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Heritage Science

RESEARCH

Making use of climate information for sustainable preservation of cultural heritage: applications to the KERES project

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Abstract

According to the final report of the European Union OMC expert group on strengthening cultural heritage resilience for anthropogenic climate change, the impacts of climate change, particularly extreme weather events, on cultural heritage in Europe have become increasingly evident in recent years and are progressing at an unprecedented speed and scale. Archaeological sites, museum collections, and historical buildings and structures are affected, among others, by rising temperatures or by heavy storms and precipitation events. Deep scientific knowledge about future climate projections is required to develop appropriate preservation strategies and measures to protect and adapt cultural heritage. In this paper we present the first set of results of the KERES project. The project focuses on the impacts of future extreme climate events on the built heritage and historic gardens. An ensemble of climate simulations is used to analyze changes in both climatology and extreme events for several climate variables at two cultural heritage sites in Germany. In this study, a methodology was developed to guide climate scientists on how to better tailor climate information for the needs of stakeholders in the cultural heritage sector. It would help the stakeholders to integrate the results of climate projections into the prevention and emergency management, in particular for the risk assessment of extreme events. The effects of interpolation from a model grid to a location of cultural heritage site and advantages of an ensemble approach have been demonstrated in the study.

Keywords Anthropogenic climate change, Extreme events, Cultural heritage, Climate information

Introduction

Climate change will be the greatest threat to natural and human eco-systems in the coming years and its consequences will impact every aspect of our lives [1–3]. Major impacts of rising temperatures on humanity and global ecosystems have already been observed. Some regions suffer more from heat waves and droughts, while others are experiencing extreme rainfalls. For example, the severe flood in several European countries in July 2021 caused widespread damages, destruction and the deaths of hundreds of people particularly in Belgium and Germany [4].

The threat of anthropogenic climate change is also considerably high for rich and diverse cultural heritage,

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which is an indispensable factor for community identification, a resource of knowledge, and a driver for future inclusive and sustainable development. The changes in weather and climate conditions aggravate the physical, chemical, and biological mechanisms causing degradation by affecting the structure and/or composition of the archeological sites, historic buildings or museum collections [5–10]. Cacciotti et al. [11] showed that the following damages are often reported at different levels:

- At site level, it can be primarily observed in the form of erosion, soil displacement, earth deposition, forest or park damage and individual trees damage.
- At building level, the main effects include material degradation, roof and façade damage, and primary and secondary structural damage.
- At the object level (i.e. movable heritage), widespread damage can be recorded widespread damage to furniture and musical instruments, to objects of art, to books and papers, to glass and ceramic objects.

To manage the cultural heritage sustainably, it is important to know how the climate will change in the future at the sites where the cultural heritage is located and to what frequency and extent the future climate will influence heritage typologies and materials [12, 13].

To address these important scientific questions, the KERES project has been launched by the German Federal Ministry of Education and Research in 2020. The full name of the project is Protecting cultural heritage from extreme climate events and increasing resilience. The idea behind the three-year research project is to use an ensemble of climate simulations from which the climate parameters required for the needs of cultural heritage will be generated. The climate data also serve as an input for modelling and building simulation tools for a better understanding and assessment of the damage risk potential for historic buildings, collections, and gardens in Germany. Furthermore, these data sets serve as the basis for sustainable and climate-friendly preventive and emergency measures to be designed. Thus, the project also makes an important contribution to the European Green Deal (https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM:2020:98:FIN). The project diagram is shown in Fig. 1.

The high-resolution climate data together with additional data from ongoing monitoring with sensors are bundled on a knowledge platform that is specifically developed to support cultural heritage institutions in both prevention and emergency management. Central to this is the structuring, linking and visual processing of data to enable risk assessment and prioritization of rescue measures and to facilitate decision-making and coordination processes. Interdisciplinary cooperation is key to providing in-depth knowledge and new insights into climate change interacts with cultural heritage. Therefore, the project team consists of natural scientists, conservators, climate scientists, building physicists, engineers, landscape architects, computer scientists and economists, among others. In addition, important players in emergency management such as fire and disaster control, German cultural heritage institutions, and an international committee of experts are involved. Within the project, high-resolution climate change projections are implemented together with the simulations of heat and moisture transport in walls and other multi-layer building components [14], as well as in and between building zones [15]. Thus, not only the impact of anthropogenic

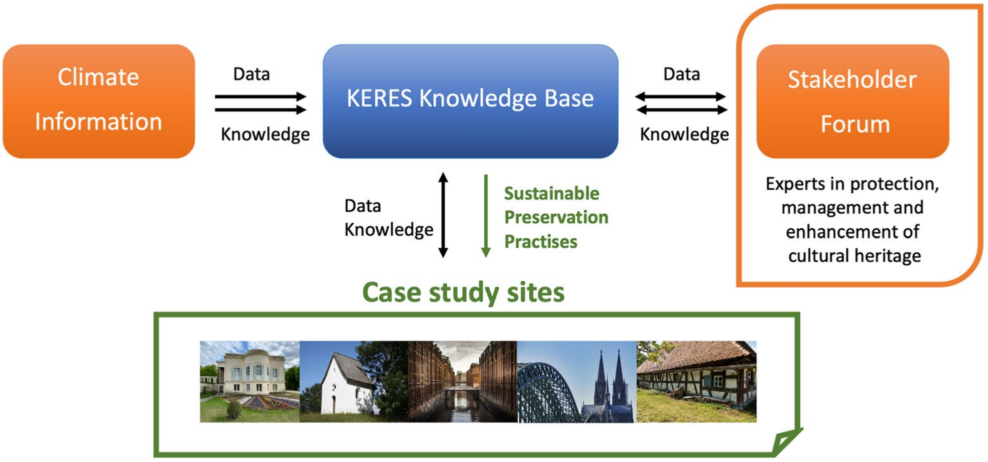


Fig. 1 KERES diagram

climate change on historic buildings can be estimated but also the possible effects on the related indoor climates, in which valuable works of art are kept, can be evaluated as well [16–19].

All of these research activities require credible information on regional climate changes. In this paper, we present the first set of results of the KERES project. We introduce the methodology that guides how to better tailor climate information and integrate the results of climate projections into the prevention and emergency management of cultural heritage sites. We analyze not only the climatological annual cycle but also the statistical characteristics of extremes and rather rare climate events related to thresholds of temperature, precipitation and wind speed. Finally, we address the issue of uncertainties and illustrate how the range of possible climate projections for selected variables can be estimated.

Methodology

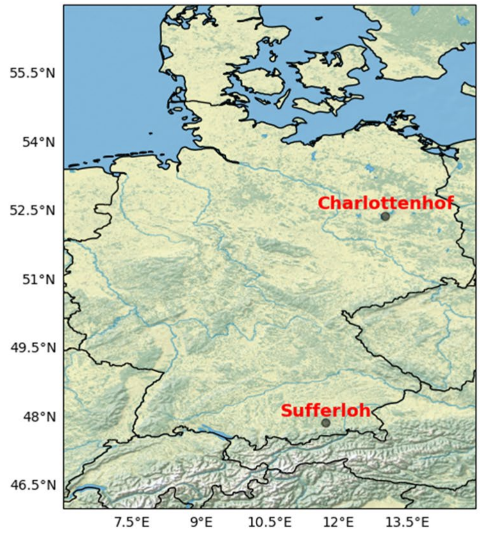
Five cultural heritage sites including historical buildings and gardens in Germany are selected in the KERES project. The analysis in this study is performed to estimate the reliability and quality of the modelled climate data for two cultural heritage sites located in two different climatic regions: the north-east and south of Germany. These are the Villa Charlottenhof (hereafter Charlottenhof) and the Frauenberg chapel in Sufferloh in Bavaria (hereafter Sufferloh). The geographic locations and orographic features of both sites are shown in Fig. 2. While Charlottenhof lies on flat land, Sufferloh is situated on the foothills of the Alps with complex orography.

Both Charlottenhof and Sufferloh are located in the temperate oceanic climate zone (Cfb), which is defined using the Köppen–Geiger Climate Classification [20]. Summers in Sufferloh are comfortable and wet; winters are freezing and snowy. Summers in Charlottenhof are generally warm and sometimes humid; winters are cold with the lowest temperatures in January and February. For both locations, climate observations were made available through the German Weather Service and Fraunhofer IBP (see Observational datasets for more details). The climate diagrams for the period of 1990–2005 are derived from these data (Fig. 3).

