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Understanding climate risks to world cultural heritage: a systematic analysis and assessment framework for the case of Spain

Haisheng Hu[1] and Richard J. Hewitt[2*]

Abstract

Understanding the spatial distribution of world cultural heritage in its present-day geographical context is the foundation for the identification of and subsequent protection from key threats and vulnerabilities, particularly those arising from anthropogenic climate change. To address this challenge, we classified 45 Spanish world cultural heritage sites (WCHS) listed in the UNESCO register (as of 2023) according to type, entry date, and creation date. To establish a basis for a detailed analysis of the specific impact of climate change on the Spanish WCHS, a spatial cartographic database was developed showing the relationships between the WCHS and key geographical and climatic variables. We then used historical climate data, combined with a review of the impact mechanism of climate conditions on cultural heritage, to quantitatively evaluate the extent to which the WCHS in Spain are affected by local climate conditions from five aspects: freeze thaw cycle, thermal stress (thermoclastism), hydrodynamic scoring, corrosion, and biodegradation. Based on the above climate condition risks, we identified the five Spanish WCHS with the greatest potential climate condition risks, including Santiago de Compostela (Old Town), Pyrénées—Mont Perdu, the Roman Walls of Lugo, the Routes of Santiago de Compostela: Camino Francés and Routes of Northern Spain, and the Tower of Hercules. Additionally, based on different shared socioeconomic pathways (SSPs), we conducted a qualitative assessment of climate risk changes for WCHS in Spain under climate change. We found that the SSP1-2.6 scenario had the lowest climate risk, emphasizing the importance of achieving carbon neutrality for the protection of the WCHS. Our work translates historical climate conditions into specific climate risk levels for cultural heritage, providing data and theoretical support for effectively assessing the climate risks to Spanish WCHS.

Keywords Spanish WCHS, Temporal and spatial distribution, Heritage protection, Climate impact, Quantitative assessment, Data interpretation

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Introduction

World Heritage is an international heritage designation that has significant political and economic benefits for both local and national communities. With the efforts of UNESCO, the number of World Heritage sites increased from 12 to 1121 in the 45 years from 1978 to 2023 (https://whc.unesco.org/en/statesparties/es). There are 869 WCHS sites, accounting for 77.5% of the total. At the same time, the number of contracting parties to the World Heritage Convention has also increased from 20 to 167, which is the minimum number required for formal implementation of the international convention

[1]. With the continuous increase in the number of sites, many factors, such as World Heritage recognition standards, policies, and the influence of contracting states, have undergone changes [2, 3]. On the one hand, the World Heritage List can improve the popularity of heritage sites and promote their protection [4]. For example, heritage sites can become national landmarks and promote tourism development [5]. On the other hand, there are also some problems, such as the difficulty in achieving fairness in the process of heritage application [6, 7], which leads to the neglect of some historical and cultural values that truly require attention and protection and difficulties in ensuring that sites in less wealthy nations are fairly represented [3]. In addition, the increase in the number and types of heritage sites has made it difficult to protect them globally [8]. Therefore, selecting countries with large numbers of WCHS as case studies, in order to explore the spatiotemporal distribution patterns and climate-related impacts of their WCHS not only helps to protect WHCS in selected case countries, but also can serve as a reference to enhance sustainable protection of the WCHS across the globe. Spain has the second largest number of WCHS after Italy. To date, it has 45 WCHS, including 42 cultural heritage sites, 3 composite heritage sites, and 1 natural heritage site jointly owned by France (https://whc.unesco.org/en/statesparties/es) (Table 1).

However, the country's WCHS face significant threats that are likely to be exacerbated under a rapidly changing future climate, for example, from events such as extreme precipitation, flooding and forest fires [9] and the potential impacts of sea level rise on coastal WCHS [2]. Previous studies have shown that Spain's WCHS are an important foundation for the promotion and development of tourism [10–15]. Therefore, the protection of WCHS is crucial [10]. At present, increasingly high concentrations of greenhouse gases in the atmosphere as a result of human activities are leading to rapid global heating and unpredictable changes in global climate. International climate policy aspires to limit global temperature rise to less than 2 °C this century, but the rate of climate warming is exceptionally rapid [16], and efforts to reduce emissions have thus far been insufficient [17]. It is argued that cultural heritage should try to maintain its authenticity and integrity, which potentially creates tension with restoration and conservation actions. However, the climate crisis will expose WCHS to stressors that most sites have never experienced, in some cases threatening outright destruction [9]. In November 2021, UN Education at the 23rd session of the Conference of the Parties to the Convention on the Protection of the World Cultural and Natural Heritage of the Scientific and Cultural Organization (UNESCO), in its 11th item of the provisional agenda, the Conference of the Parties to the Convention on the Protection of the World Cultural and Natural Heritage, pointed out that "climate change has become one of the most significant threats to the world heritage and may affect its outstanding universal values, including its integrity and authenticity, and its potential for economic and social development at the local level" [18]. Numerous studies have evaluated the specific manifestations of factors such as precipitation [19, 20], temperature [21, 22], atmospheric humidity [23, 24], and sea level rise [2, 25] in terms of their direct and indirect impacts on world cultural heritage buildings or building materials, and have summarized the underlying mechanisms of the threats posed to world cultural heritage protection by changes in these climate elements on a global scale [9]. However, there is limited research quantifying regional differences and trends in the impact of climate change on world cultural heritage from the perspectives of historical climate and future climate.

Given the importance of Spain's WCHS, the country's position as a leading cultural heritage country because of its large number of sites, the insufficient international progress in reducing greenhouse gas emissions and the large amount of "locked in" warming, detailed assessments of the vulnerability of Spain's WCHS to climate change impacts are urgently needed. In this article, we contribute to this important task. We explore the spatiotemporal distribution patterns and historical, cultural, geographical, and climatic backgrounds of Spain's WCHS and quantify the impact of current climate conditions on these patterns. We develop a theoretical framework and GIS database for analyzing the current and future vulnerability of the Spain's WCHS to develop rigorous, evidence-based policy responses to ensure its protection under our rapidly changing climate.

National policy and management of WCHS in Spain

The Next Generation EU COVID recovery fund (NGEU) and the European Green Deal are expected to help dynamize and provide new guidelines for cultural heritage preservation and climate-related projects in Spain [26]. The Next Generation EU COVID recovery fund was agreed upon at a special EU summit on July 21, 2020, with the main body of the Multiannual Financial Framework (MFF) totaling €1824.3 billion [27], which is intended to assist the EU in its post-pandemic reconstruction and recovery efforts. The recovery and resilience facility includes expenditures on science and education, and part of the fund can inevitably be applied to the conservation of Spain's WCHS, maintaining previous heritage policies while increasing expenditures on the management of cultural heritage tourism and increasing cultural heritage tourism-related employment and fiscal revenues. In addition, as Spain shares some

