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Climate risk assessment of China's Cultural World Heritage highlights urgent need for adaptation

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Climate change poses escalating risks to cultural heritage with substantial implications for adaptation to minimize losses and damages. Integrating expert elicitation with projected changes in mean and extreme temperature and precipitation, we assess climate risk for 148 heritage sites and buffer zones within 39 Cultural World Heritage properties in China. Even under a moderate-emissions pathway (SSP245), risk increases for 82% of sites by mid-century, with all sites reaching moderate to extreme risk by the 2070 s; by century's end, over one-third shift from low to high, or extreme risk. Ancient Architectural Structures are at risk in the near term, including Mount Wutai and the Yungang Grottoes. Over half of the sites are located in urban or peri-urban areas, with nine urban sites facing extreme risk by 2100 regardless of scenario. These findings underscore the urgent need for adaptation across properties and buffer zones and offer guidance for scheduling site-specific interventions.

Climate change presents an unprecedented threat to our precious cultural heritage. It is a widespread, serious and growing rapidly growing threat to World Heritage properties and sites (WHS)[1–3] that is recognized by global cultural and natural heritage bodies including UNESCO[4,5], ICCROM[6], ICOMOS[7,8] and IUCN[9,10]. But adaptation responses for heritage are far from keeping pace[11–13]. To manage the current and future impacts of climate change on heritage and minimize loss and damage we need risk assessments to inform adaptation planning. Despite some progress at the site level and for some regional assessments, we generally lack systematic assessment of how the diversity of climate hazards will affect the full range of types of heritage at local, national, regional and global scales.

Human-caused climate change has amplified extremes in climatic impact-drivers[14], such as increases in frequency and intensity in extreme temperature[15], heavy precipitation[16], and severe drought[17]. These extreme climate events can have severe impacts across important sectors and all regions[18], including on the cultural and natural heritage within them[7,19–23]. For example, temperature, precipitation, humidity, and sea level rise have already been observed to impact cultural heritage[7,23,24]. These impacts can manifest through physical[25], chemical[23], and biological mechanisms[26–28], resulting in accelerated weathering and mechanical damage such as thermoclastic action[29], freeze-thaw cycles[30], mechanical erosion, chemical corrosion and biodegradation[23,31]. Importantly, these impacts can have immediate, cascading and sometimes irreversible impacts to cultural heritage and are therefore important for recording and understanding non-economic loss and damage from climate change.

The impact of climate change on cultural heritage has therefore received increasing attention in the past decade[32,33]. Currently, research on the impact of climate change on cultural heritage is predominantly centered in Europe and North America, with fewer studies conducted by researchers from less economically developed regions nor research focusing on such regions[7]. Research on this topic has primarily focused on developing frameworks, models, and methods for qualitative and quantitative risk assessments, particularly at the site level with less work on larger-scale and regional cultural heritage sites. Such approaches have used geographic information systems (GIS) and remote sensing to analyze changes in temperature, rainfall, and relative humidity[34] or develop flood damage index (FDICH) for cultural heritage[35]. Others have estimated risk from exposure of UNESCO cultural and natural heritage sites

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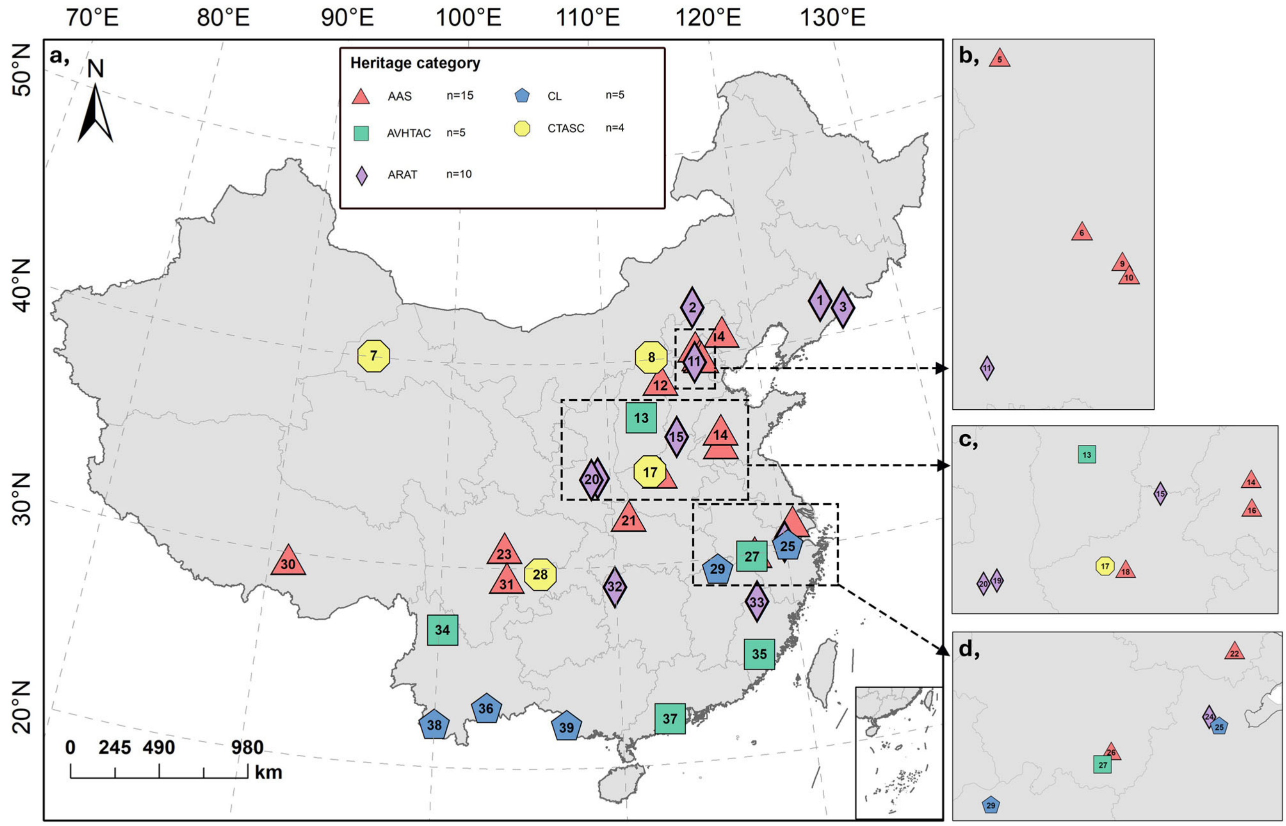

1.Imperial Tombs of the Ming and Qing Dynasties
2.Site of Xanadu
3.Capital Cities and Tombs of the Ancient Koguryo Kingdom
4.Mountain Resort and its Outlying Temples, Chengde
5.The Great Wall
6.Summer Palace, an Imperial Garden in Beijing
7.Mogao Caves
8.Yungang Grottoes
9.Imperial Palaces of the Ming and Qing Dynasties in Beijing and Shenyang
10.Temple of Heaven: an Imperial Sacrificial Altar in Beijing
11.Peking Man Site at Zhoukoudian
12.Mount Wutai
13.Ancient City of Ping Yao
14.Mount Taishan
15.Yin Xu
16.Temple and Cemetery of Confucius and the Kong Family Mansion in Qufu
17.Longmen Grottoes
18.Historic Monuments of Dengfeng in "The Centre of Heaven and Earth"
19.Mausoleum of the First Qin Emperor
20.Silk Roads: the Routes Network of Chang'an-Tianshan Corridor
21.Ancient Building Complex in the Wudang Mountains
22.Classical Gardens of Suzhou
23.Mount Qingcheng and the Dujiangyan Irrigation System
24.Archaeological Ruins of Liangzhu City
25.West Lake Cultural Landscape of Hangzhou
26.Mount Huangshan
27.Ancient Villages in Southern Anhui – Xidi and Hongcun
28.Dazu Rock Carvings
29.Lushan National Park
30.Historic Ensemble of the Potala Palace, Lhasa
31.Mount Emei Scenic Area, including Leshan Giant Buddha Scenic Area
32.Tusi Sites
33.Mount Wuyi
34.Old Town of Lijiang
35.Fujian Tulou
36.Cultural Landscape of Honghe Hani Rice Terraces
37.Kaiping Diaolou and Villages
38.Cultural Landscape of Old Tea Forests of the Jingmai Mountain in Pu'er
39.Zuojiang Huashan Rock Art Cultural Landscape