Case study history

The small, neoclassical-style villa of Charlottenhof and the surrounding park form the architectural complex was added to the Sanssouci Park in 1826 (Fig. 4), https://www.spsg.de/en/palaces-gardens/object/charlottenhof-villa/. The Prussian crown prince, later King Frederick William IV, was given the baroque country manor by his father as a Christmas present in 1825. He commissioned the architect Karl Friedrich Schinkel and the landscape gardener Peter Joseph Lenné to redesign the estate. The villa is imbued with the spirit of antiquity and its style is influenced by the architecture of Roman villas. The interior in Biedermeier style was partly designed by Schinkel and is characterized by a great variety of materials and artifacts.

The Frauenberg chapel in Sufferloh with its small baroque gable roof dating back to the first half of the 18th century is located in southern Germany, in the County Miesbach in Bavaria with partly original interior (Fig. 5), [21], https://geoportal.bayern.de/denkmalatlas/.



	Charlottenhof	Sufferloh
Coordinates	52.39N 13.03E	47.87N 11.73E
Climate zone	Temperate oceanic climate (Cfb)	Temperate oceanic climate (Cfb)
Orographic featrue	low land	foothills of the Alps
Altitude, [m]	35	680.0
Altitude in REMO, [m]	42.98	654.78

Fig. 2 Overview of the selected case studies

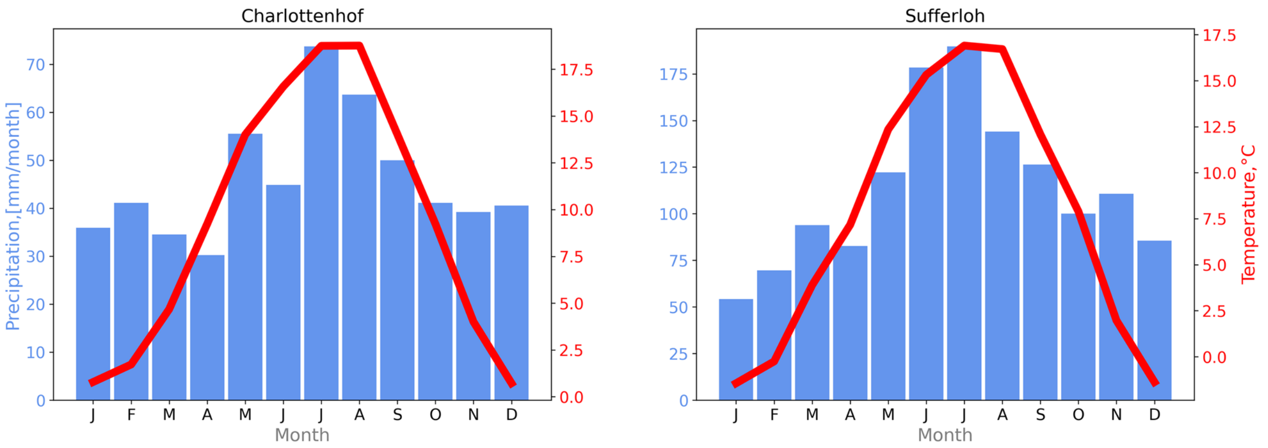


Fig. 3 Annual means of temperature and precipitation for 1990–2005

Fig. 4 Villa Charlottenhof,© J. Moßgraber

Fig. 5 Frauenberg Chapel in Sufferloh, © Fraunhofer IBP

Case study conservation status

The interior and the artistic objects in the Villa Charlottenhof appear largely in their original context and are overall in a good state of preservation. There is no climate control system in the Villa Charlottenhof, so one focus of the KERES project is on the indoor climate, with long periods of high indoor temperature and dryness in summer, that affect the valuable interior. Another focus lies on for the guidance of visitors. Moreover, the project investigates changes in wind intensity, which can cause damage not only to the historic building but also to the surrounding park.

Contrary to Charlottenhof, the main problem at Sufferloh is humidity and wind driven rain: the chapel is located on top of a small hill, directly facing westward. The extreme weather conditions of the foothills of the Alps strongly affect this small architectural monument, so that the chapel needed renovations again and again since the 1980s. So far, the recurring moisture problem has not been completely solved. Also, the wooden interior especially the wooden panel painting of the altar piece is suffering from bad indoor climate conditions. The damage to the interior is mainly caused by the high indoor relative humidity, according to former indoor climate measurements with an average of 92.7% in the time from September 2012 to September 2013. These high relative humidity values cause swelling of wooden parts and, as a consequence, lead to deformation of the wood and damage to the paint layer of the panel painting. Also mould growth occurred on the inside of the walls and on the interior. Thanks to previous examinations of the masonry, it became clear that the high moisture load results from the high driving rain load. The moisture is absorbed through the plaster and then distributed in the masonry. In consequence the damp walls lead to high indoor air humidity. Therefore, the aim of Sufferloh case study is to investigate the influence of driving rain on indoor climate via moisture transport by driving rain exposed walls.

KERES database

The KERES database is intended to serve as the foundation for further research into the impact of future anthropogenic climate change on selected cultural heritage sites in Germany until 2100. This database consists of an ensemble of high-resolution climate simulations for the time period from 1970 to 2100 with hourly temporal resolution. Climate projections are based on the RCP 8.5 emission scenario [22]. The KERES database is a part of the KERES knowledge base (see KERES knowledge base). This is an open access platform.

The climate simulations, collected at the KERES database, are intended for further use as an input to hygrothermal simulations of buildings [15, 23]. This methodology requires hourly data on different climate variables for a longer time period. These variables are among others near-surface air temperature (hereafter temperature), liquid plus solid precipitation (hereafter precipitation), wind speed at 10 m (hereafter wind speed), cloud cover, surface pressure, relative humidity and solar radiation. A number of observational datasets are stored in the KERES database as well. These are used to evaluate the performance of climate models.

Database of regional climate model simulations

Several studies [24–26] demonstrated that an ensemble of climate projections can be successfully used to study the effects of anthropogenic climate change on cultural heritage. Commonly used for century-long climate simulations are Earth System Models (ESMs) [27]. The spatial resolution of the current ESMs is approximately 100 km. However, this information is too coarse to be directly applied to study the impact of anthropogenic climate change on historic buildings. Therefore, a downscaling of the ESM output to the location of the cultural heritage site is required to reach a higher geographical resolution.

Numerous downscaling techniques have been developed to derive local climate change information from climate model outputs [28]. Dynamical downscaling uses regional climate models (RCMs) driven with the output from global ESMs to derive an anthropogenic climate change signal with higher spatial resolution. The climate projections in the KERES database are the results of dynamical downscaling performed within the EURO-CORDEX Initiative (http://www.euro-cordex.net/) [29]. EURO-CORDEX is part of the WCRP World Climate Research Programme Regional Downscaling Experiment CORDEX (http://wcrp-cordex.ipsl.jussieu.fr). Within EURO-CORDEX, the global projections from the fifth phase of the Climate Model Intercomparison Project-CMIP5 [30] were dynamically downscaled to the European domain; the exact size and location of the EURO-CORDEX domain is shown on https://euro-cordex.net/index.php.en. The core EURO-CORDEX contains the output data from a set of simulations with different regional climate models with a spatial resolution of 0.11° (12.5) km. As it is mentioned above, the building simulation tools used in KERES require hourly resolution of the input data. At the time of the project's start this requirement was fulfilled by only 10 global-regional models combinations of EURO-CORDEX. All of them are based on the regional climate model REMO. The selection of simulations for the KERES database is therefore called the ESM-REMO ensemble. The global projections used to drive the regional climate model REMO (hereafter REMO) were taken from eight global ESMs (Table 1). For the model of the Max Planck Institute for Meteorology, three simulations with different initial conditions were performed. For this reason, the KERES database yields a total of 10 combinations of the regional

Table 1 List of the CMIP5 climate models (ESM)

Global Model (abbreviation)	Organisation
CCCma-CanESM2	Canadian Centre for Climate Modelling and Analysis
CNRM-CERFACS-CNRM-CM5	National Centre for Meteorological Research, Météo-France and CNRS laboratory
ICHEC-EC-EARTH	Irish Centre for High-End Computing
IPSL-IPSL-CM5A-MR	Institut Pierre Simon Laplace, France
MIROC-MIROC5	University of Tokyo, Centre for Climate System Research, Japan
MOHC-HadGEM2-ES	Met Office Hadley Centre, UK
MPI-M-MPI-ESM-LR*	Max Planck Institute for Meteorology, Hamburg, Germany
NCC-NorESM1-M	Norwegian Climate Consortium

*Three simulations with different initial conditions were performed model REMO and eight different global models. REMO is a three-dimensional, hydrostatic, atmospheric circulation model within a limited area [31]. For the simulations in this study the latest version of REMO (REMO2015) is used. The model domain covers Europe at 0.11° (12.5 km) [29].