Table 1 WCHS in Spain

WCHS	Name	Latitude	Longitude	Date of inscription	Administrative area	Type
1	Alhambra, Generalife and Albayzín, Granada	37.17677778	− 3.589916667	1984	Autonomous Community of Andalusia	Building complex
2	Antequera Dolmens Site	37.025	− 4.544444444	2016	Autonomous Community of Andalusia	Historical relics
3	Aranjuez Cultural Landscape	40.03645	− 3.60934	2001	Province and Autonomous Community of Madrid	Building complex
4	Archaeological Ensemble of Mérida	38.91611	− 6.33778	1993	Autonomous Community of Extremadura	Cultural relic
5	Archaeological Ensemble of Tarraco	41.11472222	1.259305556	2000	Autonomous Community of Catalonia	Historical relics
6	Archaeological Site of Atapuerca	42.34972222	− 3.515277778	2000	Autonomous Community of Castile-Leon	Historical relics
7	Burgos Cathedral	42.34073333	− 3.704011111	1984	Autonomous Community of Castile-Leon	Building complex
8	Caliphate City of Medina Azahara	37.88588889	− 4.867694444	2018	Autonomous Community of Andalusia	Building complex
9	Catalan Romanesque Churches of the Vall de Boí	42.50472222	0.803611111	2000	Autonomous Community of Catalonia	Building complex
10	Cathedral, Alcázar and Archivo de Indias in Seville	37.38384	− 5.99155	1987	Autonomous Community of Andalusia	Building complex
11	Cave of Altamira and Paleolithic Cave Art of Northern Spain	43.37826267	− 4.122132455	1985	Autonomous Community of Cantabria	Cultural relic
12	Cultural Landscape of the Serra de Tramuntana	39.73083333	2.694722222	2011	Autonomous Community of Balearic	Building complex
13	Heritage of Mercury. Almadén and Idrija	38.77527778	− 4.838888889	2012	Autonomous Community of Castile-La Mancha	Building complex
14	Historic Centre of Cordoba	37.87919444	− 4.779722222	1984	Autonomous Community of Andalusia	Building complex
15	Historic City of Toledo	39.85694444	− 4.024444444	1986	Autonomous Community of Castile-La Mancha	Building complex
16	Historic Walled Town of Cuenca	40.07662	− 2.13174	1996	Autonomous Community of Castile-La Mancha	Building complex
17	La Lonja de la Seda de Valencia	39.47441667	0.378444444	1996	Autonomous Community of Valencia	Building complex
18	Las Médulas	42.46939	− 6.77075	1997	Autonomous Community of Castile-Leon	Historical relics
19	Monastery and Site of the Escurial, Madrid	40.58911111	− 4.14775	1984	Province and Autonomous Community of Madrid	Historical relics
20	Monuments of Oviedo and the Kingdom of the Asturias	43.36262	− 5.84303	1985	Autonomous Community of Asturias	Building complex
21	Mudejar Architecture of Aragon	40.34389	− 1.10722	1986	Autonomous Community of Aragon	Building complex
22	Old City of Salamanca	40.96525	− 5.6645	1988	Autonomous Community of Castile-Leon	Building complex
23	Old Town of vila with its Extra-Muros Churches	40.65645	− 4.70012	1985	Autonomous Community of Castile-Leon	Building complex
24	Old Town of Cáceres	39.47444	− 6.37	1986	Autonomous Community of Extremadura	Building complex
25	Old Town of Segovia and its Aqueduct	40.94847222	− 4.11675	1985	Autonomous Community of Castile-Leon	Building complex
26	Palau de la Música Catalana and Hospital de Sant Pau, Barcelona	41.38778	2.175	1997	Autonomous Community of Catalonia	Building complex
27	Palmeral of Elche	38.26666667	0.716666667	2000	Autonomous Community of Valencia	Building complex
28	Paseo del Prado and Buen Retiro, a landscape of Arts and Sciences	40.41533333	− 3.687055556	2021	Province and Autonomous Community of Madrid	Building complex
29	Poblet Monastery	41.38083	1.0825	1991	Autonomous Community of Catalonia	Building complex

Table 1 (continued)

WCHS	Name	Latitude	Longitude	Date of inscription	Administrative area	Type
30	Prehistoric Rock Art Sites in the Côa Valley and Siega Verde	40.6975	− 6.661111111	1998	Autonomous Community of Castile-Leon	Historical relics
31	Renaissance Monumental Ensembles of Úbeda and Baeza	38.01131	− 3.37122	2003	Autonomous Community of Andalusia	Building complex
32	Risco Caido and the Sacred Mountains of Gran Canaria Cultural Landscape	28.04438889	− 15.66119444	2019	Lslas Canarias	Historical relics
33	Rock Art of the Mediterranean Basin on the Iberian Peninsula	39.78995	− 1.03331	1998	Multiple	Historical relics
34	Roman Walls of Lugo	43.01111	− 7.55333	2000	Autonomous Community of Galicia	Historical relics
35	Routes of Santiago de Compostela: Camino Francés and Routes of Northern Spain	43.335	− 6.414722222	1993	Multiple	Historical relics
36	Royal Monastery of Santa María de Guadalupe	39.45285	− 5.3275	1993	Autonomous Community of Extremadura	Building complex
37	San Cristóbal de La Laguna	28.47788889	− 16.31177778	1999	Lslas Canarias	Building complex
38	San Millán Yuso and Suso Monasteries	42.32586	− 2.86496	1997	Autonomous Community of La Rioja	Building complex
39	Santiago de Compostela (Old Town)	42.88076	− 8.54468	1985	Autonomous Community of Galicia	Building complex
40	Tower of Hercules	43.38583333	− 8.406388889	2009	Autonomous Community of Galicia	Building complex
41	University and Historic Precinct of Alcalá de Henares	40.48138889	− 3.368055556	1998	Province and Autonomous Community of Madrid	Building complex
42	Vizcaya Bridge	43.323175	− 3.016833333	2006	Autonomous Community of País Vasco	Building complex
43	Works of Antoni Gaudí	41.41338	2.152971944	1984	Autonomous Community of Catalonia	Cultural relic
44	Ibiza, Biodiversity and Culture	38.91113889	1.435194444	1999	Lslas Baleares	Historical relics
45	Pyrénées—Mont Perdu	42.68542	0.0005	1997	Autonomous Community of Aragon	Historical relics

WCHS with other countries (e.g., France), NGEU greatly facilitates exchanges and cooperation in the economic and policy fields of EU countries [28]. Under this trend, it is boldly predicted that a favorable situation of complementarity and synergy between member states in the field of heritage and conservation policies will gradually emerge. At the same time, 30% of the total expenditure of the MFF and the NGEU will be allocated to climate-related projects, and the costs of the MFF and the NGEU will be used by the EU to achieve the UN climate-neutral targets by 2050, the EU's 2030 Paris Agreement targets. Although this measure is part of a systematic project to curb global heating [29], this initiative is a major benefit for the preservation of the WCHS. Meanwhile, in July 2021, the European Commission published the Renewable Energy Efficiency Directive (part of the European Green Deal). The deal reaffirms the EU's determination to strive for energy independence, its confidence in a 55% reduction in greenhouse gases by 2030, and that the EU will accelerate the deployment of renewable energy [30]. This policy favors, on the one hand, an increase in the use of renewable energy. On the other hand, the tentative agreement introduces a specific renewable energy development standard of 49% reduction of energy consumption in buildings by 2030, which poses new challenges for the conservation of cultural heritage in building types. This is because the indoor facilities or artifacts of cultural heritage objects require a continuous supply of energy to maintain the indoor microclimate within the appropriate temperature and humidity range [31]. In conclusion, post-pandemic policies for the conservation of WCHS in Spain need to be further adapted to the local context, in accordance with the European Green Deal and with the funding provided by NGEU projects.

Materials and methods

Data sources

Given the urgent need to understand the climate-related risks to WCHS in Spain, this study aims to qualitatively and quantitatively assess the extent to which WCHS in Spain are affected by local climatic conditions based on their spatial distribution and the historical climatic conditions of their location. To achieve this aim, we used a series of spatial analysis techniques and data sources (Table 2), as follows.

We compiled climate, geography, land use, and condition information for Spain and visualized Spain's WCHS as map overlays against key climatic variables. We

Table 2 Data sources

Model component	Data source
Spain's WCHS location, type and inscription date	https://whc.unesco.org/en/statesparties/es
Administrative boundaries, traffic and water system distribution	https://www.naturalearthdata.com/downloads/
Climate zones	Metzger, M.J., et al., A high-resolution bioclimate map of the world: a unifying framework for global biodiversity research and monitoring. Global Ecology and Biogeography, 2013. 22(5): p. 630–638
Air temperature, precipitation and climate moisture index	Hijmans, R.J., et al., Very high resolution interpolated climate surfaces for global land areas. International Journal of Climatology, 2005. 25(15): p. 1965–1978
Global Aridity Index	Zorner, R.J., et al., Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agriculture Ecosystems & Environment, 2008. 126(1–2): p. 67–80
Terrestrial Biomes	Dinerstein, E., et al., An Ecoregion-Based Approach to Protecting Half the Terrestrial Realm. Bioscience, 2017. 67(6): p. 534–545
Elevation and terrain slope	Robinson, N., J. Regetz, and R.P. Guralnick, EarthEnv-DEM90: A nearly-global, void-free, multi-scale smoothed, 90 m digital elevation model from fused ASTER and SRTM data. ISPRS Journal of Photogrammetry and Remote Sensing, 2014. 87: p. 57–67
Population Density	Center for International Earth Science Information Network, C.C.U., Gridded Population of the World, Version 4 (GPWv4): Population Density, Revision 11. 2018, NASA Socioeconomic Data and Applications Center (SEDAC): Palisades, New York

searched for recent studies summarizing the mechanisms of direct and indirect impacts of climate change on cultural heritage in Europe to provide a theoretical basis for quantifying the impacts of climatic conditions on cultural heritage sites in Spain. At the same time, we used Spanish historical climate data (Appendix 1) [32] to combine each of the mechanisms of the impact of climatic conditions on cultural heritage to qualitatively and quantitatively preliminarily assess the vulnerability of Spain's WCHS under the influence of climatic conditions. The R software programs "rgdal" and "Raster" were used to extract monthly average historical climate data for 50 years based on the latitude and longitude of each WCHS.