Fig. 1 | Cultural world heritage sites in China. a Presents the location of 39 Cultural World Heritage properties in China. Panels on right of Figure provide three detailed views of zones where locations are particularly concentrated (**b**–**d**). The China World Cultural Heritage Center classifies Chinese cultural world heritage into five categories: ancient architectural structures (AAS, orange); ancient ruins and tombs (ARAT, purple); cave temples and stone carvings (CTASC, yellow); ancient villages, historic towns and centers (AVHTAC, green); and cultural landscape (CL, blue). *n* = the number of cultural heritages included in each heritage category. Details of the geographical circumstances of each cultural heritage site are provided in the Supplementary Table 1.

in the Mediterranean from climate extremes[36] or from sea level for Africa rise[37–39].

A quantitative index assessment method has been developed to analyze long-term rain-related climate risks for China's regional provincial cultural heritage sites by grading hazard, exposure, and vulnerability[40]. Most of the assessment methods in these studies emphasizing the threat of average or extreme climate change to cultural heritage. There is a lack of large-scale quantitative comprehensive analysis of regional cultural heritage that combines average and extreme climate change with site vulnerabilities associated with the exposed heritage attributed.

China hosts 59 UNESCO World Heritage Sites, the second most by any country. These are sites recognized for their 'Outstanding Universal Value' (OUV), such as The Great Wall and the Mausoleum of the First Qin Emperor. However, China is considered particularly vulnerable to climate extremes such as compound heat, drought and flooding events[41] and mounting evidence shows an increasing trend of damages to these and local heritage sites from climate change-related impacts in recent years[42]. Climate risk assessment of these sites is urgent to inform adaptation planning as existing strategic plans related to climate change in China do not adequately address heritage protection.

This research combines expert elicitation on heritage attribute vulnerability with long-term and extreme climate change projections to estimate future climate change risks for 148 heritage sites and their

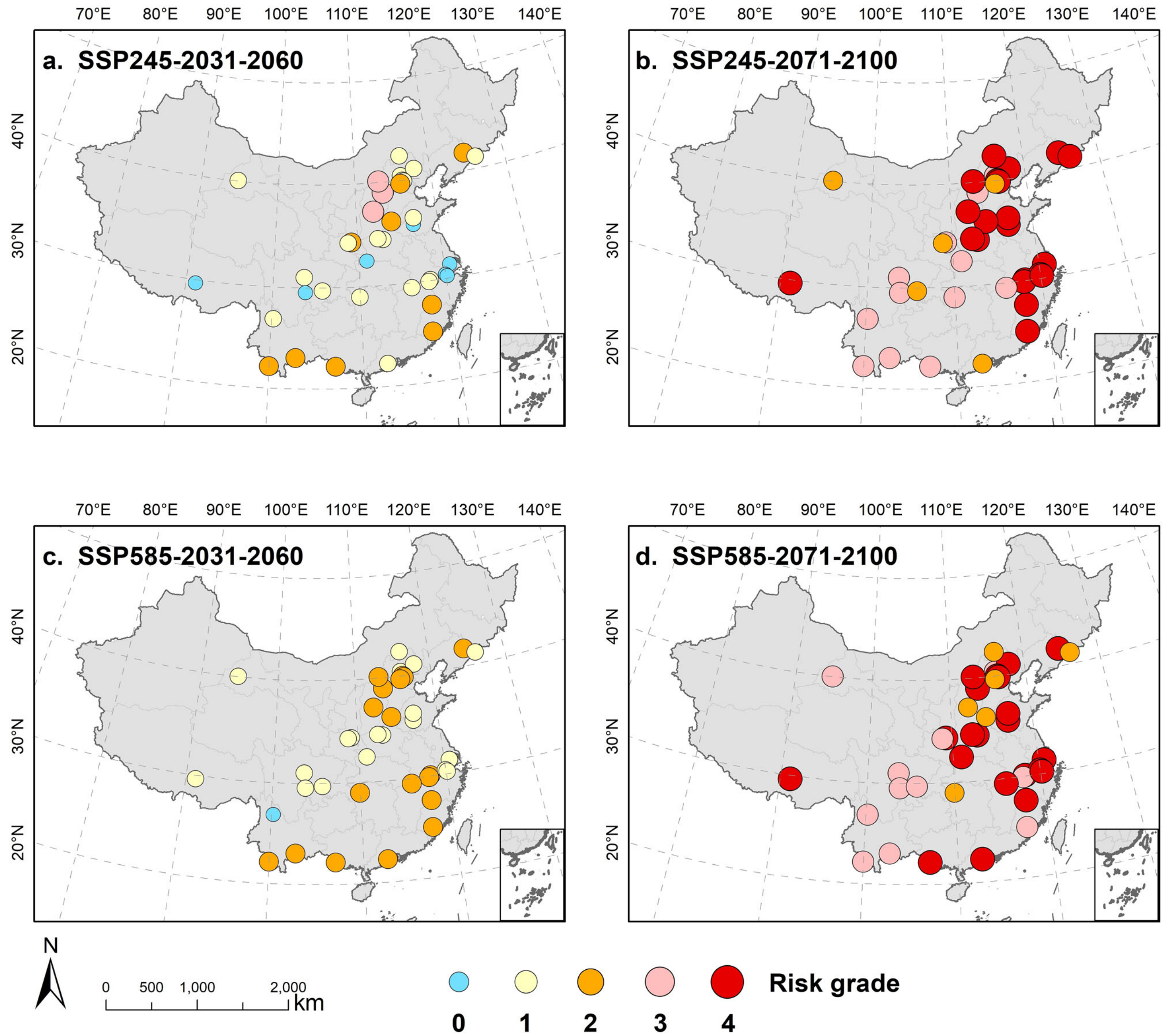

Fig. 2 | Climate risk grades of cultural world heritage in China. **a** The near-future period (2031–2060) under moderate (SSP245) emissions scenario, (**b**) the Far-Future period (2071–2100) under moderate (SSP245) emissions scenario, (**c**) The Near-Future period (2031–2060) under high (SSP585) emissions scenario, (**d**) the Far-Future period (2071–2100) under high (SSP585) emissions scenario. Risk grade is composite of future temperature change, precipitation change and extreme climate events: 0-no risk; 1-low risk; 2-medium risk; 3-high risk; 4-extreme high risk. The dominant climatic factors contributing to the high combined climate risk of each cultural heritage site are shown in Supplementary Table 2. The number of cultural heritage sites at different grades of climate risk in different periods is shown in Supplementary Figure 1.

buffer zones within 39 Cultural World Heritage properties in China (Fig. 1). Of relevance to the IPCC Special Report on Climate Change and Cities, 21 (54%) sites are located in urban or peri-urban areas and the remaining 18 are distributed across rural and mountainous regions.