To investigate the impact of the future anthropogenic climate change on cultural heritage in Germany for a long-term time period, the transient simulations from 1971 to 2100 with hourly resolution for all of 10 ESM-REMO combinations are stored in the database. For the simulations derived by MOHC-HadGEM2-ES, the transient runs are available until 2099 only. While the observed concentration of greenhouse gases (GHG) is taken into account for the historical time period of 1970–2005, the business-as-usual scenario RCP8.5 is applied for the climate projections from 2006–2100 [22]. The Representative Concentration Pathways (RCPs) illustrate the bandwidth of possible future GHG emission trajectories depending on population growth, the development of energy production, food production, and land use. RCP8.5 is a highly energy-intensive scenario as a result of high population growth and a lower rate of technological development. The KERES project is focused on the analysis of extreme events. For this reason, we took into account the scenario that shows the extreme outcomes and could help to answer the question, “What is the worst climate projection that could happen?”

When modelling the future climate, a number of uncertainties should be taken into account. This might be due to a number of anthropogenic and natural factors [27]. Therefore, it is crucial to evaluate the performance of the models. This gives valuable insights into model skills and adds confidence in the climate projections for the future. In this study, we compare the results of the EMS-REMO ensemble with the results of additional simulations with the global ERA-Interim reanalysis model (hereafter ERA-Interim) as a driving force for the regional climate model REMO [32]. ERA-Interim is a blend of observations with past short-range weather forecasts rerun with modern weather forecasting models (more details can be found at https://www.ecmwf.int/en/about/media-centre/focus/2020/fact-sheet-reanalysis). Such boundary conditions can be assumed to be of very high quality, in particularly in the Northern Hemisphere extra tropics [33]. Therefore, the skill of the climate models in reproducing the present-day state of climate when driven by realistic boundary conditions can be demonstrated [34].

Observational datasets

In addition to the evaluation of the ESM-REMO ensemble against the ERA-Interim, the individual ensemble members as well as the ensemble statistic for climate variables were compared with observations. Two observational datasets are used in this study. These are station measurements of the German Weather Service (hereafter DWD) in Potsdam and the on-site measurement of the Fraunhofer Institute for Building Physics (hereafter IBP) in Holzkirchen. For the evaluation of the performance of the model data, the data from the years 1996 to 2005 were used. The choice of this period was motivated by the availability of observational station data. The DWD weather station in Potsdam is located at 52.38 N, 13.06 E at an altitude of 81 m. It is located 2.95 km away from Charlottenhof. The temperatures in the evaluated period were measured with a PT100 air temperature sensor, the precipitation amount with a droplet counter until March 2009 and a PLUVIO rain gauge afterwards and the wind speed and direction with a WMG 201 wind sensor. Data quality was controlled by DWD and the data was downloaded from the DWD weather data platform (https://opendata.dwd.de/). The Fraunhofer IBP runs its own weather station (https://imcom2.hoki.ibp.fraunhofer.de/wetter/) located at 47.87 N, 11.73 E, with a station height of 682 m. The IBP weather station is located 3.31 km from Sufferloh. This weather station also collects all relevant climate parameters, such as temperature, precipitation, and wind speed. The observational data used in this project was quality controlled by Fraunhofer IBP.

The main aim of our study is to introduce the methodology for using climate information for sustainable preservation of cultural heritage sites, selected for the KERES project. Therefore, it is sufficient to primarily focus on evaluating the basic climate variables, which are the major thresholds for extreme and rather rare climate events. For this reason, only the observational datasets for temperature, precipitation, and wind speed were considered.

Methodological framework

Climate information cannot be treated as an isolated topic by investigating the impact of anthropogenic climate change. To tailor the output of climate models to the practical needs, a novel approach designed in the European project Climate for Culture [16] has been applied and further developed in KERES. Similar to Climate for Culture, the output of climate models in the KERES study is interpolated to the selected cultural heritage sites. In this study, further developments have been made in the application of an ensemble approach and in the methodology used to interpolate climate data from the gridded model data set to a site of cultural heritage.

Ensemble approach

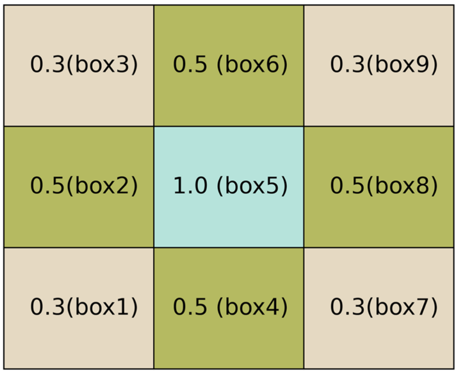
Regional climate simulations do not provide a forecast but project various possibilities of anthropogenic climate change into the future. To reduce the uncertainty in climate change projections stemming from individual models, an ensemble approach is widely used in climate and impact research. This is proven to give more reliable results than individual models [35]. As mentioned above, the ESM-REMO ensemble used in KERES consists of ten ESM-REMO combinations and corresponds to the current state of the art of climate modeling [36].

Interpolation method

Climate models separate Earth's surface into a grid of boxes and calculate the state of the climate system in each box. The regional climate model REMO used in this study has a grid box size of 12.5 km. To get the information for the location of cultural heritage sites from the model grid, the so-called weighted nine-point average is used in this study. Here, a weighted average of the nine grid boxes of the climate model centered at the location of the selected cultural heritage site is calculated. The weighting function is shown in Fig. 6. It spans over an area that is substantially larger than the area of the cultural heritage site. However, this is necessary, as the information obtained from a regional model is not fully point-specific. This is one of the standard approaches for interpolating gridded climate modelling data to a case study site [37]. For each case study site, the model data have been analysed for each of the nine closest grid boxes and for the weighted mean over them (see Results).

Statistical analysis

Comparing model results to observations provides valuable insights into the quality of model simulations. In this study, we analyse not only the mean climatology of climate variables but also show how the ESM-REMO ensemble captures the extreme events. First, the mean climatological annual cycle was analysed for all members of the ESM-REMO ensemble and compared to observations for the period of 1996 to 2005. The analysis of extreme events was targeted to the analysis of the ERA-Interim simulations only. For this, nine individual grid boxes and a weighted mean over the entire area were taken into account. We use cumulative distribution functions to show biases in observations. The cumulative distribution function indicates how often a certain threshold value of climate variables is reached or exceeded [38]. This allows for the analysis the likelihood of the occurrence of extreme events exceeding certain thresholds for climate variables such as temperature, precipitation and wind. The complementary cumulative distribution function is additionally shown to visualize the likelihood of cold temperature extremes.



0.3(box3)	0.5 (box6)	0.3(box9)
0.5(box2)	1.0 (box5)	0.5(box8)
0.3(box1)	0.5 (box4)	0.3(box7)

Fig. 6 Schematic of grid box-weighting centered on the selected case study site

The statistical analysis is based on hourly values of climate variables. In addition, a height correction for temperature was applied for comparison with the observations. It is based on the difference in orography between the location of the case study site in the REMO model and in reality using a uniform lapse rate of 0.0064 K/m^{-1} (https://en.wikipedia.org/wiki/Lapse_rate). We also investigate three different percentile indices for future climate projections (see Outlook). These are the 10th, median (50th) and 90th percentiles. A percentile threshold measures the frequency of exceedance with respect to this percentile-based threshold. For example, the 90th percentile is the threshold at which 10% of the values are above that threshold.

Results

As mentioned above, the main objective of KERES is to investigate the impact of future anthropogenic climate change, in particular extreme weather and climate events, which might impact different cultural heritage sites in Germany. Two cultural heritage sites (Charlottenhof and Sufferloh) are selected for the present paper. We also restrict ourselves to a statistical analysis highlighting the changes in extremes and rather rare climate events related to the thresholds of basic climate variables such as temperature (heat as well as cold), precipitation and wind speed, as these are the ones typically causing most damages for the selected case study sites (see Case study history).