Quantitative analysis of potential risks under climate conditions

Historical climate data (average of 1970–2020) (Appendix 1) are used to quantitatively evaluate the extent to which WCHS in Spain are affected by local climate conditions from four perspectives: freeze–thaw cycles, thermal stress (thermoclastism), fluid dynamics scoring, corrosion, and biodegradation. By quantifying the specific impacts of four aspects under climate conditions and summing and ranking them, the climate-dependent vulnerability of Spanish WHCS can be analyzed from the perspective of climate conditions. Specifically, as follows:

The prerequisite for the freeze–thaw cycle is that the annual minimum temperature of the cultural heritage site is lower than 0 ℃, there is more rainfall, and there are periods of temperatures above 0 ℃ each year. We selected the cultural heritage sites affected by the freeze–thaw cycle based on the historical average climate data for WCHS in Spain (1970–2020). The product of the absolute minimum temperature of the coldest month standardized by the Z score and the annual precipitation standardized by the Z score was used to preliminarily quantify the impact of freeze–thaw cycles under ideal conditions (Table S1).

The prerequisite for thermoclastism, which refers to damage to stone materials caused by thermally induced expansion and contraction, is that the cultural heritage site has large interannual and diurnal temperature differences and is exposed to more sunlight radiation. We selected cultural heritage sites affected by thermoclastism based on the historical average climate data for WCHS in Spain (1970–2020). The diurnal average temperature range and annual average temperature difference are positively correlated and strongly correlated (Figure S1, $R^2=0.8275$). Therefore, we use the diurnal average temperature range, which is more related to the frequency of thermoclastism, as a parameter. We use the product of the diurnal average temperature range standardized by the Z score and the solar radiation value standardized by the Z score to quantify the impact of thermoclastism on the ideal state (Table S2).

Hydrodynamic scoring is affected mainly by the annual average precipitation and annual maximum precipitation. We quantified the impact of hydrodynamic scoring on Spanish WHCS under ideal conditions by multiplying the Z score standardized annual average precipitation and Z score standardized annual maximum precipitation values based on historical average climate data (1970–2020) (Table S3).

Previous studies have suggested that corrosion and biodegradation are mainly influenced by two sets of climate data [2, 9]: (i) average annual temperature and

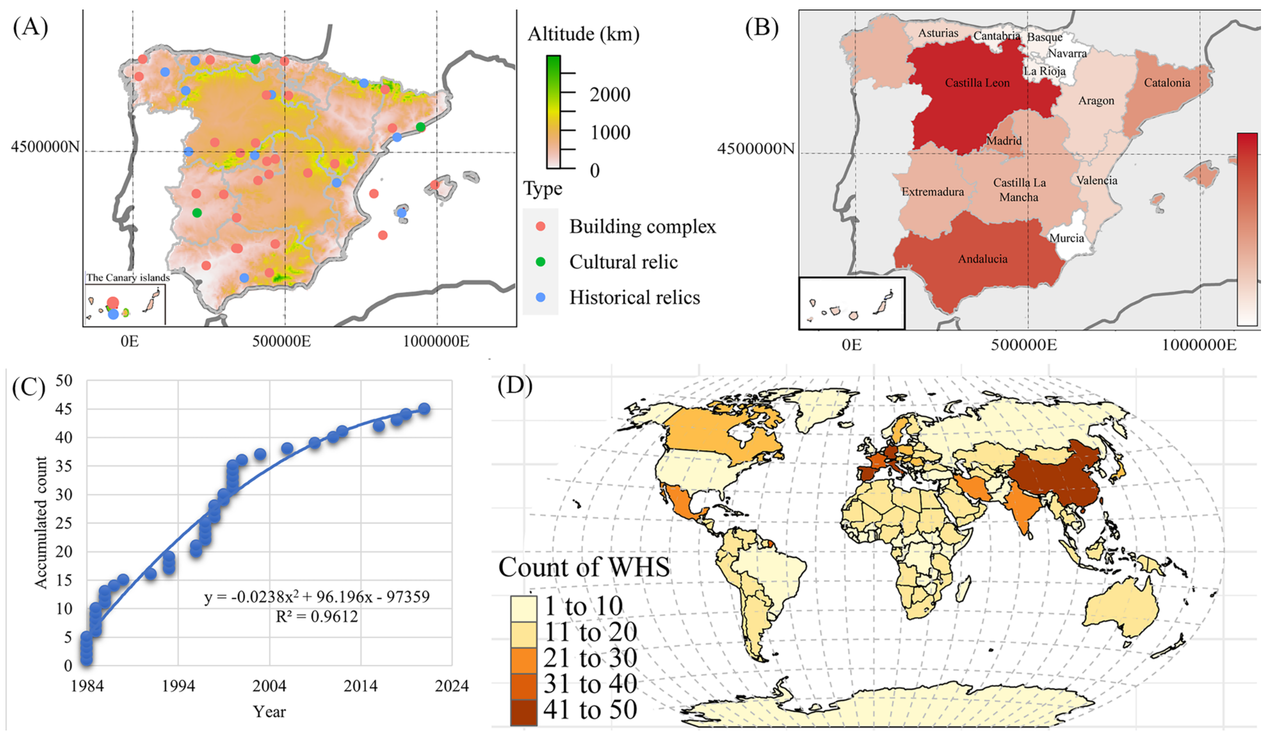

Fig. 1 Spatial and temporal distribution patterns of world cultural heritage in Spain. **A** Types and distribution of WCHS in Spain (showing WCHS classified according to UNESCO). **B** Number of WCHS in Spain by different administrative regions. **C** Temporal autocorrelation of the inscription dates of the Spanish WCHS. **D** Density of the WCHS of each state (data source: UNESCO World Heritage Centre—World Heritage List)

precipitation and (ii) mean precipitation of the wettest month and mean temperature of the warmest quarter. We quantified the impact of corrosion and biodegradation on Spanish WHCS under ideal conditions by multiplying the absolute values of two sets of climate data standardized by the Z score using historical average climate data from 1970 to 2000 and finally calculating the mean (Table S4).

The geometric mean of the four specific impact scores of the above climate conditions on cultural heritage was used as the composite score to quantify the risk level of the potential impacts of climate conditions on the local WCHS in different regions of Spain. Based on the score rankings, the climate condition risk rankings of the regions where the WCHS is located in Spain are obtained. The formula is as follows:

$$composite\ score = \sqrt[n]{X1 * X2 * \ldots\ldots Xn}$$

X is the specific impact score that is not 0, and n is the number. Evaluating the overall impact using the geometric mean can reduce the impact of extreme values on the composite score [33].

Results and discussion

Typology and geographical characteristics of world cultural heritage sites in Spain

According to the definition of UNESCO, WCHS can be divided into i. Cultural relics, buildings, carvings, and paintings of outstanding universal value from a historical, artistic, or scientific perspective, as well as inscriptions, caves, and their complexes with archaeological components or structures; ii. Architectural complexes, single or connected architectural complexes that, from a historical, artistic, or scientific perspective, have outstanding universal value in terms of architectural style, uniform distribution, or integration with environmental scenery; iii. Sites, artificial engineering or joint works of humans and nature with outstanding universal value from a historical, aesthetic, ethnographic, or anthropological perspective, as well as archaeological sites. According to the description on the official website (https://whc.unesco.org/en/statesparties/es), we calculated the number of different types of World Heritage sites in Spain (Fig. 1A). We found that Spanish WCHS mostly comprise architectural complexes (n = 30), followed by sites (n = 12) and cultural

