to the given task. According to the lift chart the relative humidity isn't predicted well. Further investigations in both parameters could provide more precise results and thus a funded conclusion about differences and causes.

3.2 Interior Climate Assessment

An analysis of the interior conditions requires besides applicable exterior boundary conditions a building simulation model which allows "converting" the exterior into interior conditions. This building model needs to take into account all relevant boundary conditions and needs to solve the interior balances for energy and mass, but also the coupled heat and moisture transfer equations for the building envelope. Especially in the case of interior sensitive to humidity the moisture transfer is crucial. Before modelled exterior boundary conditions can be applied, the building model needs to be calibrated. Simulation results with applied measured boundary conditions are for that purpose compared to measurement results of the interior temperature and relative humidity.

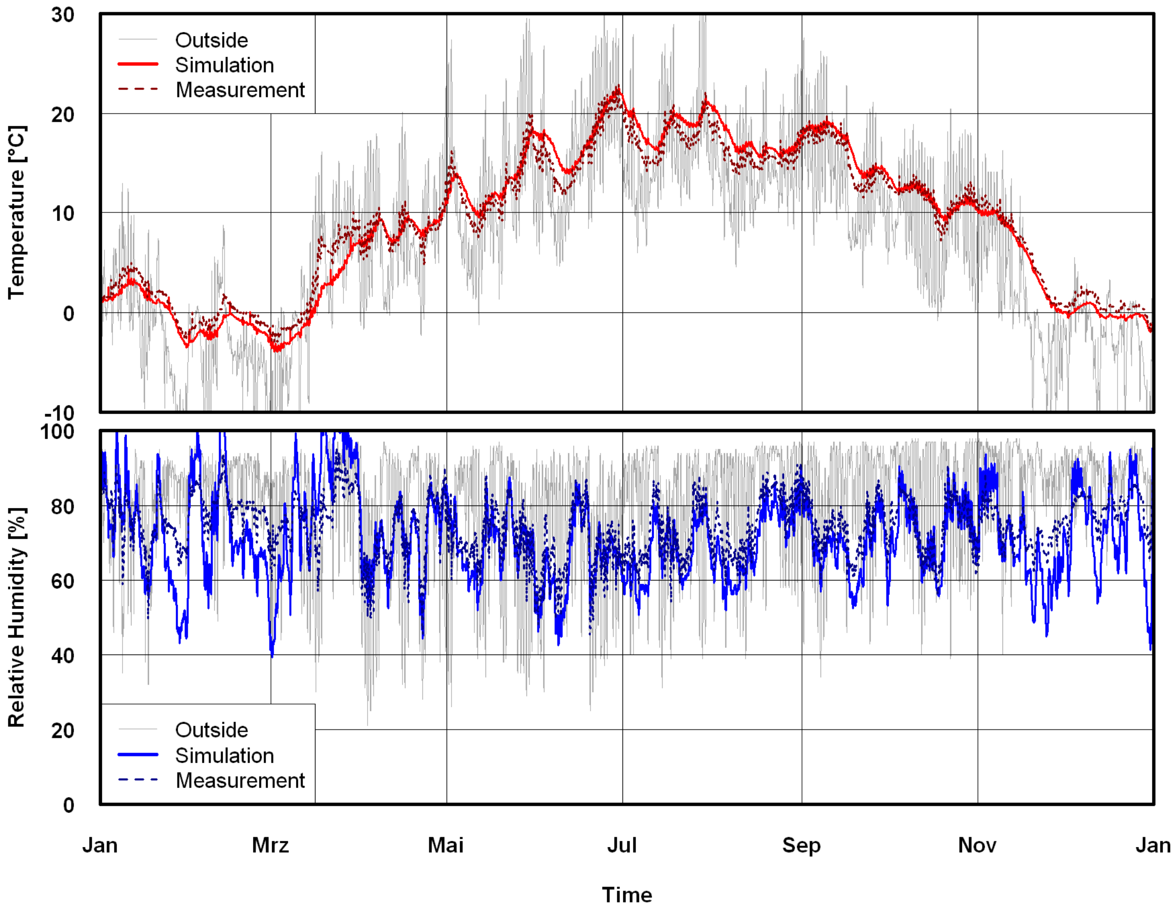

Figure 5: Calibration results for the year 2005 for interior temperature and relative humidity

In Figure 5 the first calibration results are shown. These can be further optimized, especially by taking more exact air change rates into account. Still, the agreement between measurement and simulation is ok. For a more detailed analysis of the agreement and the acceptability of the calibration simulation the same statistical methods as above described could be applied.