The relative damage weight of different climate factors to each category of cultural heritage reflects synthesis on climate change and heritage attribute exposure factors to show that extreme climate changes will cause more severe damage to cultural heritage compared to average climate changes (see "Methods"). In general, precipitation is deemed more harmful to cultural heritage than higher temperatures. This is because damages to building materials can be caused by the presence or movement of moisture within the physical properties of heritage sites. The durability of these materials can be significantly affected by future precipitation changes, especially extreme precipitation events[43,44].

Results

Climate risk assessment of cultural world heritage in China

Even under moderate emissions, future climate risks to China's cultural heritage rises incrementally in the near term (2031–2060) for 82% sites (32 of 39); and to moderate, high, and extreme high risk for all 39 sites by (2071–2100) (Fig. 2).

Under moderate emissions, climate risk to cultural heritage will continue to increase throughout the century with 14 (36%) cultural heritage sites seeing a shift from no or low risk to high or extreme high risk by the end of the century (Figs. 3 and 4). This corresponds to 546.0 km^2 of heritage areas and 1124.9 km^2 of buffer zones transitioning from no or low risk to high or extreme high risk by the end of the century. Among the five categories of cultural heritage, the ancient architectural structures (AAS) category shows the highest proportion of increased risk, with 10 (66.7%) of the 15 sites experiencing a significant rise in climate risk over time. Two (5%) cultural heritage sites, Mount Wutai and the Yungang Grottoes, will face moderate or high risk in the near term

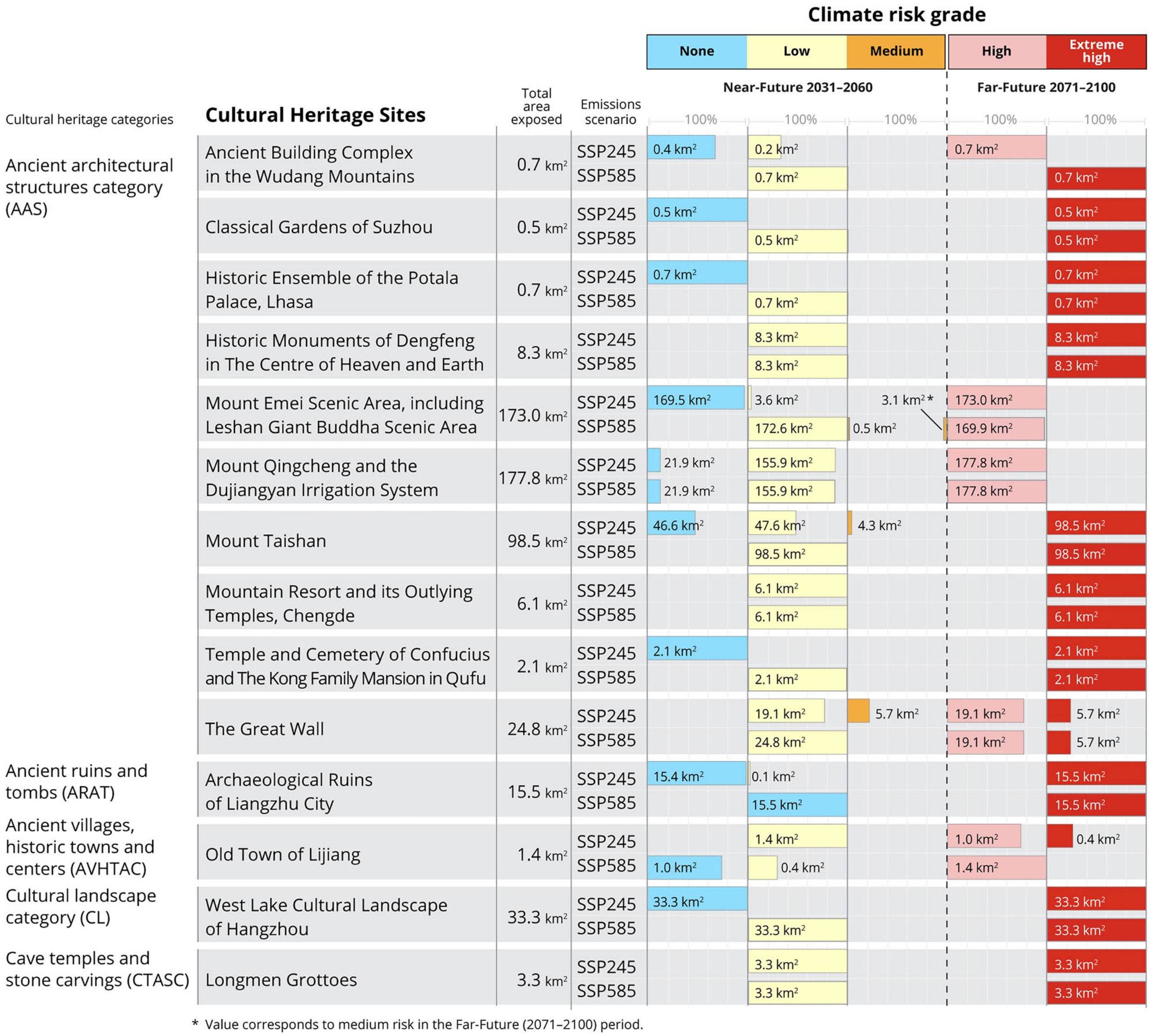

Fig. 3 | The area of cultural heritage sites exposed at each climate risk grade under the SSP245 and SSP585 emissions scenarios. Results for all cultural heritage sites are provided in Supplementary Tables 3 and 4.

(2031–2060) and high or extreme high risk by 2071–2100 under SSP245 and SSP585 emission scenarios with the substantial corresponding exposed buffer areas covering 200.5 km^2 and 628.1 km^2, respectively.

As greenhouse gas emission increase, the grade of climate risk generally shows an upward trend as increasing areas of heritage properties and their buffer zones are affected. Under SSP585, the climate risk grade of 17 (44%) Cultural Heritage properties increases faster compared to SSP245 and with a greater total extent exposed to potentially damaging climate conditions. The corresponding heritage and buffer areas affected are 1352.3 km^2 (37.9%) and 5238.8 km^2 (47.1%), respectively. Among the five categories of cultural heritage, 9 (60%) of the 15 AAS sites and 3 (60%) of the 5 the cultural landscape (CL) sites will see increases in climate risks with higher greenhouse gas emissions, representing the highest proportion of change. These findings indicate that future climate change poses an increased threat to cultural world heritage sites in China, with the most rapid increase and spatial extent of risk at higher GHG concentrations.

Sites particularly at risk

Two sites that see the most urgent exposure in the near term are Mount Wutai[45] and the Yungang Grottoes[46] (Fig. 5). Under both emissions scenarios (SSP245 and SSP585), they are projected to experience moderate or high risk in the near term (2031–2060) and high or extreme high risk by 2071–2100.

Shanxi Province is situated in the middle section of the Yellow River and the eastern part of the Loess Plateau. Characterized by mountainous plateaus with significant undulations, the region experiences a temperate continental climate. The terrain is complex and the hydrological conditions vary considerably across the province. The distinct landform pattern and geographical positioning contribute to a complex climate change scenario in Shanxi Province, resulting in highly uneven precipitation distribution across both time and space[47,48].