Both the climatological annual cycle and the statistical characteristics of these variables are compared with observations (see Observational datasets). In addition, we compare these results with the results of the additional simulation of REMO driven by ERA-Interim for the period of 1996 to 2005. To show their own uncertainties, all individual ESM-REMO ensemble members and their statistics have been considered for the analysis of the annual cycle. These results are presented for a weighted mean over nine grid boxes (as shown in Fig. 6). To show the distribution of extreme events, the cumulative distribution functions are presented not only for the weighted mean over nine grid boxes but also for all individual cells (see Fig. 6). To keep the number of figures small, we restricted ourselves to present only the results of simulations driven by ERA-Interim. The data are displayed as an integral over the probability density function and describe the likelihood of exceeding a certain threshold. The weighted mean (box 9AM), the results for each of the nine surrounding grid boxes, and observations are shown as well.

Temperature

The climatological annual cycle of temperature for the period of 1996 to 2005 is shown in Fig. 7.

For Charlottenhof, the differences between the DWD measurements (black line) and the REMO simulation

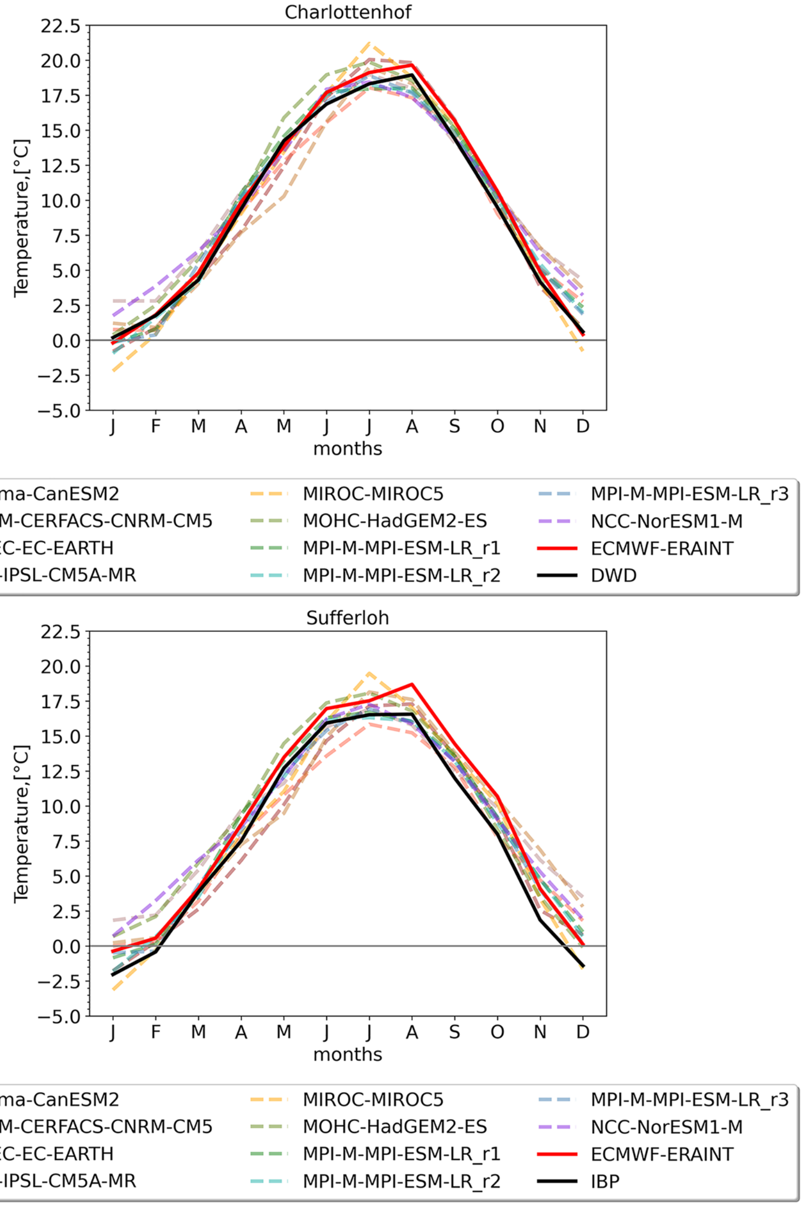


Fig. 7 Climatological annual cycle of temperature for the period of 1996–2005. Observations are in black; the REMO simulation driven by ERA-Interim is in red; different colors represent different ESM-REMO ensemble members. Upper panel shows the results for Charlottenhof; lower panel for Sufferloh. The results are shown for the weighted mean over nine grid boxes

driven by the ERA-Interim (red line) are small. At first glance, the simulated annual cycles for all ensemble members agree reasonably well with the observations. In winter most model simulations show a warm bias except for MOHC-HadGEM2-ES and MIROC-MIROC5, which show a considerably cold bias. In the summer months (June to August), the biases are in generally small. IPSL-IPSL-CMA5-MR show a relatively large cold bias in spring.

Similar results are obtained for Sufferloh. The REMO simulation driven by ERA-Interim (red line) shows the best agreement. Except for the simulation driven by MIROC-MIROC5, most of the simulations show a positive bias for the winter period from December to February. The largest biases appear in the simulations driven by MOHC-HadGEM2-ES and NCC-NorESM1-M. The analysis reveals the cold biases in spring from March to May. The largest positive bias appears in MIROC-MIROC5 in July. In autumn from September to October, the simulations slightly overestimate the observations.

The cumulative distribution functions of observed and simulated hourly temperatures for the period of 1996–2005 for Charlottenhof and Sufferloh are shown in Fig. 8.

This graph can be used as described in the following: When asked the question, how often a certain warm temperature is either reached or exceeded, one has to find this temperature on the x-axis. On the y-axis of Fig. 8, the cumulative distribution function reveals the likelihood of occurrence (either as a fraction or as a number of hours/year) for the weighted mean as well as for each of the nine surrounding grid boxes. For the likelihood of extreme cold events, the complementary cumulative distribution function is used.

For Charlottenhof, the REMO model underestimates the temperature maximums. The REMO model overestimates the cold extremes roughly by 10 °C. For moderate temperatures, the distribution agrees well with the observations. For Sufferloh, the REMO model overestimates the warm extremes. Similar to Charlottenhof, the cold extremes are considerably overestimated. REMO exhibits significant biases for temperatures below the freezing point. Whereas the hot extremes for Charlottenhof and Sufferloh show a similar spread between the nine grid boxes, Sufferloh shows for the cold extremes a rather large spread of almost 10 degrees between the nine grid boxes.

Precipitation

The climatological annual cycles for precipitation for Charlottenhof and Sufferloh are shown in Fig. 9. The largest differences between the simulations are found for Sufferloh, the case study with the complex orography.

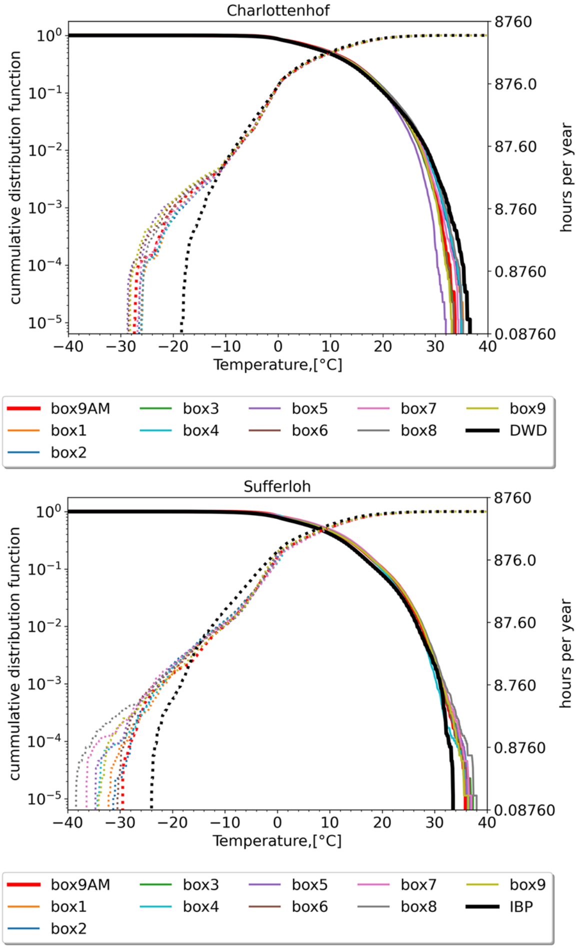


Fig. 8 Cumulative (solid) and complementary cumulative (dotted) distribution functions for temperature for the period of 1996–2005 for nine selected grid boxes, the weighted mean (grid box 9AM, red line) for the REMO simulation driven by ERA-Interim and observations (black line). Upper panel shows the results for Charlottenhof; lower panel for Sufferloh

For Charlottenhof, differences between the observed and the simulated climatological precipitation are small, particulary for the REMO simulation driven by ERA-Interim. However, a wet bias is found for most of the ESM-REMO ensemble members. It is more pronounced for the REMO run driven by NCC-NorESM1-M in December. The wet biases are larger in the winter months (December to February) than in the summer (June to August). All ESM-REMO ensemble members show wet biases in spring and autumn. While the ESM-REMO ensemble captures the shape of the annual cycle of the precipitation for Sufferloh, there is a wet bias in the months from January to May. A dry bias can be seen in most of the simulations in summer and autumn, especially for August and September.

