

REVIEW

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Effects of climate change on open air heritage: a review and the situation in the region of Mediterranean

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Abstract

This paper collects research information and registered data regarding the relationship between climate change and heritage, aiming to present a comprehensive state of studies and research on the subject. This relationship between these two cores is basically the main subject of this research, as well as the discovery of the areas with little information. Nowadays, there is a remarkable increase in the concern of the damage of cultural heritage and the research of methods and means of protection and of interpretation of its value. In the meanwhile, climate change is the other pillar of this paper, with evident damage, eminent jeopardy and accumulative downgrade of heritage assets. The aforementioned facts create a threatening background for the safeguarding of cultural and natural heritage and the transmission to the next generations. In general, stakeholders should focus on the mitigation of the human causes of climate change and the necessary adaptation to the climatic conditions for heritage protection. Through the collection of data, this paper presents the region of Mediterranean, as it has a strategic geographic location and the climatic conditions have already shown notable deviations. The presented information relates to the indices and measurements of the effects of climate change and the overall assessment of the risks of heritage, the irreversible impairment, the most common cultural aspects of the studies and the urgent need of protection. The scope of these data is the design of the appropriate management plan, taking into account the unique identity of each piece of heritage and its environment. To sum up, the kinds of heritage incorporated into the environment structuring a completed landscape with immediate exposure to the conditions, seem to lack the essential research for their preservation. For this reason, the adequate management of cultural and natural heritage in jeopardy, such as the cases in the Mediterranean region, require multidisciplinary assessment for heritage management.

Highlights

- The effects of climate change are relevant to every aspect of society and its activities, as well as the sustainability and the transmission of heritage to the next generations.
- Heritage is in jeopardy of losing its character, due to the exposure to natural hazards and anthropogenic factors, both responsible for climate change.
- Mitigation and adaptation are indispensable for the protection and management of heritage.
- There is lack of research and data for endangered heritage assets incorporated into the landscape, such as Open-air Greek Theatres.

Keywords Natural and cultural heritage, Climate change, Mitigation, Adaptation, Management plan

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Introduction

Heritage is undoubtedly connected to humanity and society by providing identity, history, virtues and discrete traditions. For this reason, the protection and the transmission of these values to subsequent generations is of vital importance and ensures the sustainability of cultural diversity. Climate change is a confirmed threat, not only for the planet and the natural processes, but also for humanity and cultural and natural heritage. The exposure of monuments, historical buildings, natural and cultural landscapes to the effects of climate change has already been stated of alarming significance by ICOMOS and other international organizations.

Up until 2017 [1], the disciplines that related to heritage protection and climate change dealt with their corresponding issues and problems separately of each other, resulting to data that was an could not be verified as a whole pertaining to the effects of climate change to cultural heritage. The resulting published research was spread into a variety of academic fields and in order to be able to study the effects of climate change on heritage, one had to have access to publications of different disciplines, as well as the knowledge of the subjects that needed attention. This is the fundamental purpose of the present review; the collection of the research on the topic of the effects of climate change on heritage, in order to examine the basic pillars of interest and to track the areas with less information.

In 2024 there is still inefficient publication that incorporates the different disciplines of archaeology, heritage protection, climatology and engineering together, into an integrated discipline that can address all issues related to the protection of cultural heritage from the effects of climate change. Moreover, the effects of climate change and their immediate destructive implications are ongoing and rapidly growing in both frequency and intensity, thus making the integration of disciplines of outmost importance. Also, it is important to accentuate the incorporation of the topic of heritage protection into the educational sector; a Greek initiative is the Master's degree Programme «Protection of Cultural Heritage and Monuments of Nature from the Effects of Climate Change», provided by the Hellenic Open University (HOU), Greece in collaboration with the Academy of Athens. This gentle gesture creates a significant framework of knowledge of the risks of cultural and natural heritage due to the effects of climate change and it is a bright example of cultivating awareness, proactive management and understanding of the need of mitigation and adaptation techniques.

The destructive capability of the effects of climate change is even more evident in regions, such as the Mediterranean, which incorporate not only exposed

monuments, but also monuments that are still being used by humans, after their initial construction. To this end, open-air heritage, such as the ancient Greek Theatres which are part of the Mediterranean culture, provide a unique example on how monuments can cope with, not only the effects of climate change, but also with the combined synergistic effects of conventional material failure, the frequency and intensity of climatic extremities and human made deterioration from continuous usage of the monuments and their surroundings.