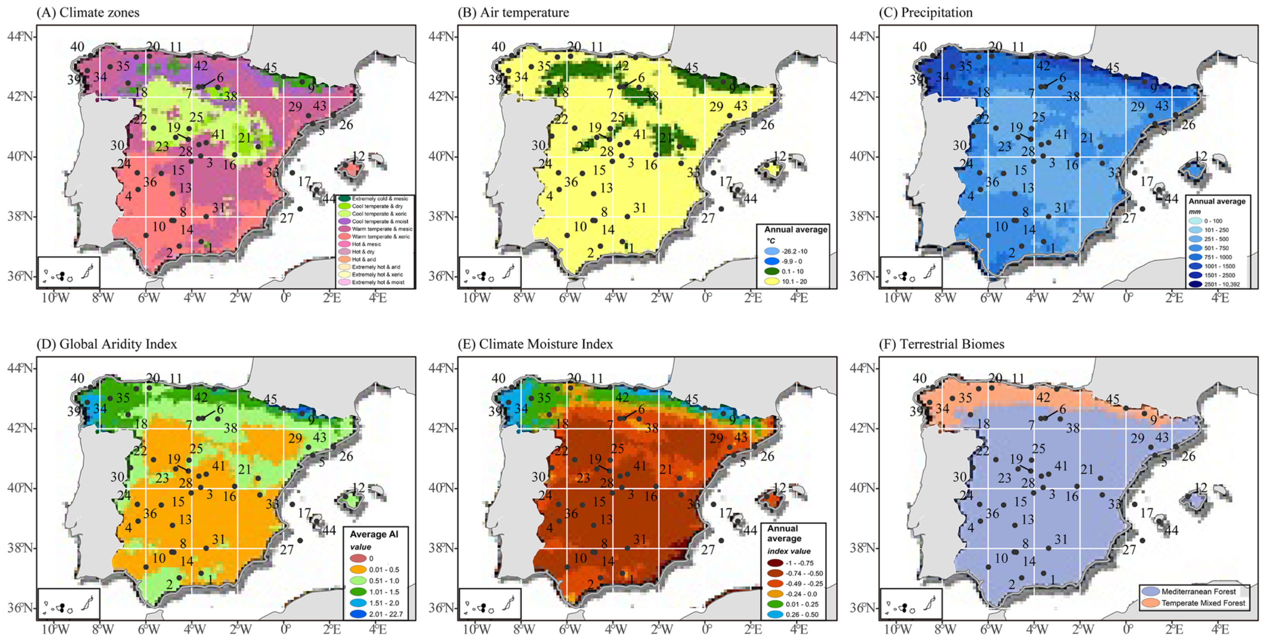

Fig. 2 Climatic conditions in Spain, with WCHS, numbered following Table 1. (Data source: Table 2)

relics (n = 3). Of course, individual WCHS may belong to multiple types, e.g.—in Granada, Andalucia, the WCHS of Alhambra, Generalife and Albaycín is both an architectural complex and includes cultural relics. Accordingly, we base our classification on the main characteristics of each cultural heritage site. From a typological perspective, Spain is representative of the cultural heritage types of European Mediterranean coastal countries [34], with more architectural communities and fewer sites. Previous studies on countries such as Italy [3, 35] have also found the same pattern.

We annotate cultural heritage on a map of Spain (Fig. 1A, Table 1) according to the longitude and latitude provided by UNESCO. Due to Spain being a former maritime power state [36], its cultural heritage is widely distributed along the coast and on many islands. Therefore, there are certain historical reasons for the densely populated sites in the central and western regions of the Iberian Peninsula. According to the division of Spanish first-level administrative units and autonomous regions (Fig. 1B), we found that there are more than two WCHS in seven autonomous regions, and the total number of cultural heritage sites in the seven autonomous regions is close to 70% of the comprehensive cultural heritage of Spain. Among them, Castile Leon, the largest autonomous region in northwestern Spain, has the most cultural heritage (with 7 sites), but most of them are distributed in the high-altitude areas of the border of the autonomous region (Fig. 1B). Andalusia is located in southern Spain, with a large area and 6 cultural heritage sites that are all architectural complexes and related to religious beliefs. As the capital region, Madrid, despite its small size, still has four cultural heritage sites, all of which belong to modern architecture or architectural relics (Table 1).

World cultural heritage sites are mainly concentrated in the three primary ancient civilizations of the Eurasian continent, namely, the “Two Rivers Civilization”, “Ancient Indian Civilization”, and “Chinese Civilization”, as well as the secondary classical civilization, “Ancient Greek and Roman Civilization” (Europe) [3]. Italy, Spain, China, Germany, France, and India have the greatest number of cultural heritage sites in the world [3] (Fig. 1D). In terms of climate (Fig. 2), the WCHS cluster in central Spain is mainly distributed in the cool temperature and xeric climate zone, while other cultural heritage sites are mainly distributed in the warm temperature and mesic, warm temperature and xeric warm climate zones. Only the two cultural heritage sites in the north, Santiago de Compostela (Old Town) and Pyrenees, Mont Perdu, are distributed in cold climate zones (Fig. 2). In physical terms, Spain has diverse terrain relief and a large plateau area (*the meseta*) [2] (Fig. 3). Looking at the altitude distribution of cultural heritage in the four major countries with WCHS, we find that most of Italy, China, and France’s WCHS is distributed in lower-lying areas (especially China and France), while the Spanish WCHS are more distributed in the highlands [3] (Fig. 3). In summary, the Spanish WCHS is evenly distributed, with a wide altitude gradient and a

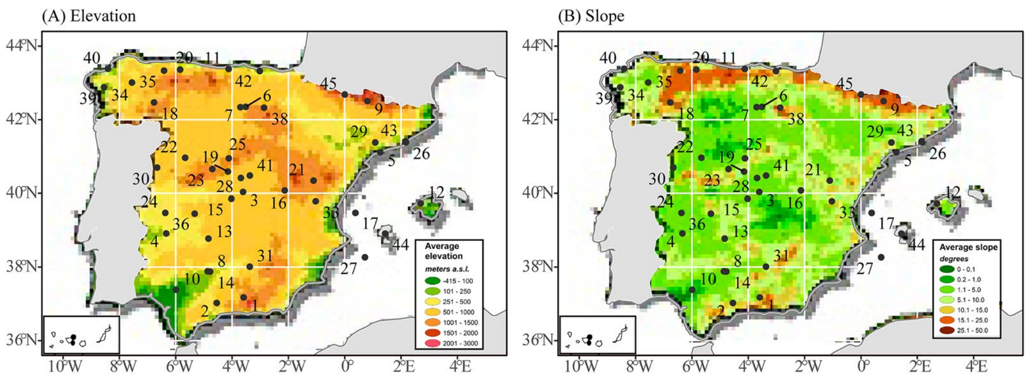

Fig. 3 Physical landscape characteristics, with WCHS, numbered following Table 1. (Data source: Table 2)

long coastline, which reflects the unique distribution of the Spanish WCHS on a global scale.

The number of WCHS admitted to the list in the 1980s and 1990s was relatively large, while the number of WCHS members admitted in the 2000s and 2010s was relatively small (Table S1). As shown in Fig. 1C, although the frequency of entry has decreased in recent years, Spanish excavation and application work for domestic WCHS have continued, and there have been more entries in recent years. The period with the highest number of cultural heritage entries per unit time in Spain was from 1996 to 2000, followed by 1984 to 1990. In 1982, Spain joined the UNESCO Convention for the Protection of the World Cultural and Natural Heritage and took the following measures in connection with other World Heritage countries or international organizations: i. contributing to the UNESCO World Heritage Fund; ii. The Spanish Institute of Historical Heritage provides annual funding of €35m for maintenance and rehabilitation work; iii. Spain has reached an agreement with the World Heritage Center to provide €3m euros in foreign technical assistance; iv. Conduct overseas training courses on heritage [37]. In addition to the recording time of cultural heritage, this study also sorted out the historical periods to which the Spanish WCHS belonged (Fig. 4).

Quantitative assessment of the impact of local climate conditions on the Spanish WCHS—recent past

In the following section, we describe the impact mechanism of climate conditions on cultural heritage using examples from the literature and present the results of the detailed analysis of the WCHS in Spain using historical climate data (Appendix 1).

Freeze thaw cycle

During freezing, the volume of water in porous material increases, resulting in changes in internal stress. However, under climate change, the frequency of freezing and thawing mechanisms in most parts of Europe is expected to be relatively low [38]. The resulting mechanical weathering will lead to damage and disintegration of stone, brick and ceramic material structures [39].

Thermal stress and thermoclastism

Cracking is the expansion and contraction of surface mineral particles caused by seasonal changes, diurnal changes in temperature and thermal changes caused by direct sunlight and may lead to microcracks, the spalling of stones and the erosion of the surface of building materials [40]. It is expected that with climate change, the risk of thermoclastism in the Mediterranean region will increase, especially for the widely used Carrara marble [41]. Some adjustments have been made in the area; for example, Malta's megalithic temple sites are free-standing and open to the air [42]. These prehistoric structures date to the 3rd and 4th millennia B.C.E, and are mainly constructed of globigerina limestone, a relatively soft and porous local limestone. Since excavation, these sites have been exposed to solar radiation, as well as rain, salt and wind, leading to their degradation. Clearly, thermoclastism is a key threat to these important sites.