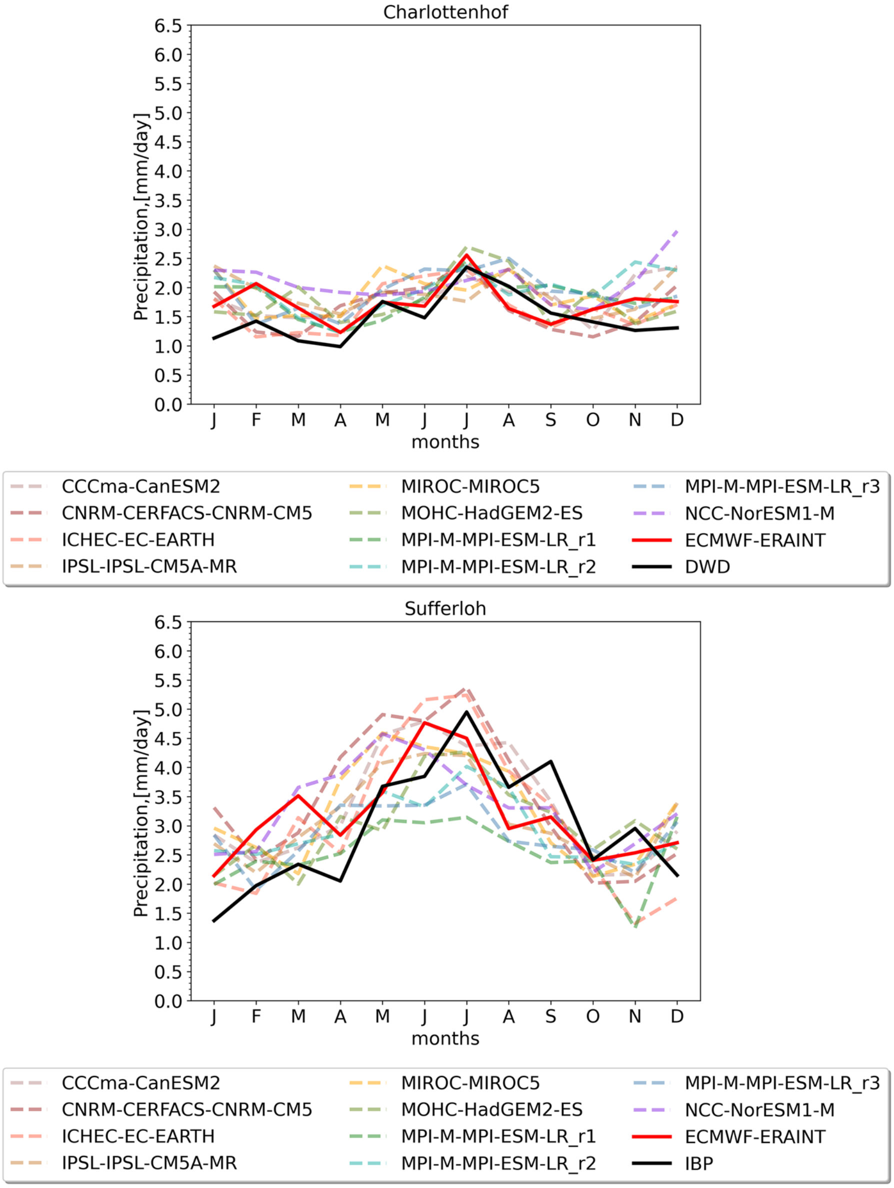


Fig. 9 Climatological annual cycle of precipitation for the period of 1996–2005. Observations are in black; the REMO simulation driven by ERA-Interim is in red; different colors represent different ESM-REMO ensemble members. Upper panel shows the results for Charlottenhof; lower panel for Sufferloh

The cumulative distribution function of precipitation for both cultural heritage sites is shown in Fig. 10. The results of the ensemble simulations are shown in Additional file 1.

The cumulative distribution function for precipitation at Charlottenhof indicates that REMO produces too strong extreme precipitation events larger than 20 mm/h, whereas the likelihood for precipitation rates between 5 and 15 mm/h is clearly underestimated in REMO. For Sufferloh, the situation is quite different. Here, the cumulative distribution function from REMO is clearly underestimated compared to observations for all precipitation rates. It is obvious that the nine-point average weighted mean even more underestimates the extreme precipitation events in comparison to the results from individual grid boxes, and the weighted mean of the boxes also lies outside the spread of the ensemble of individual grid´ boxes. This effect is particularly obvious for Sufferloh. This clearly

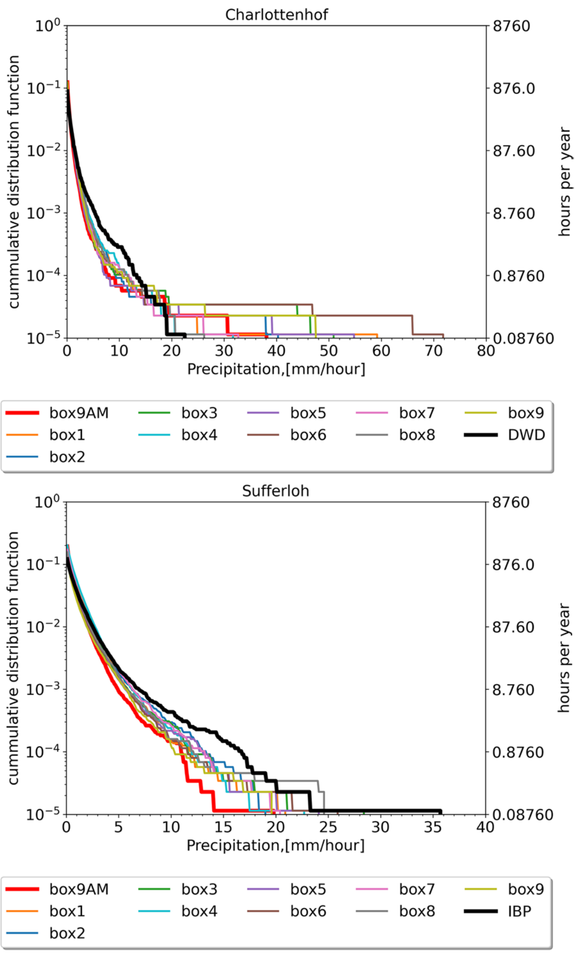


Fig. 10 Distribution of hourly precipitation for the period of 1996–2005 for nine selected grid boxes, the weighted mean (grid-box 9AM, red line) for the REMO simulation driven by ERA-Interim and observations (black line). Upper panel shows the results for Charlottenhof; lower panel for Sufferloh

demonstrates the disadvantages of using nine-point averages for the analysis of extreme precipitation.

Wind speed

The climatological annual cycle of wind speed is shown in Fig. 11. There is a good agreement between all members of the ESM-REMO ensemble and the observations for Charlottenhof in all seasons. All ensemble members exhibit a positive bias in all four seasons of Sufferloh. This is a problem related to the complex orography.

The cumulative distribution function for wind speed is shown in Fig. 12.

For Charlottenhof, the results for seven out of nine grid boxes produce the extreme events from ERA-Interim very well, while two grid boxes show weaker extreme winds. These two grid boxes are affected by surface parameters representative for Berlin. On the other hand, the model overestimates the likelihood of the occurrence of moderate winds between 5 and 10 m/s. For Sufferloh, the wind events stronger than 6 m/s are highly underestimated. This result could not be expected from the bias in the mean climatology, where REMO overestimates the measurements by typically 37–45%.