This review paper focuses on the published data of different disciplines on the relationship of heritage with climate change. We discuss the region of Mediterranean as an example, since it has a vast array of examples of monuments in threat by synergistic factors of climate change and continuous use, such as the ancient theatres and other open-air heritage types, which are exposed to extreme and more frequent climate conditions that pose a serious threat and are the focus of this research. Climate change, its effects on heritage and the needed adaptation create a necessity for a methodology based on the collection of data. Thus, the contribution of the present study is the synthesis of the data of degradation of heritage due to climate change, with a combination of the information regarding the necessary protection. By presenting the data of research on methodology of adaptation and mitigation, the stakeholders of heritage could determine and detect the management plans and the proactive thinking. It is important to highlight that climate change is a multidimensional issue and there is a common misconception that global warming is its only manifestation, while it is merely the beginning of a domino effect, with often huge consequences on the anthropogenic and natural environment [2]. Studies and literature so far underline that damage to a cultural heritage site can mean the loss of irreplaceable cultural, social, and economic assets to local, national, and global communities, as heritage interacts with the environment, considering the weathering processes [1, 3]

Overall, this review paper deals with the combination of published information and regards on the strategy of forecasting, analysing, interpreting, acting, exploiting new technologies, climate projections, awareness and dissemination, mitigating and adapting to the weather phenomena and the effects of climate change.

Methods

According to the World Meteorological Organisation (WMO) the term 'climate' can be defined as 'the statistical description in terms of the mean and variability of relevant weather quantities over a period of time'. The alarming observation of climate change has affected the various aspects of life and thus cultural heritage.

The main method of the present review paper is the literature search on published materials and sources. The study is structured by bibliographic research, assessment of documents, plans and relevant evidence such as tables, photos and in-situ information. When accessible and public, also some author's comments were taken into account. For the selection, classification or even rejection of studies, the current review focused on the topic of heritage and its degradation due to climate change, but with geographical criteria, because of the Mediterranean region, as the main region of study. Also, of great importance is the time of publication and documents, as we searched for the updated versions of data and the latest information.

Taking into account the aforementioned methodological orientation, the basic keywords used are about cultural and natural heritage, landscape, heritage values, risk assessment, effects of climate change on heritage, vulnerability and resilience, as well as mitigation and adaptation.

Climate change and its effects on heritage

Climate change is an ongoing phenomenon obtaining global concern and interdisciplinary awareness. Climate change is evaluated and measured by indices, capable of detecting the alteration of weather conditions; the most basic of them are temperature (parameters of range, freeze thaw, thermal shock), humidity (parameters of precipitation, humidity cycles, time of wetness) and wind (air pressure, wind driven rain, sand and salt) [4, 5]. These indicators are directly and indirectly related to human activities affecting heritage, both natural and cultural, as well as tangible or intangible. For the adequate management and longevity of heritage, the effects of climate change impose an emergency of creating improvised mechanisms dedicated to the protection of heritage [1]. The interpretation of the impacts of climate change to cultural heritage involves the collaboration of many scientific disciplines, composing a model of four-pillar approach. These pillars are: science, mitigation, adaptation, and communication [1]. The interpretation and the function of the aforementioned approach starts with the collection of data relevant to climate change, gathering measurements, modelling, and techniques of analysis. The critical interpretation and the constant validation of the collected data with the multidisciplinary assessment of the impact of climate change on heritage are needed (Fig. 1).

It has already been documented that climate change affects natural processes (greenhouse enhancement, ozone depletion and enhancing the El Niño effect), water resources (rainfall reduction, degradation of subsoil and coastal ecosystems, strong evaporation of lakes, sea level

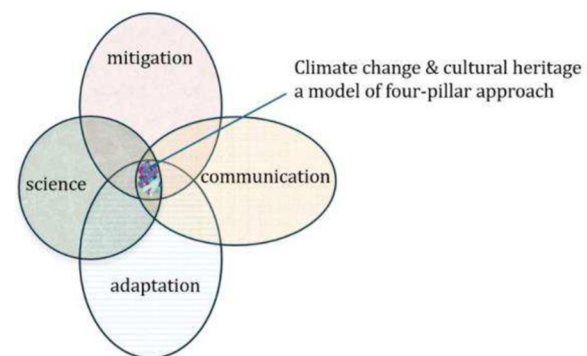


Fig. 1 visual interpretation of the four-pillar approach

rise, storm tides, sea shading, ice melting, icebergs and snowfall), flora and fauna (coral destruction, increase in fires, invasion of alien species, killing of fauna and flora, loss of vegetation due to extreme weather events, invasion of insects, disturbance of fauna, loss of habitats, migration and extinction of species), human activities (fisheries, agriculture, tourism, mining, transport and construction), human beings (indirect/direct effects of all above, increased mortality and morbidity, and Climate Migrants/Refugees) and is responsible for extreme weather phenomena, that add to the effects of all the above [2]. Fires and floods are also categorized as phenomena with extremity, due to climate change. Also, Sardella et al. [6] mention the hydro-meteorological and climate extremes that are: (1) Flood events in large basins (sites in the Czech Republic and Austria); (2) Fire due to drought periods (site in Croatia); 3) Extreme events of heavy rain (sites in Italy, Hungary, Croatia, Poland, and Slovenia).