Precipitation changes

Martin-Vide [43] calculated the concentration index (CI) for evaluating the weight of diurnal precipitation changes from 1951 to 1990 and divided the spatial distribution of diurnal precipitation in Spain: the precipitation in the eastern region is high; 25% of the rainfall days account for 70% or more of the annual precipitation, while the precipitation in other regions is more regular. The area with the highest diurnal rainfall is the southern part of Valencia Bay, which is also the area with the highest diurnal and hourly rainfall intensity in Spain. De Luis et al. [44] calculated and compared the seasonal precipitation observed during two consecutive 30 years (1946–1975 and 1976–2005). The spatial variation in the seasonal precipitation on the Iberian Peninsula overlaps with the complex temporal variation pattern, and there are two

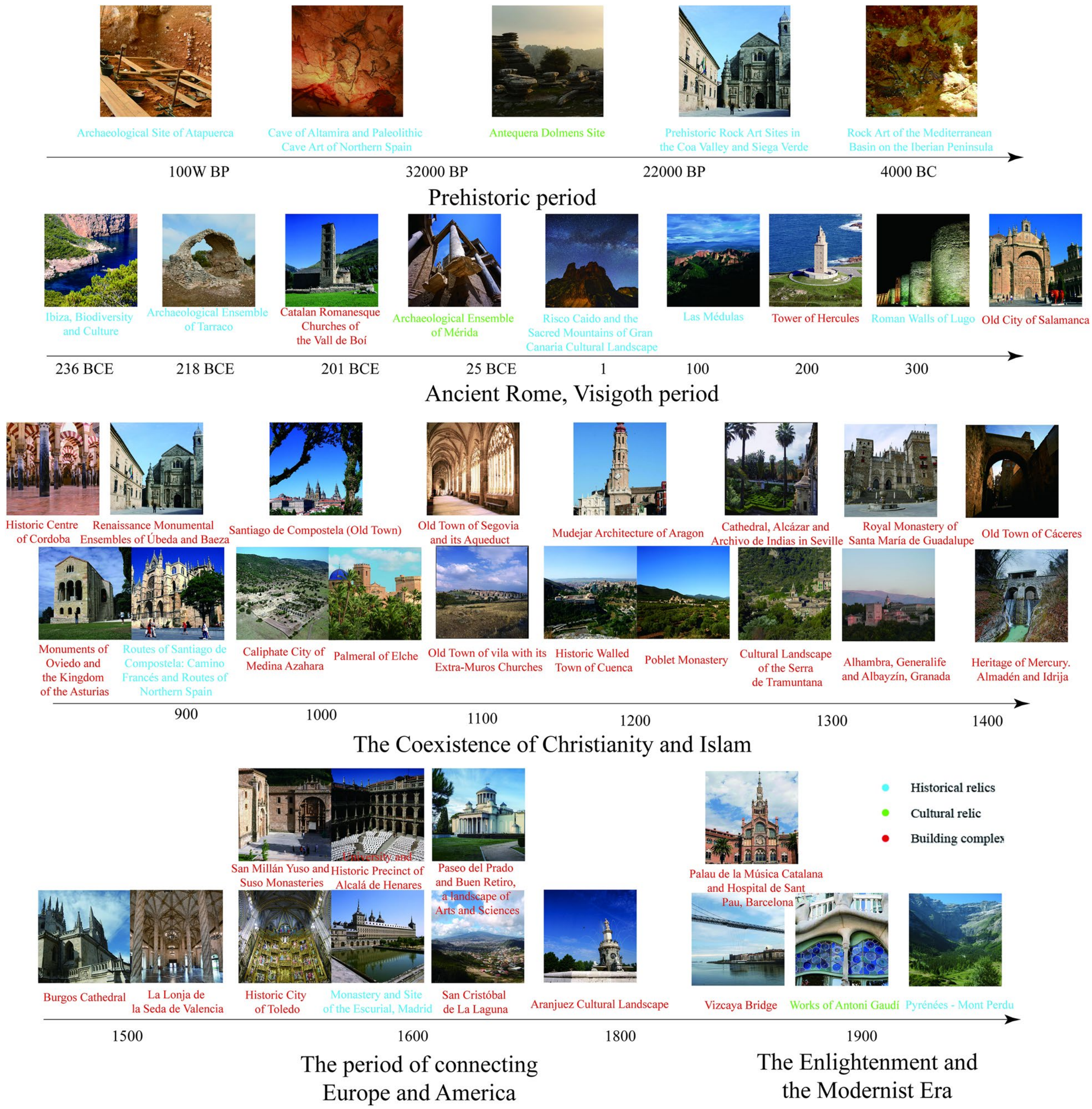

Fig. 4 The timeline of WCHS in Spain. Representative photos of the Spanish World Heritage Convention (single photographs of the WCHS source from the Spain-UNESCO World Heritage Convention)

patterns: (i) the climate is subtropical, and the rainfall decreases from winter to summer; and (ii) the percentage increase in autumn rainfall. Therefore, the spatial and temporal distributions of precipitation in Spain are uneven. The increase in water volume due to climate change may lead to soil saturation and the overloading of drainage ditches and downspouts. The risk of moisture infiltration in historical materials, including masonry walls, is greater. Water infiltration into porous materials may also be due to condensation and capillarity in the presence of soil moisture. Inflow water causes material degradation through corrosion and biological activity [9].

Corrosion

In a warm climate, more precipitation will increase the corrosion of metal and glass materials, as well as the surface degradation of carbonate rocks [45], such as limestone and marble. Corrosion is a chemical phenomenon. It is usually deposited with salt (usually chloride) under the action of water, leading to gradual deterioration of materials. High atmospheric concentrations of carbon dioxide (CO_2) are more common in acid rain and carbonate rocks. Grøntoft [46] predicted that due to the warmer and wetter climate, the corrosion of various metals in Northern Europe, namely, steel, zinc, copper and bronze, as well as Portland limestone and painted surfaces, will increase, while it is expected that the corrosion of southern Europe, which has a dry climate, will decrease. They also found that in areas with high chloride deposits, such as coastal areas and areas where deicing salts are used in cold seasons, the corrosion of zinc, copper and lead is expected to increase, while the corrosion of glass materials throughout Europe is expected to decrease overall, albeit to a small extent [47]. For the facades of stone buildings in northern Europe where precipitation is expected to increase, this may lead to further corrosion of stone building surfaces, such as Portland limestone [46, 47] and low-porosity carbonate rocks [48]. The corrosion pH of marble and dense limestone is approximately 5.6. Therefore, slightly acidic precipitation leads to carbonate rock degradation, which is called the *karst effect* [49]. Due to the increase in atmospheric CO_2 concentration caused by human activities and the subsequent further acidification of rainfall, the karst recession of carbonate rocks will increase.

Biodegradation

A change in humidity will affect the growth of microorganisms on stone and wood heritage materials, and an increase in relative humidity will aggravate the biological degradation of cultural heritage sites when the climate is warming [24, 50]. A long period of humidity increases the relative humidity and increases the water content in the materials. With increasing temperature, conditions conducive to various biological activities are created. The accumulation and decay of biomass from fungi, algae, molds, lichens and insects have led to the degradation of wooden historical buildings. The action of termites will lead to the collapse of wooden structures, and their range of activities may further expand to the north in the case of climate warming [24].

For a study area in the UK, Smith et al. [51] predicted that an increase in the risk of water infiltration into porous stones under wet conditions is conducive to the growth of algae, and the amount of algae biofilms on stone buildings will increase. This result is consistent with that of McCabe et al. [52]. The mild marine climate of Galicia, Spain, which is similar to that of the United Kingdom, is therefore likely to experience similar effects. According to an experimental study, the composition of the biofilm may change, leading to faster stone degradation [53]. For example, in the mild but humid climate of Northern Ireland, sandstone buildings in areas with high rainfall and water content are more vulnerable to biological pollution and stone decay.