The calibrated building simulation model allows assessing the changes in interior climate by changed exterior boundary conditions. A combination of the results of applying 15 years of past measured and past modelled data as well as future modelled data is shown in Figure 5. Again the scale and location of the interior temperatures with measured and modelled exterior boundary conditions for the last 15 years seem similar. The future level of interior temperature is significantly higher, whereas the scale seems to prevail. Furthermore times with interior temperatures below 0 °C seem to diminish. All these further evaluations would go beyond the scope of this paper but are – in a real assessment case – necessary.

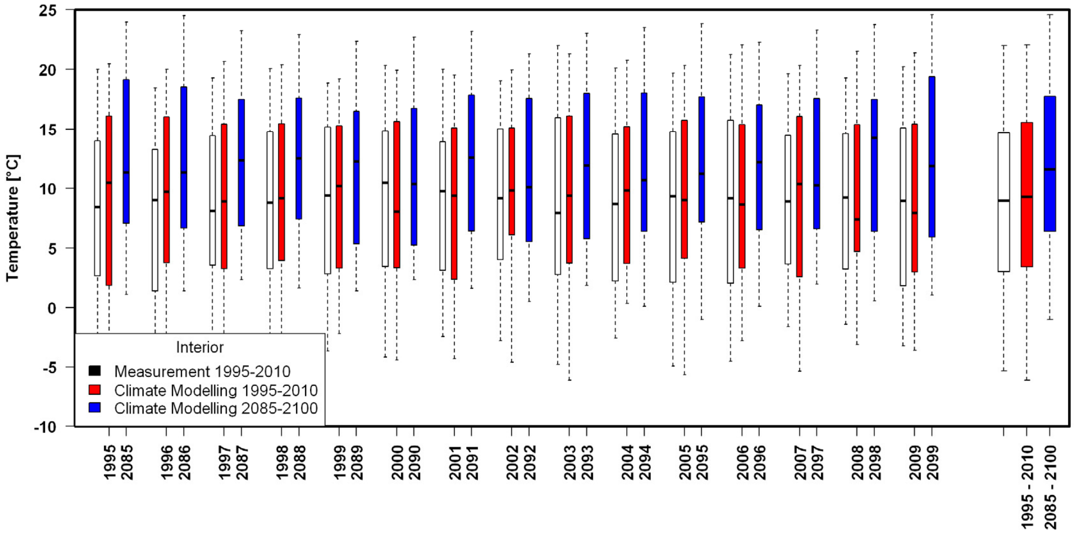

Figure 5: Boxplots of interior temperature conditions

4. Discussion and Conclusions

4.1 Usability of modelled exterior climate

It is shown, that the modelled exterior climate conditions represent the conditions on the location of the example building quite well. Some more analysis is necessary to determine the disagreement between measured and modelled humidity conditions, as these are main influencing parameters in the assessment of possible damages of cultural heritage items. The available statistical methods allow an evaluation, if modelled climate conditions are applicable. It is to assess, if the methods can be applied to all kinds of relevant parameters, or if the different distributions of these parameters require new methods.

4.2 Assessment methods for long term hygrothermal whole building simulations

The assessment of the changes in mean values and interquartile ranges of the results of hygrothermal whole building modelling gives a first overview if changing interior conditions are to be expected. This method can not only be applied on the resulting temperatures and relative humidity's but also on other critical values like daily fluctuations or count of freeze-thaw cycles. Further methods need to be applied to these long term simulation results to develop a methodology that best suits the assessment of climate change impact on buildings containing cultural heritage and to develop mitigation strategies.

4.3 General Conclusions

Long term hygrothermal whole building simulations to assess the climate change impact provide very detailed information. The resulting dataset is huge and requires new methods for the analysis. Different methods suggested in literature for similar problems are applied. They seem to be applicable to all necessary steps in a holistic assessment:

- assessment of the exterior climate on its applicability
- simulation model calibration
- long term past measured and modelled conditions assessment
- long term future conditions assessment

A more thorough methods analysis is required to define a comprehensive methodology for the above mentioned steps

5. Acknowledgements

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