Discussion and outlook

Within this study, a methodology was developed to guide how to better tailor climate information for the needs of stakeholders in the cultural heritage sector. Our results highlight the changes in extremes and rather rare climate events related to the thresholds of temperature, precipitation and wind speed. It would help the stakeholders better integrate the results of climate projections into the prevention and emergency management, in particular for the risk assessment of extreme events. For this, the accuracy of climate models in capturing the effects of anthropogenic climate change significant at a location of cultural heritage is of the utmost importance [39]. However, in the present study we do not aim at ultimately explaining the biases of individual ESM-REMO ensemble members. Nowadays the tools of climate model evaluation are well-established. In-depth validation and the ability of the global-regional models selected for the KERES ensemble to capture the basic features of the European climate, including its variability in space and time, are presented in numerous publications within the EURO-CORDEX Initiative [34, 40]. Recent research by Vautard et al. [36] showed, that for many climatological aspects, the simulations with an ensemble of global-regional models might reproduce fairly well the recent past climate.

Two assumptions should be considered to tailor climate information and make it useful for the sustainable preservation of cultural heritage: First, the point accuracy of interpolation from a model grid to a specific location of a cultural heritage site should be taken into account. Furthermore, our research confirms the advantages of the ensemble approach for an assessment of regional climate changes.

Effect of interpolation

The misleading effect of interpolation is pronounced especially for precipitation and precipitation-based extremes, but also for areas with complex orography as illustrated in Figs. 8 and 10. The distribution of extreme warm temperatures is similar between the center grid boxes with the geographical locations of Charlottenhof and Sufferloh (box 5 in Fig. 6) and surrounding grid boxes (Fig. 6). At the same time, the distribution of

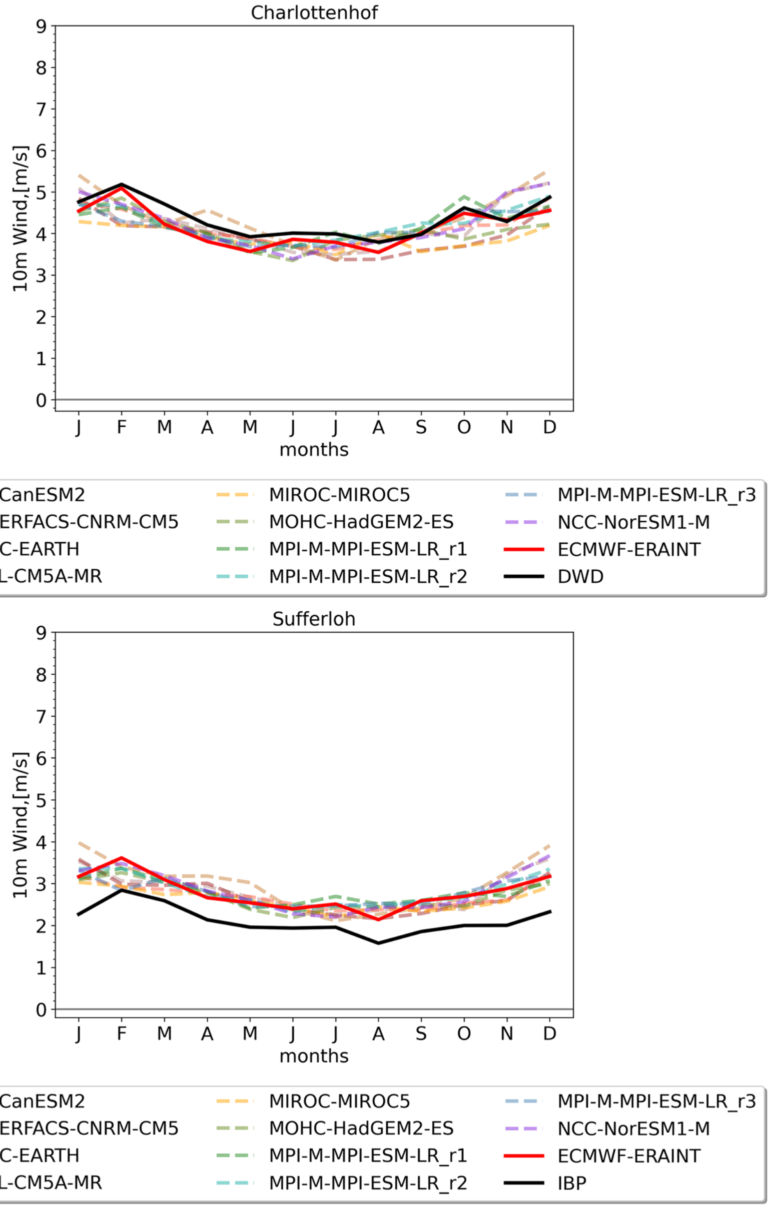


Fig. 11 Climatological annual cycle of wind speed for the period of 1996–2005. Observations are in black; the REMO simulation driven by ERA-Interim is in red; different colors represent different ESM-REMO ensemble members. Upper panel shows the results for Charlottenhof; lower panel for Sufferloh

extreme cold temperatures below −30 °C might slightly vary between different grid boxes for Sufferloh, which is located in the foothills of the Alps. In contrast to extreme warm temperature, extreme precipitation events are often rather small scale, such as, local thunder showers or the passage of a sharp front. So, the highest values of precipitation might be concentrated at the isolated points that are surrounded by the regions with less extreme values [41]. This can be clearly seen in Fig. 10, which shows the distribution of precipitation for the different grid boxes for Sufferloh. The scatter between the grid boxes is considerable, but the weighted mean of the nine grid boxes underestimates the median of the nine grid boxes by roughly 25%, with the weighted mean clearly below each of the individual ensemble members.

Therefore, our experience underlines that the point accuracy of the interpolation method in areas with orographic complexity and for the evaluation of precipitation and precipitation-based extremes should be taken into account. In this case, the analysis should be

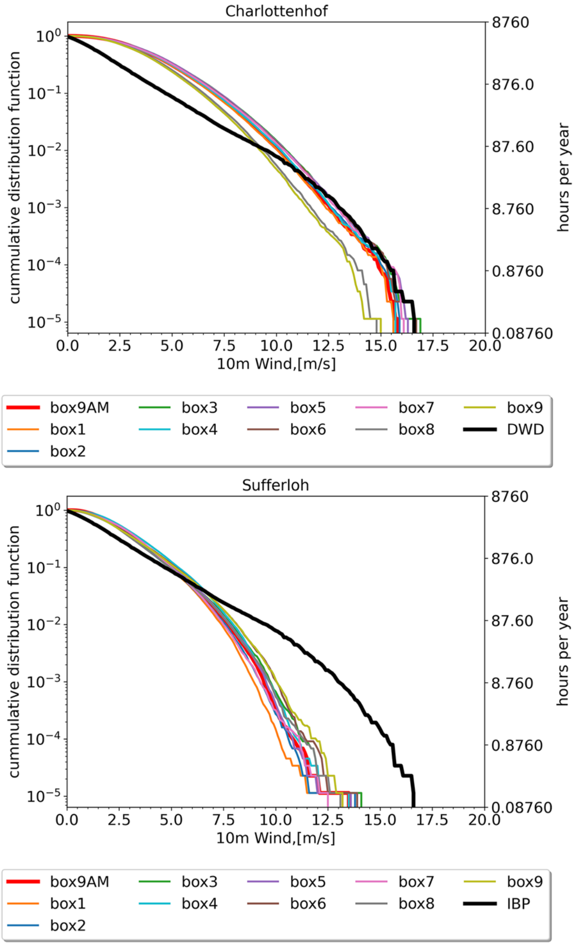


Fig. 12 Distribution of wind speed (hourly values) for the period of 1996–2005 for nine selected grid boxes, the weighted mean (grid-box 9AM, red line) and observations (black line) for the REMO simulation driven by ERA-Interim. Upper panel shows the results for Charlottenhof; lower panel for Sufferloh

undertaken not only for a grid-box, that represents a cultural heritage site but also for all surrounding grid boxes. The reason for this is that averaging over nine grid boxes involves averaging over points with extreme precipitation and points with moderate/no precipitation. For precipitation, extreme events are relatively small scale (thunder storms, front passage) so that even for neighboring grid points maxima are reached at different times. This might lead to a severe spatially-dependent interpolation error by downscaling the modelled data to the location of cultural heritage sites as this approach leads to a systematic underestimation of the severity of extreme events. This effect is less severe for variables, where the extremes are more large-scale, like, e.g., extreme temperatures. Given the benefits of point accuracy, we recommend that this method be considered for interpolation of temperature extremes such as heatwaves and extreme winds. Even though these extremes have a somewhat larger spatial scale, and spatial averaging captures grid boxes with extreme or very strong signals, thus less diluting the effect of extreme signals in individual grid boxes.