Fungal attack is one of the main causes of wood degradation. Haugen and Mattsson [50] determined that temperature, air humidity and wood moisture content are the three main variables leading to biological degradation caused by fungi, molds and insects. Wood moisture content is affected by increased precipitation, storms and floods [54]. With increasing temperature and humidity, wooden buildings in northern and eastern Europe and northwest of the British Isles will face greater risk of fungal attack. In Norway, it is predicted that the risk of decay of wooden historic buildings will increase [55]. In contrast, the risk of fungal growth is expected to be low in southern and western Europe due to the expected dry conditions in the region. Changes in temperature and rainfall have changed the distribution and abundance of lichens and the richness of lichen species [56].

Comprehensive assessment of the climate risks of Spain's WCHS

Our analysis revealed that 10 WCHS in Spain have a freeze thaw cycle risk, among which Pyrénées—Mont Perdu has a much greater freeze thaw cycle risk than other WCHS due to its minimum temperature of the coldest month, which is much lower than 0 ℃, and the highest annual precipitation (Table S1). This cultural heritage site is located on the windward slope of high-altitude mountainous areas (Fig. 3). We quantitatively ranked the degree of thermal stress and thermoclastism on the Spanish WCHS (Table S2) and confirmed that the impact on Risco Caido and the Sacred Mountains of Gran Canaria Cultural Landscape, San Cristóbal de La Laguna and Tower of Hercules far exceeds that of other WCHS. The annual temperature range, mean daily range, and solar radiation in these areas are significantly high. Regarding hydrodynamic scoring effects, we found that Santiago de Compostela (Old Town) is at a much greater risk than other WCHS (Table S3). Due to its particularly high annual precipitation and high concentration of precipitation, hydraulic erosion caused by precipitation has become an important climatic pressure that this cultural heritage site needs to face. By evaluating the degree of corrosion and biodegradation scoring effects on the Spanish WCHS (Table S4), we found that Pyrénées, Mont Perdu, is at the highest risk and far exceeds other WCHS, which is closely related to its warm and humid climate conditions. Finally, based on the above climate condition risks, we identified the Spanish WCHS with the highest potential climate condition risks, including Santiago de Compostela and Pyrénées—Mont Perdu (Old Town) (Table 3).

Future qualitative assessment of the impact of local climate conditions on Spain's WCHS

The future climate is expected to impact the variables used in this study in a number of ways, which we discuss with

Table 3 Quantitative assessment of the impact of local climate conditions on the Spanish WCHS

WCHS	Name	Freeze thaw cycle	Thermal stress	Hydrodynamic scouring	Corrosion and Biodegradation	Composite score	Rank
39	Santiago de Compostela (Old Town)	0	2.25	10.45	1.995	3.61	1
45	Pyrénées - Mont Perdu	6.12	0.46	5.6	9.41	3.49	2
34	Roman Walls of Lugo	0	0.58	5.94	1.465	1.72	3
35	Routes of Santiago de Compostela: Camino Francés and Routes of Northern Spain	0	1.27	2.04	1.62	1.61	4
40	Tower of Hercules	0	3.13	1.05	0.5	1.18	5
42	Vizcaya Bridge	0	1.28	1.63	0.405	0.95	6
37	San Cristóbal de La Laguna	0	3.5	0.43	0.56	0.94	7
32	Risco Caido and the Sacred Mountains of Gran Canaria Cultural Landscape	0	3.84	0.52	0.355	0.89	8
1	Alhambra, Generalife and Albayzín, Granada	0	1.54	0.56	0.655	0.83	9
31	Renaissance Monumental Ensembles of Úbeda and Baeza	0	1.23	0.53	0.57	0.72	10
11	Cave of Altamira and Paleolithic Cave Art of Northern Spain	0	1.69	0.67	0.265	0.67	11
18	Las Médulas	0	0.22	1.62	0.6	0.6	12
15	Historic City of Toledo	0	0.25	0.98	0.86	0.6	13
20	Monuments of Oviedo and the Kingdom of the Asturias	0	2.36	0.31	0.255	0.57	14
9	Catalan Romanesque Churches of the Vall de Boí	1.02	0.04	0.99	2.28	0.55	15
3	Aranjuez Cultural Landscape	0	0.32	0.78	0.635	0.54	16
44	Ibiza, Biodiversity and Culture	0	0.32	0.43	0.75	0.47	17
33	Rock Art of the Mediterranean Basin on the Iberian Peninsula	0	0.37	0.93	0.145	0.37	18
13	Heritage of Mercury. Almadén and Idrija	0	1	0.17	0.26	0.35	19
25	Old Town of Segovia and its Aqueduct	0.22	0	0.48	0.37	0.34	20
7	Burgos Cathedral	0.23	0.43	0.33	0.365	0.33	21
23	Old Town of vila with its Extra-Muros Churches	0.3	0.06	0.74	0.575	0.3	22
30	Prehistoric Rock Art Sites in the Côa Valley and Siega Verde	0	0.07	1.15	0.225	0.26	23
6	Archaeological Site of Atapuerca	0.12	0.31	0.24	0.43	0.25	24
28	Paseo del Prado and Buen Retiro, a landscape of Arts and Sciences	0	0.05	0.63	0.455	0.24	25
16	Historic Walled Town of Cuenca	0.27	0.25	0.37	0.115	0.23	26
21	Mudejar Architecture of Aragon	0.05	0.3	0.8	0.21	0.22	27
38	San Millán Yuso and Suso Monasteries	0.11	0.21	0.17	0.525	0.21	28
2	Antequera Dolmens Site	0	0.99	0.05	0.15	0.2	29
10	Cathedral, Alcázar and Archivo de Indias in Seville	0	0.7	0.03	0.39	0.2	30
41	University and Historic Precinct of Alcalá de Henares	0	0.08	0.44	0.225	0.2	31
4	Archaeological Ensemble of Mérida	0	0.98	0.03	0.2	0.18	32
5	Archaeological Ensemble of Tarraco	0	0.12	0.2	0.255	0.18	33
36	Royal Monastery of Santa María de Guadalupe	0	0.25	0.18	0.14	0.18	34
19	Monastery and Site of the Escurial, Madrid	0.12	0.24	0.1	0.29	0.17	35
14	Historic Centre of Cordoba	0	0.99	0.01	0.29	0.14	36
22	Old City of Salamanca	0	0.08	0.19	0.165	0.14	37
8	Caliphate City of Medina Azahara	0	1	0.01	0.18	0.12	38
24	Old Town of Cáceres	0	0.15	0.06	0.21	0.12	39
26	Palau de la Música Catalana and Hospital de Sant Pau, Barcelona	0	0.54	0.03	0.08	0.11	40
17	La Lonja de la Seda de Valencia	0	0.13	0.06	0.08	0.09	41
29	Poblet Monastery	0	0	0.22	0.03	0.08	42
43	Works of Antoni Gaudí	0	0.57	0.01	0.045	0.06	43
12	Cultural Landscape of the Serra de Tramuntana	0	0.14	0.01	0	0.04	44
27	Palmeral of Elche	0	0	0.04	0.01	0.02	45

The colors indicate a comparison of climate impact risk levels, which are divided into four levels of risk assessment based on numerical magnitude: > 3, 1–2, 0.1–1, and 0–0.1

reference to the well-known shared socioeconomic pathways framework [57]. Under shared socioeconomic pathways (SSPs), climate change trends from global models are translated into qualitative trends to aid in understanding the impacts on society. Table 4 shows how the defined trends under each SSP are expected to influence the different variables used in the analysis. We predict that under SSP1-2.6, the climate potential risk for the Spanish WCHS

Table 4 Qualitative projections of potential climate risk for WCHS in Spain under different social economic paths (SSPs) for future climatic conditions

SSP	Freeze thaw cycle	Thermal stress	Hydrodynamic scouring	Corrosion and Biodegradation
SSP1-2.6	↔	↔	↔	↔
SSP2-4.5	↓	↑	↑	↑
SSP3-7.0	↓+	↑+	↑+	↑+
SSP5-8.5	↓++	↑++	↑++	↑++