Among the 14 climate factors, R95p, Rx1day, and Rx5day (all extreme precipitation indices) are the dominant factors leading to the high climate risk in Mount Wutai and Yungang Grottoes. In 2017, the east hall of Foguang Temple in Mount Wutai leaked due to heavy rain, and the relevant departments took emergency rescue and shelter measures. Site inspections of the Foguang Temple thousands of years of rainfall that have damaged the roof tiles leading to leakage[45]. The large local temperature range that includes winter freezing and thawing coupled with days of heavy rain has also had an effect on the condition of the roofing tiles. These climatic factors highlight

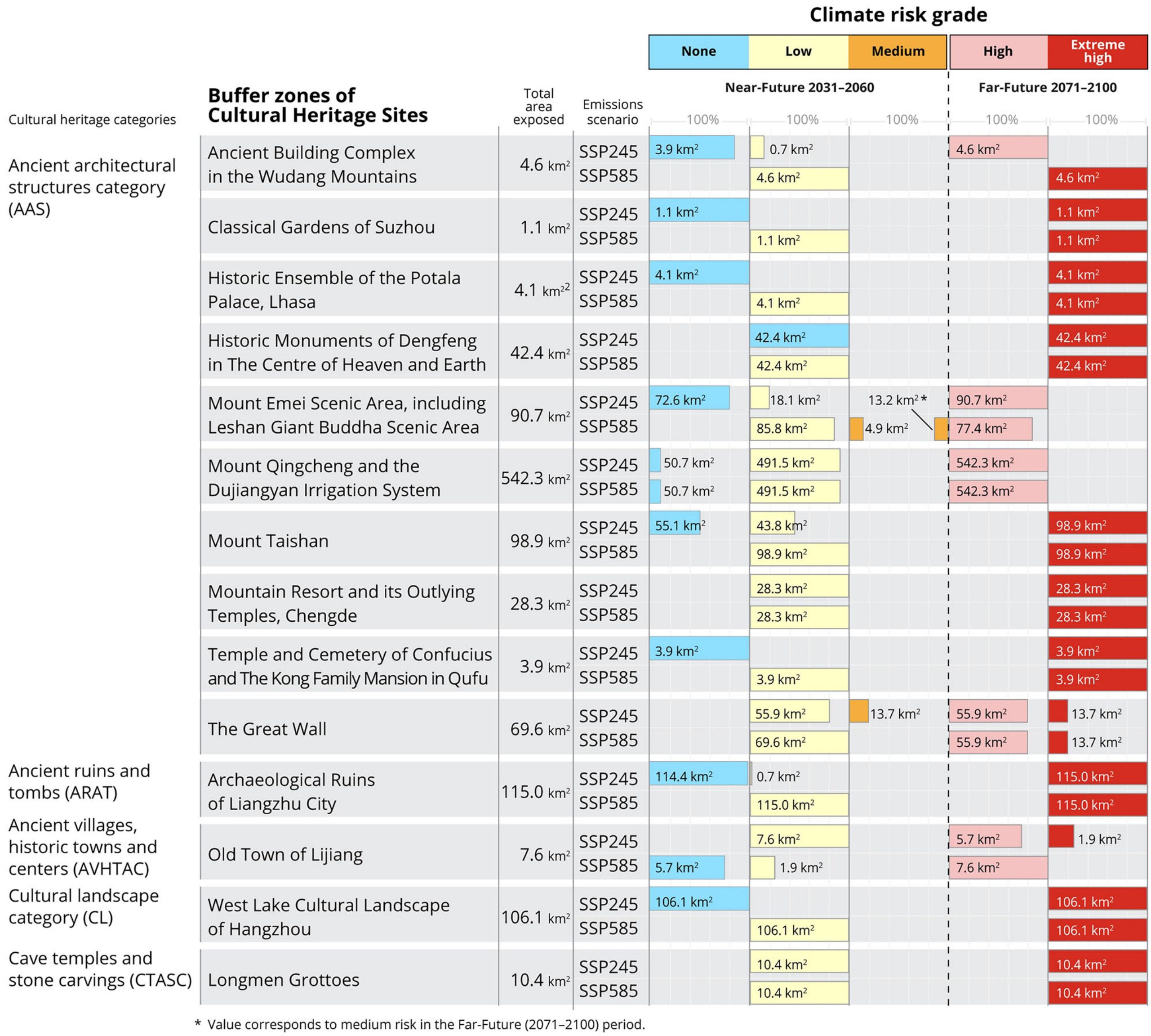

Fig. 4 | The area of the buffer zones of Cultural Heritage Sites exposed at each climate risk grade under the SSP245 and SSP585 emissions scenarios. Results for all cultural heritage sites are provided in Supplementary Tables 5 and 6.

the urgency of strengthening the protection measures of Mount Wutai and Yungang Grottoes and improving their ability to cope with climate change. There is an urgent need to develop more targeted conservation strategies in the future to ensure the long-term preservation of these two cultural heritage sites under changing climate conditions. For example, the performance of traditional clay tiles can be improved related to material science by changing their raw material ratio and firing process. A study[49] showed that when clay tiles were fired with 15% Ferrosilicon slag instead of kaolin and fired at 1000 °C, the tiles produced had lower water absorption (as low as 9.8%) and higher transverse fracture strength (by about 34.9%). This means that such modified tiles may be more resistant to drastic temperature changes and freeze-thaw cycles in the Wutai Mountain area[49].

The inclusion of heritage as a thematic consideration under the Global Goal on Adaptation[50–52] and within forthcoming IPCC Special Report on Climate Change and Cities highlights the importance of understanding climate change risk to heritage in cities. Over half of the heritage sites assessed here are within cities or peri-urban areas and nine of which are of particular concern. The Mountain Resort of palaces and gardens at Chengde with its Outlying Temples, Chengde, is the largest existing imperial palace-garden and temple complex in China and an iconic example of AAS[53]. The full extent of this heritage site and its buffer zone is projected to move from low risk in the near future to extreme high risk by end of century regardless of scenario. The site's historic wooden and stone structures are increasingly vulnerable to extreme temperature fluctuations and air pollution. In response, in addition to integration of heritage protection into urban planning, a decade-long renovation initiative has been implemented at the site alongside afforestation efforts that have raised vegetation cover to over 90%, helping to buffer climatic impacts[54].

Substantial shift from no or low risk to extreme high risk by end of century regardless of scenario are also projected for the Temple and Cemetery of Confucius and the Kong Family Mansion in Qufu[55]; Longmen Grottoes[56]; Historic Monuments of Dengfeng in "The Centre of Heaven and Earth"[57]; Classical Gardens of Suzhou[58]; Archeological Ruins of Liangzhu City[59]; West Lake Cultural Landscape of Hangzhou[60]; Historic Ensemble of the Potala Palace, Lhasa[61]; and all of their and these sites' buffer zones. These seven sites face diverse but intensifying impacts associated with exposure to extreme rainfall, temperature fluctuations, and associated hydrological and ecological changes. Ongoing responses that may help in reducing climate impacts at these sites include, for example, in Qufu, humidity and precipitation compromise ancient wooden architecture and tombstones,