Ensemble approach

In summary, the ensemble approach provides scientifically robust climate information leading to meaningful results for cultural heritage. Climate models are simplified representations of the Earth's climate system. Furthermore, different models apply different physical parameterizations and numerical approaches to describe physical processes. This leads to a spread in the results and might be considered as the advantage of climate model ensembles to estimate the confidence in the projected changes. Thus, for example, if the same response is seen in several models, the confidence of projected changes might be achieved. This can be illustrated by Figs. 7 and 9, and 11.

Another advantage of using the ensemble is that this approach might give a broad idea of the range of uncertainty before fine-tuning the experimental strategy for the selected cultural heritage sites. The hygrothermal simulations performed in KERES are sensitive to systematic deviations between the simulated and actually observed climate variables, such as temperature, precipitation, and wind speed. It is therefore crucial to evaluate the performance of not only one individual climate projection, but an entire ensemble of climate simulations. By doing so, the strengths and weaknesses of each ensemble member can be analyzed and taken into account. As it is mentioned by Vautard et al. [36], the ensemble of climate simulations could provide more opportunities to identify simulations with realistic behavior for the region of interest or application considered or at least eliminate unrealistic ones. However, the authors emphasize that using too strict criteria may result in the selection of simulations that best fit the criteria but are unrealistic in other ways.

Outlook

In this chapter, we want to give the examples of how the developed methodology will be embedded in the research of KERES. First, the hourly timeseries can be used as an input for the simulations of heat and moisture transport in walls and other multi-layer building components. The use of the timeseries of all ensemble members and for all grid boxes, 90 datasets in our case, would help to estimate the bandwidth of possible changes in different multilayer building components. Furthermore, the results can be used to calculate the statistics of climate-based indices for building parameters. For example, in the case of

Sufferloh the future development of driving rain in times of climate change is very important to understand the hygrothermal behavior of building components. In the case of Charlottenhof, the statistics on climate change could be used for recommendations for preservation measures for the valuable interior, for example on how to deal with shading devices and window ventilation. The results could also be valuable for the visitor management in the future. Second, the projected changes in climate in the future and their ranges can be shown. This climate information together with the results of hygrothermal simulation is a substantial part of the KERES knowledge base to support innovative solutions for the maintenance and conservation of cultural heritage.

Future climate projections

The annual cycles and the distribution of temperature, precipitation and wind speed for the ensemble median (50th percentile) as well as for the 10th and 90th percentiles within historical (1971–2000) and near future (2036–2065) and far future (2070–2099) time periods under the RCP8.5 emission scenario are shown in Fig. 13. The ensemble statistics are integrated over all individual ESM-REMO ensemble members and over all nine individual grid boxes shown in Fig. 6. There are ninety time-series in total. The weighted mean over nine grid boxes was excluded from the analysis. As it was shown above, this approach has turned out to be problematic for extreme climate events, in particular for precipitation due to spatial variations in rain patterns. The range of possible climate projections in the future is shown by the ranking of climate variables with percentiles. Thus, for example, 10th percentile shows the driest and 90th percentile shows the wettest ensemble member of precipitation in the corresponding time period. Furthermore, the point accuracy of interpolation reduces biases caused by the complex orography at the location of the cultural heritage site, and the analysis of precipitation-based extremes becomes more confident.

For both cultural heritage locations and all climate variables, the ensemble shifts into the same direction. Not surprisingly, a substantially larger change is projected for the far future 2070–2099, compared to the near future 2036–2065. There is a clear trend towards warming temperatures in the future (Fig. 13a). The mean warming for the near-future is 2 °C for both Sufferloh and Chalottenhof. For the end of the century, warming of 3.3 °C for Charlottenhof and 3.6 °C for Sufferloh are projected. In all cases, warming is most pronounced in winter and minimal in spring. For the temperature maxima, changes in extremes are roughly consistent with the changes in mean summer temperature. The projected change in cold extremes, however, is roughly twice as large as the projected warming for winter mean temperatures. The projected changes in annual mean precipitation are relatively small. There is, however, a projected shift in the seasonal distribution. In the future, summers will tend to be drier, whereas the precipitation in winter will increase (Fig. 13b). The projected change in heavy precipitation is much stronger. The likelihood for precipitation events with more than 20 mm/h increases for the far future by 55% for Charlottenhof and 40% for Sufferloh relative to the historical period. Whereas for both sites heavy precipitation events rarely exceed 20 mm/h for the historical period, heavy precipitation events exceeding 30 mm/h are projected for the far-future. The projected changes in wind speed are relatively small (Fig. 13c). This is valid both for the mean seasonal cycle as well as for the likelihood of extreme storm events.

KERES knowledge base

Information about possible future anthropogenic climate changes is necessary to assess the potential impact of various climate-related factors on buildings, their interiors and the collections housed therein. For this, the best decision about adaptation and mitigation options should be made by bringing together the information from different sources about the building, its history and conservation status (including restoration measures), its climate history, past outdoor and indoor climate records and future projections.

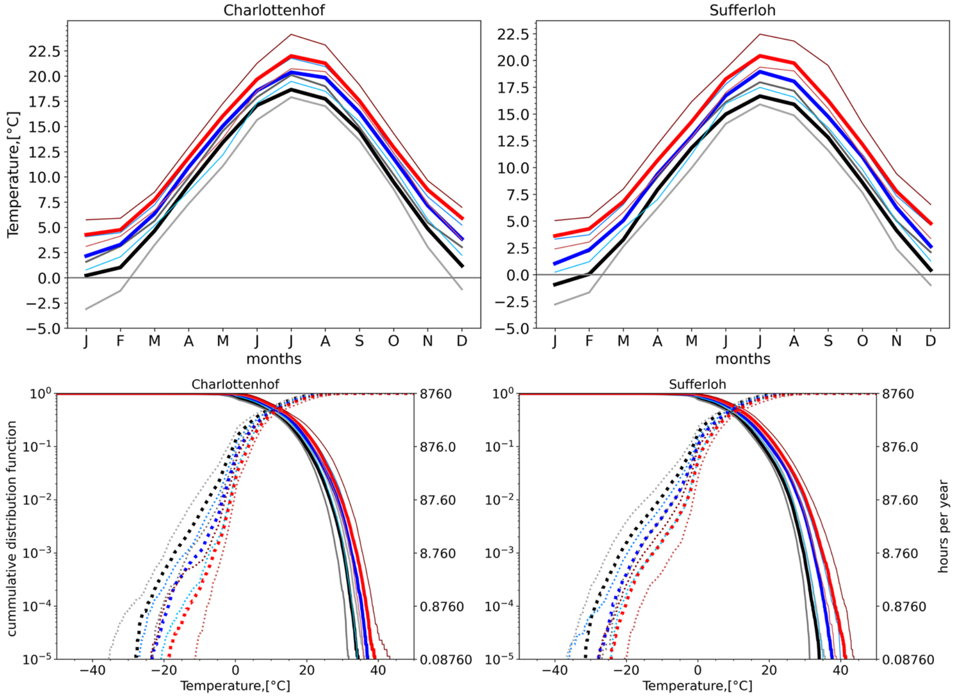
In order to best exploit available information and collected data, the KERES project developed a knowledge base, a platform that brings together relevant and necessary information from different sources. It is intended to serve as a support platform and to raise decision-makers' awareness of the situation in the cultural heritage sector. There are several levels of data integration, aggregation and linking:

- Integration of expert knowledge;
- Connection of sensors for comprehensive monitoring and reporting;
- Data analysis of complex processes with an open interface for easy integration of new algorithms; and.
- Semantic and geographic linking of analysis data and multiple domain information.

The backbone of this information network is an ontology, which connects the data of the different domains, like cultural heritage, climate change, crisis management, regulations, sensor data management, buildings, materials and many more.