Keywords: Freeze thaw cycle: minimum temperature of coldest month and annual precipitation; thermal stress: diurnal average temperature range and solar radiation; hydrodynamic scouring: annual average precipitation and annual maximum precipitation; corrosion and biodegradation: mean annual temperature and precipitation and mean precipitation of wettest month and mean temperature of warmest quarter. changes: ↑ projected increase; ↓ projected decrease; ↔ no change; Strength of changes: + strong; + + very strong

will likely remain almost unchanged in the future (until ~ 2100). The multi-model ensemble mean temperature under SSP1-2.6 is projected to be significantly less than 2 °C by 2100, supporting research on the 2 °C warming target. This scenario represents a combination of low vulnerability, low mitigation pressure, and low radiative forcing [58]. In this case, quantifying the future climate risk for the Spanish WCHS shows minimal changes, indicating that the climate potential risk will remain relatively stable. Therefore, energy efficiency and emissions reduction (i.e., carbon neutrality) are highly important for the preservation of WCHS [59]. Furthermore, SSP2-4.5 represents a combination of medium socioeconomic vulnerability and medium radiative forcing, SSP3-7.0 represents high socioeconomic vulnerability and relatively high anthropogenic radiative forcing, and SSP5-8.5 is the only shared socioeconomic pathway that achieves an anthropogenic radiative forcing of 8.5 W/m^2 by 2100. These four SSPs form a gradient of socioeconomic vulnerability, and the perceived radiative forcing increases [57]. We found a potential decline in the freeze–thaw cycle risk for the Spanish WCHS along this gradient, attributed to the increasing degree of climate warming associated with the four SSPs, resulting in a reduction in the annual temperature below 0 °C and a decrease in the number of freeze–thaw cycles in regions where the Spanish WCHS with a potential freeze–thaw cycle risk is located [60]. However, we expected the risks of thermal stress, hydrodynamic scouring, corrosion, and biodegradation to increase under SSP2-4.5, SSP3-7.0, and SSP5-8.5, with the greatest increase observed under SSP5-8.5 (Table 4). Previous studies have predicted an increase of 70% in the persistence of heatwave events (frequency and duration) in Asian coastal regions under SSP2-4.5 and a 90% increase under SSP5-8.5, indicating significant increases in surface radiative forcing under different SSPs [61]. Additionally, the comparison between scenarios revealed that SSP5-8.5 exhibited the largest future diurnal temperature range. Therefore, by qualitatively estimating the risk of heat cracking under future climate conditions, we can infer that the risk will increase the most under SSP5-8.5. Similarly, previous research has indicated future warm-humidization trends in Mediterranean coastal areas [62], along with increased frequencies of extreme heavy precipitation and floods [63]. Hence, we predict a significant increase in the risks of hydrodynamic scouring, corrosion, and biodegradation under future climate conditions.

Recommendations to address the trends of future climate risks on Spain's WCHS

i) Based on the findings of this study, the climate risk levels and inventory of the WCHS in Spain were classified. This classification considers the specific architectural structures and material properties of WCHS to categorize the efforts and funding allocations for risk prevention and protection.
ii) Active participation and response to the European Green Deal are crucial for achieving the climate goals set by the EU's Paris Agreement for 2030. While this initiative is part of a comprehensive project to mitigate global warming [29], it also offers significant benefits for the protection of WCHS. In July 2021, the European Commission introduced the Renewable Energy Efficiency Directive as part of the European Green Deal. This directive reaffirms the EU's commitment to achieving energy independence, building confidence in reducing greenhouse gas emissions by 55% by 2030, and accelerating the deployment of renewable energy [30]. On the one hand, this policy promotes the increased use of renewable energy. On the other hand, the provisional agreement introduces specific renewable energy development standards to reduce building energy consumption by 49% by 2030, presenting new challenges for the preservation of cultural heritage in the built environment. This is because indoor facilities or cultural heritage artifacts require a continuous energy supply to maintain appropriate temperature and humidity levels [31]. In conclusion, the post-pandemic policies for protecting WCHS in Spain need to adapt further to local conditions based on the funding provided by the European Green Deal and Next Generation EU projects.
iii) Physical and structural issues and recommendations for moisture-proofing and insulation in Spanish world cultural heritage buildings. In the field of cultural heritage architectural complexes, the most urgent interven-

tion measure is to dismantle the steeples on the roofs of cultural heritage buildings. Currently, the wooden structures of these steeples are in very poor condition and serve as a source of biological infection that could cause the remaining healthy parts of the roof structure to collapse into the cultural heritage building [64]. The reinforcement of the framework grid system of the roof structure and the ceiling structure of the nave might require strengthening the foundations of cultural heritage buildings. Cultural heritage buildings should provide insulation [65] and moisture-proofing [66]. The use of insulation and moisture-proofing materials should not affect the historical qualities of cultural heritage buildings, specifically the area beneath the external wall cladding and the top of the ceiling. The cladding should be protected, including the removal of multiple paint layers and impregnation. Additionally, improvements in precipitation and groundwater clearance systems should be prioritized. The land surrounding cultural heritage buildings should be managed to guide water toward roads, rivers, or reservoirs.

Limitations of the study

This study has not investigated the attributes of cultural heritage itself, such as the proportion of porous structures in buildings, the proportion of wooden structures, the amount of marble used, or the length of time-specific sites. Moreover, this study does not address the impacts of climate change leading to sea level rise, changes in flood frequency, or the impacts of extreme meteorological events (i.e., extreme precipitation and extreme heat events). These topics could provide a promising focus for future studies.

Conclusion

World cultural heritage sites (WCHS) need to be managed and protected in different ways based on a systematic assessment of climate risks. The ongoing and worsening climate crisis is likely to expose WCHS to stressors that they may never have faced before due to the emergence of climatic extremes not previously known in human history. In this study, we address this urgent need for Spain, which has the second largest number of WCHS in the world (after Italy). Our main contribution has been to transform simple historical climate conditions into specific quantitative climate-related condition risks. Most of Spain's WCHS are architectural complexes that are widely distributed across various administrative regions (Fig. 1), climate zones (Fig. 2) and elevations (Fig. 3) throughout Spain. We integrated geographical data from different sources with recent historical climate data from Spain and reviewed the impact mechanism of climate conditions on cultural heritage. We quantitatively evaluated the extent to which Spanish WCHS were affected by local climate conditions from four aspects: freeze–thaw cycles, thermal cracking, fluid dynamics scoring, corrosion, and biodegradation. Based on the above climate condition risks, we identified five Spanish WCHS with the highest potential climate condition risks, including Santiago de Compostela (Old Town), Pyrénées—Mont Perdu, Roman Walls of Lugo, Routes of Santiago de Compostela: Camino Francés and Routes of Northern Spain, and Tower of Hercules. In terms of the climate conditions in which Spain's WCHS are located, Santiago de Compostela (Old Town) and Pyrénées—Mont Perdu are far more exposed to climate risks than other WCHS. Santiago de Compostela (Old Town) is most affected by hydrodynamic scoring, far exceeding other Spanish WCHS. The mean annual precipitation of the region where this WCHS is located is as high as 1670 mm, making it the region with the highest annual precipitation among all cultural heritage sites. The historical average precipitation during the wettest season is 657 mm, far exceeding that in other regions. Similarly, Pyrénées Mont Perdu is influenced mainly by freeze thaw cycles and corrosion and biodegradation, and its score far exceeds that of other WCSs. Furthermore, based on different shared socioeconomic pathways (SSPs), we qualitatively evaluated the climate risk changes for Spanish WCHS under climate change and found the lowest climate risk in the SSP1-2.6 scenario, emphasizing the importance of "carbon neutrality" for WCHS protection. The results of this study will contribute to a better understanding of the role of World Heritage sites in shaping Spain's identity, history, and culture and provide data for the management, protection, and promotion of the country's heritage. At the same time, we propose a methodology for the assessment of specific climate-related condition risks to cultural heritage, which is likely to be broadly relevant to other countries wishing to carry out similar assessments.

Appendix 1

Temperature and precipitation related bioclimate data for 1970–2020 of the Spanish WCHS[1]

[1] *bio1: annual mean temperature (°C); bio2: mean diurnal range (mean of monthly (max temp—min temp)) (°C); bio3: isothermality (bio2/bio7) (×100); bio4: temperature seasonality (standard deviation×100); bio5: maximum temperature of the warmest month (°C); bio6: minimum temperature of the coldest month (°C); bio7: annual temperature range (bio5-bio6) (°C); bio8: mean temperature of the wettest quarter (°C); bio9: mean temperature of the Driest Quarter (°C); bio10: mean temperature of the warmest quarter (°C); bio11: mean temperature of the coldest quarter (°C); bio12: annual precipitation (mm); bio13: precipitation of the wettest month (mm); bio14: precipitation of the Driest Month (mm); bio15: precipitation seasonality (coefficient of variation); bio16: precipitation of the wettest quarter (mm); bio17: precipitation of the Driest Quarter (mm); bio18: precipitation of the Warmest Quarter (mm); bio19: precipitation of the coldest quarter (mm). The correspondence between WCHS and their names in our study can be found in* Table 1.