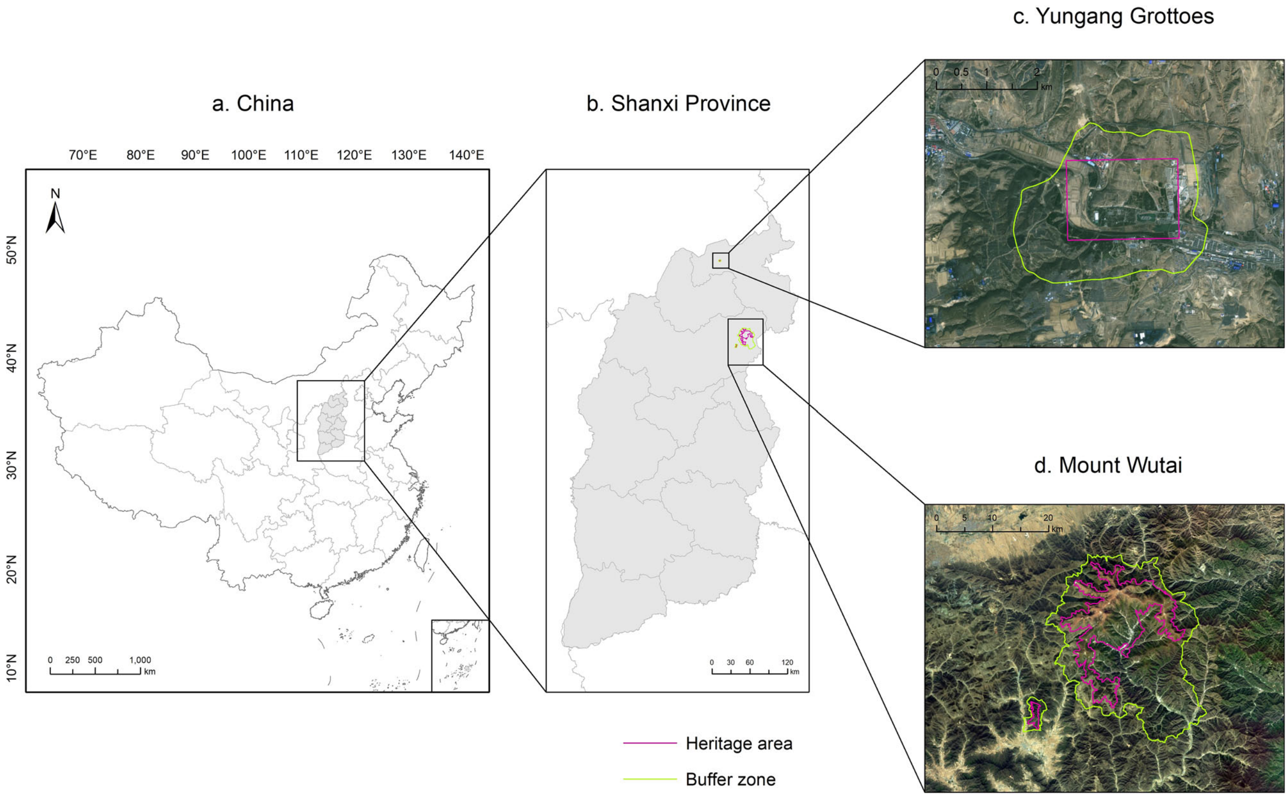

Fig. 5 | Mount Wutai and Yungang Grottoes. Mount Wutai and the Yungang Grottoes are both located in North China's Shanxi Province (**a**, **b**). Mount Wutai is renowned as a significant Buddhist pilgrimage site, encompassing 41 temples[45]. Notably, the East Hall of Foguang Temple stands out as the most extensive, well-preserved wooden structure dating back to the Tang Dynasty. The Yungang Grottoes boast 254 caves and 59,000 stone statues, showcasing remarkable Buddhist artistic mastery during the 5th–6th centuries AD in China[46]. The core heritage area (pink) and buffer zone (yellow) of Yungang Grottoes (**c**) and Mount Wutai (**d**) are shown in their topographical context.

prompting the implementation of a comprehensive management plan mandating heritage impact assessments and stricter development controls[55]. As the Longmen Grottoes are carved into vulnerable limestone cliffs they are exposed to water seepage, chemical weathering, and biological degradation. Here ongoing conservation efforts are focused on environmental monitoring and material deterioration analysis[56]. At West Lake in Hangzhou, extreme rainfall and urban encroachment threaten the ecological and esthetic integrity of the cultural landscape, while the Potala Palace in Lhasa faces compounded risks from humidity, temperature extremes, and fire hazards[61]. Adaptation measures at these two sites include fire prevention systems, traditional restoration techniques, and visitor flow management to preserve both physical and spiritual heritage[60,61].

Although projected to experience relatively less severe exposure, the Old Town of Lijiang is still expected to reach a high-risk classification by century's end, likely due to its altitude and exposure to flooding and humidity. Conservation planning and boundary adjustments at Old Town of Lijiang have improved resilience in the near term, though tourism pressure and fragmented governance continue to pose challenges[62].

Discussion

The findings indicate an increased climate risk for Cultural World Heritage sites in China under future greenhouse gas emission scenarios (SSP245 and SSP585), underscoring the critical need for urgent GHG emissions reduction and development of feasible and effective adaptation options for each heritage site. Climate risks to cultural heritage sites increase with the greatest rate of change under SSP585, but even under SSP245, 14 (36%) of China's Cultural World Heritage Sites will shift from no or low risk to high or extreme high risk by the end of the century. After analyzing each climate factor, under the moderate emission scenario, the leading climate factors causing a significant increase in climate risk to 14 cultural heritage sites by the end of this century include the warm days (TX90p), the warm nights (TN90p), the warm spell duration (WSDI), the very wet days (R95p), and the extremely wet days (R99p). In addition to these five climate factors, the dominant climate factors for the West Lake Cultural Landscape of Hangzhou and Archeological Ruins of Liangzhu City also include maximum 1 day total (Rx1day) and maximum 5 day total (Rx5day), while the dominant climate factor for Mount Qingcheng and the Dujiangyan Irrigation System includes the continuous precipitation index (CWD). The managers of relevant heritage sites need to carry out a more comprehensive and detailed climate risk assessment for these heritage sites as soon as possible, and take appropriate adaptive measures according to the assessment results to achieve preventive protection.

With global warming, extreme temperature indices related to high temperatures and extreme precipitation indices related to heavy rainfall are on the rise in most regions of China. Specifically, the CWD and intensity indices (Rx1day, Rx5day) are increasing primarily in the eastern regions. As China is generally expected to become warmer and wetter in the future[63–66], these results caution that future climate risk to cultural heritage will increase in accordance with these changes.

It is worth noting that although the weight of climate factors in this study is based on heritage type characteristics, it is limited by data availability and does not directly introduce material parameters. It does not fully quantify the site-level impact of material resistance parameters (such as porosity and compressive strength) on the actual damage rate on a site by site basis. At the same time, we only invited 10 experts to judge the weight, which will also limit the results. We hope that more experts will join in the future. In addition, the dynamic effects of existing protection measures, such as rock mass reinforcement projects, were not included and may overestimate long-term risks. The current result is a large-scale risk assessment of the damage of each type of heritage in China based on climate factors. In the future, for specific heritage sites, the quantitative relationship between material damage threshold and climate factors can be established through interdisciplinary cooperation and integration of material science experimental data, combined with accelerated aging experiment and monitoring data, so as to improve the assessment granularity.