The KERES knowledge base is publicly available. It is accessible for users through the web interface available via keres.k3s.ilt-dmz.iosb.fraunhofer.de. There also exists

a) Temperature



b) Precipitation

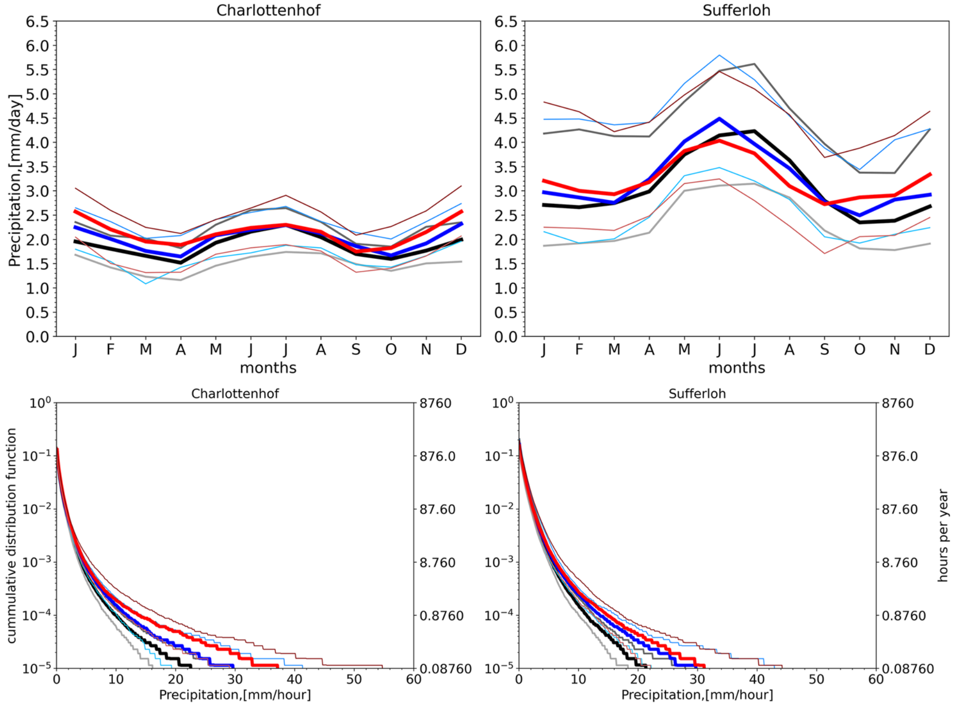


Fig. 13 Annual cycles & distribution functions of different climate variables within historical (1971–2000, black lines) and future (2036–2065, blue lines & 2070–2099, red lines) simulations under the RCP8.5 emission scenario for median, 10th and 90th percentiles. Left panels show the results for Charlottenhof; right panels for Sufferloh

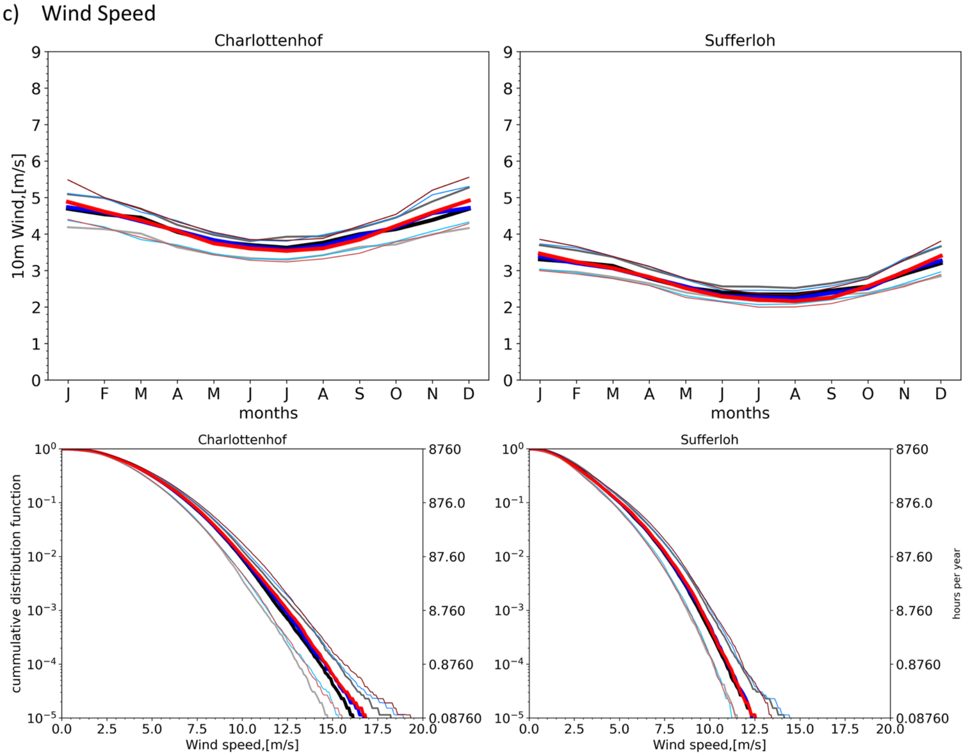


Fig. 13 continued

a machine-interface through a dedicated SPARQL-endpoint, through which queries can be processed and the requested data can be downloaded. The knowledge base offers different levels of access. Unauthenticated users can browse/read available information, whereas authenticated users can add or download data sets.

Pending issues

Despite the advantages of the developed methodology, the major challenges to better identify, characterize and to understand the origin of the climate model uncertainties still remain [42]. One of the major sources of uncertainties in climate modeling is the approximation of processes that cannot be explicitly resolved, in particular convection. Convection is one of the key processes in the heat and moisture budget of the atmosphere and plays an important role when simulating precipitation. Convection cannot be represented by grid-scale processes at the grid scale used in EURO-CORDEX, and thus it is parameterized. In this context, convection-permitting climate models on a kilometer-scale could provide more reliable climate information on convective processes, regional extremes, and over mountains [43].

Furthermore, Vautard et al. [35] underlines, that the climate simulations can have both small biases for a set of variables and large biases for others. The same diversity appears across different regions. The authors [35] conclude, that even with strong systematic biases on temperature, precipitation or other dynamical variables, none of the models/simulations can be defined as the best or the worst on all criteria. The authors [35] highlighted, that in many cases, a major difficulty in a model evaluation could arise from uncertainties in the observations, that are used for the evaluation of climate simulations. In addition, it is important to maintain high standard control in weather stations (e.g., following WMO standards), as these high-quality data are beneficial as input of models and for calibration and verification purposes (Additional file 1).

Conclusion

In summary, our research shows that the developed methodology would provide expert knowledge for the sustainable preservation of cultural heritage sites, selected for the KERES project. Thus, for example, the clear trends towards warming temperatures are shown for Charlottenhfof and Sufferloh with a substantially larger change for the far-future 2070–2099, compared to 2036–2065. Further information about possible future anthropogenic climate changes for all case studies in KERES will be summarized in the knowledge base.

On the other hand, our work could also be considered as a reference for providers of climate information. It gives a guidance to climate scientists on how to better tailor climate information for the needs of stakeholders in the cultural heritage sector. By doing so, the value and limitations of climate model data for the cultural heritage sector could be highlighted as well. The research in the cultural heritage sector should be continuously complemented by the achievements in the climate science on model developments and model evaluations. The ensemble of available climate simulations increases contentiously in size, including more climate models. A new generation of models, such as convection-permitting models, is being developed [43]. This would allow for more in-depth statistical analysis. Furthermore, the developed methodology could be applied for the evaluation of further climate variables such as humidity or solar radiation, that play an important role in the damage analysis of cultural heritage.

Nevertheless, challenges of bridging supply and demand for climate information relevant for developing mitigation strategies to prevent damages of cultural heritage still remain and will be addressed in the further studies of KERES.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40494-022-00853-9.

Additional file 1. Distribution of hourly precipitation for the period of 1996–2005 for nine selected grid boxes, the weighted mean (gridbox 9AM, red line) for the REMO simulation driven by the global models listed in the Table 1 (color lines) and observations (black line). Upper panel shows the results for Charlottenhof; lower panel for Sufferloh.

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Author contributions

Conceptualization, LK and UM; methodology, LK, UM; software, LK, UM; validation, LK, MW and FA; writing—original draft preparation, JL, KM, MR, RK, JM, TH, UM, JR, SB; writing—review and editing, LK, JL, UM, RK, KM, MW, FA, JM; visualization, LK, TH. All authors have read and agreed to the published version of the manuscript. All authors read and approved the final manuscript.

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Availability of data and materials

The climate simulations with an hourly resolution, driven by the global climate models CNRM-CERFACS-CNRM-CM5, IPSL-IPSL-CM5A-MR and MPI-M-MPI-ESM-LR-r3 (Table 1) are available at the Earth System Grid Federation portal, https://esgf-data.dkrz.de/search/esgf-dkrz/. The climate simulations with an hourly resolution, driven by other global climate models, listed in the Table 1, are available from the corresponding author on reasonable request. DWD data was downloaded from the DWD weather data platform (https://opendata.dwd.de/). The Fraunhofer IBP runs its own weather station (https://imcom2.hoki.ibp.fraunhofer.de/wetter/).

Declarations

Competing interests

The authors declare no conflicts of interest.

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