WCHS	bio_01	bio_02	bio_03	bio_04	bio_05	bio_06	bio_07	bio_08	bio_09	bio_10	bio_11	bio_12	bio_13	bio_14	bio_15	bio_16	bio_17	bio_18	bio_19
1	15.88	13.39	42.11	651.03	34.23	2.42	31.81	9.35	24.34	24.34	8.55	408	56	3	52.74	159	25	25	150
2	15.76	12.32	41.98	601.04	32.61	3.26	29.35	9.93	23.44	23.69	9.02	602	98	2	65.3	275	23	27	255
3	15	12.08	37.81	706.85	33.26	1.32	31.94	10.72	24.04	24.21	6.97	382	48	9	40.32	137	43	45	117
4	16.78	12.58	41.06	638.03	34.33	3.68	30.65	10.22	24.91	24.97	9.43	536	89	6	58.91	236	34	37	210
5	15.81	9.1	38.39	540.34	28.24	4.52	23.72	16.99	10.26	22.84	9.73	525	71	16	36.41	189	98	135	103
6	10.42	11.38	40.22	611.6	27.12	− 1.16	28.29	11.92	18.34	18.34	3.51	548	65	24	28.32	168	89	89	154
7	11.25	11.64	40.47	615.85	28.22	− 0.54	28.76	12.81	19.2	19.2	4.26	513	63	23	29.32	160	83	83	142
8	16.86	12.76	41.3	642.37	34.52	3.62	30.91	10.31	25.01	25.18	9.51	556	90	3	62.3	247	26	31	219
9	6.65	10.52	37.81	624.25	22.72	− 5.1	27.82	3.77	14.81	14.81	− 0.33	1142	122	66	16.78	327	240	240	276
10	18.63	11.82	41.39	591.47	34.58	6.02	28.55	12.56	26.09	26.22	11.74	539	94	2	66.87	253	23	27	224
11	13.53	8.97	45.5	397.01	23.82	4.11	19.71	11.84	18.38	18.71	9.02	997	117	49	26.57	325	159	176	279
12	13.85	9.1	37.53	557.4	27.48	3.22	24.26	11.64	20.95	21.17	7.86	683	96	12	43.43	260	67	106	205
13	15.3	12.96	40.6	667.75	33.82	1.89	31.93	8.47	23.93	23.93	7.72	505	76	6	52.9	203	36	36	185
14	17.74	13.06	41.68	648.81	35.48	4.14	31.35	10.99	25.94	26.08	10.25	540	87	3	62.19	240	26	31	210
15	15.53	11.52	36.52	706.84	33.56	2.03	31.53	11.23	24.59	24.77	7.52	357	44	9	38.53	120	42	48	103
16	12.63	12.47	39.84	674.79	30.88	− 0.41	31.29	8.67	21.4	21.52	5.15	501	59	15	34.22	158	68	74	146
17	14.48	11.6	40.26	617.21	30.93	2.06	28.87	10.71	21.6	22.5	7.49	583.38	79.69	15.5	44.69	216.06	67.63	75.63	186.13
18	12.15	10.2	38.97	570.73	27.28	1.09	26.18	8.8	19.47	19.47	5.51	1055	143	28	45.17	410	108	108	371
19	10.35	8.76	32.83	652.63	25.97	− 0.7	26.67	6.69	18.93	18.96	3.2	582	70	19	36.95	201	74	81	166
20	12.99	8.57	42.77	427.28	23.7	3.66	20.04	11.56	18.31	18.56	8.13	961	107	49	26.22	286	155	155	274
21	12.18	14.2	42.55	681	31.21	− 2.16	33.37	14.41	5.63	21.08	4.37	377	56	15	39.56	136	52	111	54
22	12.2	11.71	39.85	624.67	29.52	0.14	29.39	5.73	20.19	20.27	5.09	533	67	14	38.56	189	63	69	181
23	10.93	10.11	35.68	652.32	27.38	− 0.96	28.33	12.64	19.35	19.48	3.64	408	49	16	32.16	133	62	73	103
24	16.05	11	36.87	668.38	33.53	3.7	29.82	9.38	24.72	24.77	8.52	532	85	7	55.86	228	39	40	194
25	11.14	10.15	35.73	676.42	27.42	− 1	28.42	13.17	19.75	19.89	3.36	473	60	20	31.2	148	70	79	125
26	15.93	8.76	37.11	547.58	28.68	5.08	23.6	20.9	10.37	23.11	9.84	622	85	25	30.88	218	122	158	132
27	13.56	10.82	39.02	610.68	29.42	1.62	27.8	11.05	19.59	21.51	6.67	606.84	80.04	18.91	39.94	216.94	75.66	88.79	182.13
28	14.69	11.02	36.65	684.72	32.01	1.94	30.07	10.49	23.65	23.65	6.95	412	52	10	40.72	147	49	49	123
29	13.25	10.82	38.6	624.15	28.85	0.82	28.03	14.21	21.17	21.29	6.09	541	64	17	29.87	177	102	113	111
30	12.99	10.21	39.04	571.4	28.23	2.06	26.16	6.64	20.51	20.51	6.64	957	144	15	55.32	402	74	74	402
31	15.27	13.47	40.21	711.72	34.88	1.39	33.49	11	24.44	24.61	7.33	427	58	5	48.39	158	32	34	147
32	15.38	8.15	45.11	347.37	26.04	7.99	18.06	11.56	19.32	20.12	11.56	366	62	2	73.03	176	9	17	176
33	13.81	12.25	41.14	630.68	30.7	0.93	29.77	15.43	7.62	22.02	6.74	373	48	18	31.52	121	66	78	73
34	12.52	10.02	44.65	450.3	25.44	3	22.44	8.15	18.17	18.45	7.44	1447	196	38	43.94	546	142	176	531
35	10.39	9.36	42.65	464.34	22.9	0.96	21.94	8.14	16.25	16.46	5.2	1181	139	51	32.39	402	165	174	364
36	14.25	11.26	38.51	633.45	31.08	1.85	29.23	7.89	22.52	22.52	7.11	517	69	6	49.23	197	38	38	188
37	17.57	7.89	48.92	291.37	26.93	10.8	16.13	15.55	20.33	21.44	14.44	372	69	1	79	187	6	14	160
38	9.79	10.25	39.5	567.95	24.88	− 1.06	25.94	11.17	17.11	17.11	3.35	568	66	28	24.99	177	98	98	153

WCHS	bio_01	bio_02	bio_03	bio_04	bio_05	bio_06	bio_07	bio_08	bio_09	bio_10	bio_11	bio_12	bio_13	bio_14	bio_15	bio_16	bio_17	bio_18	bio_19
39	13.01	7.83	42.8	390.6	23.41	5.11	18.3	9.29	17.87	18.11	8.54	1670	242	37	47.04	657	161	198	657
40	14.49	7.04	44.66	317.22	23.1	7.33	15.77	11.74	18.28	18.73	11.01	987	131	28	42.08	375	106	128	357
41	14.04	12.48	38.65	697.65	32.7	0.42	32.28	9.92	23.15	23.15	6.17	433	64	8	45.87	170	43	43	132
42	14.52	9.51	46.16	421.63	25.83	5.22	20.61	10.57	19.68	20.02	9.88	1185	134	57	25.13	369	210	217	331
43	15.73	8.72	36.9	548.68	28.54	4.92	23.62	20.7	10.17	22.93	9.63	644	86	27	30.26	224	126	165	134
44	17.81	9.4	39.55	534.38	30.96	7.2	23.76	15.68	24.5	24.83	11.92	429	68	5	50.26	173	36	71	131
45	0	9.15	33.26	649.42	16.73	−10.78	27.51	−5.75	8.65	8.65	−6.97	1585	169	82	22.19	486	275	275	452

Supplementary Information

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Supplementary Material1.

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Author contributions
Both authors were involved in the conception, design and selection of the topic for this study. Haisheng Hu was responsible for the preparation of the material, data collection and preliminary analyses. Richard J Hewitt was responsible for the planning and supervision of the research topic. The manuscript was drafted by Haisheng Hu, and Richard J Hewitt provided comments and edits. Both authors read and approved the final manuscript.

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Availability of data and materials
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Declarations

Competing interests
The authors of this manuscript declare no competing interests.

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