The level and magnitude of climate risk vary across different categories and cultural heritage sites, necessitating follow-up site-specific assessments. For China's Cultural World Heritage Sites, the climate risk grade of 66.7% of AAS is projected to increase significantly over time, with 60% of these sites experiencing greater risk with higher greenhouse gas emissions. Increased precipitation can accelerate the degradation of traditional materials used in AAS, such as wood, stone, and tiles[23,67]. Additionally, the expansion and contraction of materials due to temperature fluctuations can lead to cracks and structural damage[68,69]. As climate change leads to more extreme precipitation and more frequent freeze-thaw cycles in some regions[70], these effects are likely to intensify, threatening the integrity of AAS. To mitigate the damage caused by temperature and precipitation changes to the cultural heritage of AAS, strategies must be adopted to prevent and minimize ongoing damage. While heritage adaptation is a nascent field, emerging research highlights potential strategies include improving drainage systems[71], structural reinforcement, and employing advanced conservation and restoration techniques[72].

Coupled Model Intercomparison Project Phase 6 (CMIP6) models generally offer higher spatial resolution, allowing for better representation of physical processes and more accurate local climate predictions, especially in complex terrains[73,74]. Additionally, CMIP6 introduces new Shared Socioeconomic Pathways (SSP), integrated with Representative Concentration Pathways (RCP), to provide a more comprehensive set of future emissions and land use scenarios, enhancing the realism of future climate projections[75,76]. Despite these improvements, differences remain among CMIP6 models, particularly in simulating precipitation patterns and extreme weather events[77–79], leading to uncertainties in regional climate projections. Further research is needed to identify climate risk from a broader range of variables, as the climate data and its applicability to heritage properties becomes available. This study only considers exposure to climatic factors and heritage categories, excluding these broader variables of vulnerability and response from the risk assessment, which also limits results.

The Analytic Hierarchy Process (AHP) is extensively utilized to handle multi-criteria decision issues because it is flexible and easy to apply[80]. However, subjectivity in weight determination through AHP contributes to result uncertainty[81]. Future research could extend and validate the weighted measures used here based on consensus from a larger number and more diverse range of experts, particularly through inclusion of more heritage experts drawn from the five categories of heritage type assessed here as well as extension to a wider range of heritage contexts globally. In addition to the varying degrees of damage to each Cultural Heritage Site, different protection management units and monitoring practices result in differences in the protection measures and levels of preservation across various Cultural World Heritage Sites.

China is home to one of the world's richest and most continuous cultural landscapes[82], yet the 39 World Heritage properties examined in this study represent only a very small fraction of the nation's total endowment. Considered from a national heritage perspective, they are drawn from just eight batches of State Priority Protected Sites that collectively list more than 5000 cultural relics[83]. These iconic places were selected for inscription precisely because they possess Outstanding Universal Value and generally benefit from comparatively robust conservation resources and public attention[83]. By contrast, thousands of lesser-known sites remain outside the global spotlight: they often lie in remote locations, have scant documentation, and receive far weaker stewardship. Our findings on risk therefore characterize just a sample of climate risk to the full landscape of China's heritage.

Even under a moderate-emissions pathway, over 80% of these flagship sites will face markedly higher climate risk by mid-century, and one-third will shift to high or extreme risk by the 2100s. If this pattern is extrapolated to the broader national inventory, the absolute number of imperiled assets could rise dramatically. Moreover, many unassessed sites are situated in regions with harsher baselines, experiencing more intense heatwaves, heavier downpours, or prolonged droughts, and lack the buffer zones, formal conservation strategies, or engineered defences enjoyed by World Heritage properties. Their building materials, structural integrity, and community support networks are often more fragile. Consequently, the urgency of climate adaptation for China's cultural heritage is profound and twofold. First, systematic risk screening must be expanded from these Cultural World Heritage properties to the full spectrum of protected and unprotected relics, creating an open, multi-level database of exposure and vulnerability. Second, limited conservation resources must be rebalanced to safeguard the unseen majority of heritage leveraging digital inventories, community-based management, and nature-based solutions[84] to secure an adaptation window before accelerating climate impacts become irreversible. Only by acting now can China prevent representativeness from becoming survivorship bias and ensure that five millennia of civilization endure in a rapidly warming world.

Heritage practice and policy must shift from a passive adaptation approach to active and planned adaptation strategies to improve the resilience of cultural heritage sites to future climate conditions[85–87]. Integrating climate risk assessments into heritage management and planning frameworks at national levels, together with long-term maintenance and monitoring plan is essential. Many local heritage site managers are unaware of or do not use existing climate change projections due to a lack of actionable, user-friendly interfaces, and detailed information[86]. For effective policy development, risk assessments must be translated into actionable data to guide robust adaptation and mitigation strategies. These may include enhanced conservation measures for at-risk sites, such as restoration forests to increase interception and soil retention capacity in areas located upstream of heritage sites to combat flooding[88], barriers to prevent coastal erosion[89,90], and emergency response strategies to protect cultural heritage sites during extreme events[91].

Engaging local communities in these efforts not only draws on practitioner and traditional knowledge for climate adaptation strategies but also strengthens the social and cultural significance of heritage sites, promoting collective responsibility for their conservation[92]. A comprehensive policy framework that recognizes diverse knowledge systems and how they can be effectively integrated to better inform climate risk and response for heritage[93,94] could effectively bridge the gap between climate science and cultural heritage conservation, ensuring the longevity and resilience of heritage sites in the face of climate change.

In the context of complex, changing, and variable climates, climate risk assessment of cultural heritage is becoming increasingly urgent. Future research can focus on the following five aspects. Firstly, integrating multiple climatic factors and their interactions such as wind speed, humidity, and sea level rise, to assess the vulnerability of heritage sites more comprehensively will enhance the understanding of climate risks and improve the accuracy of risk assessments, and is particularly important for understanding the escalated risk to heritage from compound climate events where two or more hazards affect each other with potentially cascading effects. Secondly, integrate in the assessment site specific vulnerability characteristics that affect overall climate change risk. Thirdly, integrate how responses to climate change both GHG mitigation and adaptation options affect the risk identified, as well as what residual risk remains after response options are deployed. Forth, community engagement and traditional knowledge can significantly enhance scientific understanding of the environmental processes affecting cultural heritage sites and help mitigate the effects of climate change. Finally, establishing long-term monitoring plans and impact assessment frameworks is essential for the sustainable implementation of adaptation strategies. This will also help update and refine risk assessments and adaptation measures as climate science evolves.

Methods

Overview

This research combines long-term and extreme climate change projections to predict future climate change risks for Cultural World Heritage properties in China. In accordance with the Operational Guidelines for the Implementation of the World Heritage Convention[95], the officially inscribed area of a World Heritage property contains all the attributes that convey its Outstanding Universal Value (OUV) and is the primary focus of protection. Encircling this property is a buffer zone, which is not part of the inscribed site but is a designated management area established to 'give an added layer of protection to the property' by mitigating potential threats from the external environment and development pressures[95]. The exposure of both the World Heritage property itself and its buffer zone to climate threats poses a direct risk to the heritage attributes and values, necessitating priority intervention. Assessing the exposure of the buffer zone is particularly critical, as it helps to identify potential pathways of risk transmission to the core heritage values, thereby informing the development of comprehensive and systematic conservation strategies. The research digitized the polygon shapefile of 39 of China's 59 World Heritage properties and calculated the area using ArcGIS, encompassing all heritage site data based on the heritage areas and buffer zones boundaries defined by the China World Cultural Heritage Center. The total combined area of the heritage areas is extensive at 3567.4 km^2, and the buffer zones around the heritage areas cover a further 11,116.6 km^2. The analysis utilizes two Shared Socioeconomic Pathway (SSP) scenarios: moderate (SSP245) and high emission (SSP585) and uses monthly and daily temperature and precipitation data for China from 1981 to 2100. Future climatic changes are assessed for the Near-Future (NF) period (2031–2060) and the Far-Future (FF) period (2071–2100), using 1981–2010 as the baseline. Heritage polygons are overlayed spatially with climate projections for the region of the occurrence of climate trends (mean and extreme precipitation and temperatures). The exposure assessment is combined with and Analytic Hierarchy Process (AHP) and expert elicitation process to identify risk to heritage based on the relative magnitude of potential damage caused by different climatic factors for each category of cultural heritage based on its physical heritage attributes.

The research objects in this study are the cultural parts of the 35 UNESCO Cultural World Heritage sites in China and the 4 dual Cultural and Natural World Heritage sites, for a total of 39 cultural heritage sites (excluding the 15 Natural World Heritage sites in China) (Fig. 1). Five cultural sites were excluded from this study due to the lack of detailed heritage area and buffer zone boundary data for the Grand Canal, Beijing Central Axis, and the serial site of Quanzhou, as well as the lack of climate data coverage for Kulangsu and the Historic Centre of Macao.

Data

The monthly and daily temperature and precipitation datasets for China from 1981 to 2100 are sourced from the National Qinghai-Tibet Plateau Scientific Data Center (https://data.tpdc.ac.cn/home). The 1 km monthly temperature and precipitation dataset utilizes the latest SSP scenarios released by the Intergovernmental Panel on Climate Change (IPCC) 6th Assessment, including SSP119, SSP245, and SSP585, each containing climate data from three General Circulation Models (GCMs): EC-Earth3, GFDL-ESM4, and MRI-ESM2-0[96]. The 0.25° daily temperature and precipitation dataset includes maximum temperature, minimum temperature, and precipitation data under the SSP245 and SSP585 scenarios[97], with each scenario incorporating six CMIP6 models: CanESM5, FGOALS-g3, GFDL-CM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, and MRI-ESM2-0.

This study, utilizes multi-model ensemble average data under the SSP245 and SSP585 scenarios. The monthly temperature and precipitation dataset is used to calculate the average climate change using ArcGIS, while the daily temperature and precipitation dataset is employed to calculate extreme climate indices using Python, and then the extreme climate change is further calculated through ArcGIS. Extreme high temperature, low temperature and other temperature changes can increase cracks, spall and rupture. Changes in rainfall can lead to changes in humidity in the environment surrounding cultural heritage sites, which can affect the growth of microorganisms on stones and wood, leading to biodegradation, which in turn destroys the materials and structures of cultural heritage sites. The increase of extreme precipitation can cause impacts associated with heavy rain, floods, landslides, and debris flows, resulting in surface pollution, fragile fragmentation and even collapse of cultural heritage. Drought causes long-term dryness, which can lead to drying and cracking of wood structures and affect their structural stability[98].

Table 1 | Extreme climate indices used in this assessment

Extreme climate index	Index	Descriptions	Unit
Temperature	TX10p	cold days	day
	TN10p	cold nights	day
	TX90p	warm days	day
	TN90p	warm nights	day
	WSDI	warm spell duration	day
	CSDI	cool spell duration	day
Precipitation	R95p	very wet days	mm
	R99p	extremely wet days	mm
	CDD	consecutive dry days	day
	CWD	consecutive wet days	day
	Rx1day	maximum 1 day total	mm
	Rx5day	maximum 5 day total	mm

The extreme climate index is selected from 27 indices defined by the Expert Team on Climate Change Detection and Indicators (ETCCDI), including 11 precipitation and 16 temperature indices. The quantitative expression of extreme climate events using the principle of statistics can better detect extreme climate events[99,100]. Six of these temperature indices and six of these precipitation indices were selected to characterize the magnitude, duration, and intensity of extreme climate events in historical and future periods (Table 1). The selected indices comprehensively cover the different characteristics of extreme climate events estimated in this study. Through these indices, the potential risks of cultural heritage in the context of climate change can be more effectively identified and quantified, and the scientific basis for the development of targeted conservation measures can be provided.

The heritage areas and buffer zones boundaries of cultural heritage are provided by the World Cultural Heritage Center of the China Institute of Cultural Heritage (https://www.wochmoc.org.cn/).

Long-term climate change

We use 1 km monthly temperature and precipitation data to predict long-term future climate changes under the SSP245 and SSP585 scenarios. Referring to Sardella et al.[101], the data are employed to calculate annual mean temperature and precipitation changes for the Near-Future (NF) period (2031–2060) and the Far-Future (FF) period (2071–2100), with 1981–2010 as the baseline. The annual mean temperature change (Ct) can be calculated using the following:

$$C_t = F_t - B_t \tag{1}$$

where Ft is annual mean temperature in NF and FF, Bt is annual mean temperature in the base years (1981–2010). The annual mean precipitation change rate (Cp) can be calculated using the following:

$$C_p = \frac{F_p - B_p}{B_p} \tag{2}$$

where Fp is annual mean precipitation in NF and FF, Bp is annual mean precipitation in the base years (1981–2010).

Climate extremes

We use 0.25 °C daily temperature and precipitation data to predict extreme future climate changes under the SSP245 and SSP585 scenarios. The daily maximum temperature, minimum temperature, and precipitation data are

Table 2 | Range of changes in climate factors assigned in SSP245-2031-2060 period

Climatic factor	Value				
	−1	1	2	3	4
Temperature	CF <0	0 <CF ≤ 0.75	0.75 <CF ≤ 1.5	1.5 <CF ≤ 2.25	CF > 2.25
Precipitation	CF <0	0 <CF ≤ 1	1 <CF ≤ 2	2 <CF ≤ 3	CF > 3
TX10p	CF <0	0 <CF ≤ 1	1 <CF ≤ 2	2 <CF ≤ 3	CF > 3
TN10p	CF <0	0 <CF ≤ 1.3	1.3 <CF ≤ 2.6	2.6 <CF ≤ 3.9	CF > 3.9
TX90p	CF <0	0 <CF ≤ 1.2	1.2 <CF ≤ 2.4	2.4 <CF ≤ 3.6	CF > 3.6
TN90p	CF <0	0 <CF ≤ 1.1	1.1 <CF ≤ 2.2	2.2 <CF ≤ 3.3	CF > 3.3
WSDI	CF <0	0 <CF ≤ 1.5	1.5 <CF ≤ 3	3 <CF ≤ 4.5	CF > 4.5
CSDI	CF <0	0 <CF ≤ 2.5	2.5 <CF ≤ 5	5 <CF ≤ 7.5	CF > 7.5
R95p	CF <0	0 <CF ≤ 0.5	0.5 <CF ≤ 1	1 <CF ≤ 1.5	CF > 1.5
R99p	CF <0	0 <CF ≤ 0.15	0.15 <CF ≤ 0.3	0.3 <CF ≤ 0.45	CF > 0.45
CDD	CF <0	0 <CF ≤ 20	20 <CF ≤ 40	40 <CF ≤ 60	CF > 60
CWD	CF <0	0 <CF ≤ 5	5 <CF ≤ 10	10 <CF ≤ 15	CF > 15
Rx1day	CF <0	0 <CF ≤ 1.1	1.1 <CF ≤ 2.2	2.2 <CF ≤ 3.3	CF > 3.3
Rx5day	CF <0	0 <CF ≤ 3	3 <CF ≤ 6	6 <CF ≤ 9	CF > 9

employed to calculate changes in extreme climate indices for the Near-Future (NF) period (2031–2060) and the Far-Future (FF) period (2071–2100), with 1981–2010 as the baseline. Extreme climate index change (Cei) can be calculated using the following:

$$C_{ei} = F_i - B_j \tag{3}$$

Where i is each extreme climate index, a total of 12, Fi is the mean of each extreme climate index in NF and FF, Bi is the mean of each extreme climate index in the base years (1981–2010).

Integrated climate change risk

The climate data of different resolutions were converted to uniform resolution by ArcGIS, and the data were assigned by reclassify tool. To facilitate the weighting calculation of all climate factors for both long-term and extreme climate change, and to obtain integrated climate change values for each grid in the Chinese region, we assign values ranging from −1 to 4 to each climate factor based on the range of Near-Future (NF) changes under the SSP245 emission scenario (Table 2). The assignment method is described in detail by Kapsomenakis et al.[36]. All other time periods use the same range of climate factor variation as in SSP245-2031-2060 to assign values.

Info: CF indicates change in each climate factor; When CF is less than 0, it indicates negative growth and is defined as reducing risk, resulting in a value of −1; When CF equals 0, the value equals 0.

Integrated future climate change risk(R) can be calculated using the following:

$$R = VC_t W_t + VC_p W_p + \sum VC_{ei} W_{ei} \tag{4}$$

Where VCt, VCp, and VCei are the values assigned to future temperature change, precipitation change and extreme climate index change reference Table 2, respectively, Wt, Wp, and Wei is the corresponding weight.

Different categories of cultural heritage comprise various key materials that constitute the physical structures and which are closely associated with the heritage attributes of the heritage property. Different climatic hazards and their effects on the physical and chemical environment, their intensity, spatial extent and duration, can cause varying levels of damage to the materials constituting cultural heritage properties. For example, historic buildings comprised mainly of wood will be affected by extreme rainfall and by extreme humid heat differently to a rock or brick structure[102]. Therefore, weights need to be determined based on the relative anticipated magnitude of damage caused by different climatic factors to each category of cultural heritage.

In this study, we use the Analytic Hierarchy Process (AHP) to determine climate risk weights for heritage sites. The specific weight determination method is described in more detail in ref. 40 that long term changes in precipitation is projected to affect ancient culture sites and ancient tombs more than other heritage types in China under future climate change. AHP is a multi-level weight analysis method that derives priority scales through pairwise comparisons, relying on expert judgment[103–109]. This method integrates experiential and knowledge-based insights, combining qualitative and quantitative approaches for systematic analysis and evaluation. The analytic hierarchy process (AHP) software was used to construct the hierarchical structure model of different climate factors and generate a scoring table for experts to fill in refs. 40,110. A survey was conducted of 10 experts from the fields of environmental science, meteorology, architecture, cultural relic protection engineering, and cultural relic museum research to score the relative damage weights of different climatic factors of the five types of cultural heritage. Finally, the scoring results of 10 experts were input into the judgment matrix, and the relative damage weights of different climatic factors of various cultural heritage sites were obtained through feature vector extraction and normalization (Table 3).

Among the AAS category, cultural heritage is mainly composed of wood, stone, brick and tile materials. In addition to the damage caused by heavy precipitation, the more frequent freeze-thaw cycles caused by temperature fluctuations also accelerate the weathering of materials[111,112]. Therefore, the relative damage weight of climate factors related to low temperatures around freezing point (TN10p, CSDI) for AAS is relatively high.

The ancient ruins and tombs (ARAT) category are usually made of rammed earth and stone. Long-term high temperature (WSDI) will lead to repeated expansion and contraction of rammed earth materials, especially in arid areas with large diurnal temperature differences (such as Northwest China), resulting in cracks and damage.

The cave temples and stone carvings (CTASC) category is usually directly exposed to the atmosphere, and continuous hot weather (WSDI) is the main factor leading to the weathering of the rock surface, resulting in the loss of details and patterns of carvings[113]. Among the cultural landscape (CL) category, Cultural Landscape of Honghe Hani Rice Terraces and Cultural Landscape of Old Tea Forests of the Jingmai Mountain in Pu'er are agricultural heritage in content. Extreme cold or heat events are unfavorable for crop growth[114], so the relative damage weights of WSDI and CSDI in the cultural landscape category is high.

Table 3 | The relative damage weight of different climate factors to each category of cultural heritage

Climatic factor	Cultural heritage category				
	AAS	ARAT	CTASC	AVHTAC	CL
Temperature	0.0269	0.0406	0.0466	0.0265	0.0477
Precipitation	**0.0831**	**0.0828**	**0.0767**	**0.1085**	**0.0823**
TX10p	0.032	0.0405	0.0437	0.0124	0.0562
TN10p	**0.1053**	0.0391	0.0594	0.0189	**0.0786**
TX90p	0.0291	0.0547	0.0573	0.0143	0.0529
TN90p	0.0272	0.0582	0.0414	0.0096	0.0563
WSDI	0.0276	**0.0947**	**0.0931**	0.0307	**0.1023**
CSDI	**0.0918**	0.0611	0.0641	0.0391	**0.1289**
R95p	**0.1324**	0.0471	**0.0871**	**0.0773**	**0.0796**
R99p	**0.2133****	**0.146***	**0.1516***	**0.2686****	**0.0983**
CDD	0.0195	0.0229	0.0208	0.0224	0.0583
CWD	0.0263	0.0592	**0.0876**	0.0345	0.0314
Rx1day	0.0625	**0.0861**	0.0573	**0.1212**	0.0273
Rx5day	**0.123**	**0.167***	**0.1133**	**0.216****	**0.0999**

Bold indicates risk factor >0.7 (medium risk); * indicates risk factor >1.4 (high risk); ** indicates risk factor >2.1 (extreme high risk). The higher the value, the higher the relative weight.
AAS AASs category, *ARAT* ancient ruins and tombs category, *CTASC* is the cave temples and stone carvings category, *AVHTAC* ancient villages, historic towns and centers category, *CL* cultural landscape category.

Table 4 | Classification range of climate risk grades

Grade	0	1	2	3	4
Range	$R < 0$	$0 < R \le 0.7$	$0.7 < R \le 1.4$	$1.4 < R \le 2.1$	$R > 2.1$

R is integrated climate risk. 0-no risk; 1-low risk; 2-medium risk; 3-high risk; 4-extreme high risk.

For ease of comparison, the calculated integrated climate risk values are divided into five grades (Table 4). These grades are placed into bucketed categories of: no risk (0), low risk (1), medium risk (2), high risk (3), and extreme high risk (4).

Data availability

The datasets generated and/or analyzed during the current study are not publicly available due to sensitivities associated with specifying World Heritage Sites, but are available from the corresponding author on reasonable request.

Code availability

Code is available from the authors on request.

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T.L.: Methodology, formal analysis, investigation, writing original draft. J.W.: Conceptualization, formal analysis, writing. Y.J.: Investigation and formal analysis. S.S.: Investigation and visualization. N.P.S.: Conceptualization, visualization, writing—review and editing, supervision. X.P.: Investigation and validation. B.S.: Investigation and validation. Yo.W.: Conceptualization. Ya.W.: Conceptualization. Q.W.: Validation and visualization. G.H.: Writing—review and editing. Y.Z.: Writing—review and editing. R.J.: Resources, conceptualization, formal analysis, writing—review and editing, supervision. T.L. and J.W. contributed equally.

Competing interests

The authors declare no competing interests.

Additional information

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