Heritage assets are increasingly at risk because of the impact of natural and anthropogenic hazards, the frequency and intensity of which continue to be amplified by climate change [7]. Also, the effects on heritage have been detected as follows:

Uniqueness of heritage assets

There are changes in land use and economies, because of the different composition of the land and the need to adapt [8]. Sites and monuments are affected by various environmental agents, acting in synergy, which leads to varying frequency and intensity. The majority of these agents, such as wind erosion, ground water level changes [9] air pollution, and climate change [1, 10, 11] can be extremely harmful when they affect a site over a long period of time [12].

The study of the collected data and the necessary measurements can result in the understanding of the impacts of climate change on pieces of heritage. For

instance, according to Cassar [13] archaeological sites and some buildings have survived for at least two periods of global warming (around 1500–1200 BC and 800–1200 AD) and the intervening cold periods and the assessment of this heritage offers valuable information. In the meantime, local weather is heavily influenced by local topography and land use, implying an intense interaction between weather, the particularities of the place and the role of the community concerning land use [13]. This means that there is uniqueness in each case study, as special characteristics of every region of study deserve a tailor-made management plan for their past and current condition in combination with heritage values. Each heritage site is threatened by specific climate change impacts, asking for different management decisions and actions that respond to trends and events, resource priorities, budget availability, management strategy, expertise, and visitor access [15]. With respect to heritage buildings, conservation and sustainability should consequently follow a management plan for the correlation of cultural values with energy sufficiency.

Environmental factors

Natural and cultural heritage have always been and will continue to be subjected to interactions with their environment, including the climatic conditions, the climate change and the risks of damage, which affects physical, chemical, and biological characteristics, temperature and humidity fluctuations, sea level rise and relative coastal problems and extreme weather events [16]. markedly as a result of human activities since 1750 C.E. and now far exceed pre-industrial time. Cold days, cold nights and frost have become less frequent, while hot days, hot nights, the increased frequency of heat waves and heavy precipitation events may also increase the intensity of storm events. Nevertheless, these events are characterized by their intensity, while their frequency may decrease [14]. Measurement and historic data reveal an increase in greenhouse gas levels, documenting carbon dioxide (CO₂) as the first on the list. The increase in gas levels continues with air pollutants such as methane, halocarbons, ozone and aerosols that significantly affect the thermal balance of the atmosphere. These compounds absorb the earth's radiation, and then they re-emit it. As a result, they augment the heat of earth's surface as well as the lower layer of atmosphere [17].

Natural features are often threats for heritage. Change in weather patterns is primarily a threat that has physical impacts. It affects cultural heritage through temperature changes, soil erosion, flooding and storms as well as natural heritage through the melting of glaciers and habitat changes [15]. More specifically, water is

assessed as a threat to heritage, as it can be transformed into intense rain, flood, as well as storm surges, penetrating materials, delivering pollutants, as well as change in overall humidity that affects the growth of microorganisms on stone and wood, and the formation of salts that degrade surfaces and influence corrosion. Meanwhile, the wetting and drying, the intense rainfall, the tree planting, the changes in hydrology, in vegetation and in the distribution of pests are at an alarming point of evaluating the effects of climate change [14]. Water-derived parameters are driving factors, being involved in several deterioration processes, such as structural damage and erosion in the case of extreme rain events; surface recession on carbonate stones due to chemical dissolution; decohesion and fracturing in the case of salt crystallization; and freeze–thaw cycling and biological accumulation [18]. Chemical composition and porosity, with the associated texture and surface roughness, are recognized as crucial geological controls on weathering. In the specific case of events of heavy rain, erosion and loss of materials are major effects for stones, while swelling and shrinkage due to moisture gradients can easily occur on wood with associated biodeterioration [18].

The increasing global temperature is the mostly known consequence of the impacts of human activities on the climatic equilibrium of the planet, as it can easily and accurately be measured with modifications of precipitation patterns, droughts, storminess, ocean temperature, acidification, sea level rise leading to structural damage to buildings and monuments and changes in seasonal and diurnal [9]. Moreover, Letcher [12] mentioned that global surface temperatures are a broadly used indicator of climate change and they can provide data for related but nonidentical temperatures, such as land surface air temperature (LSAT), land surface temperature (LST), marine air temperature, sea surface temperature (SST), ice surface temperature, lake surface temperature etc. Briefly, the extreme evidence of climate change includes sea level rise, rise in temperature, hurricanes and storms, erosion, flooding, increase of rainfall, events of drought and desertification [14]. Further support for the conclusion that the world has warmed arises from our understanding of changes in a suite of co-related variables such as tropospheric temperatures, glacier volume, sea ice, surface humidity and ocean heat content [12]. Moreover, the effects include: wet frost, i.e. days of rain followed by frost, sheffer-type indices for fungal growth, evaporation–soil moisture, desiccation and water table, thermohydraulic shock, directional wind driven rain–damp penetration and redistribution of deposited atmospheric particles and decreasing temperature and

increasing humidity/hydrated salts [5]. Therefore, these trends provoke modifications of precipitation patterns, droughts, storminess, ocean temperature, acidification, coastal erosion and tidal flooding. Changes to the hydrological, chemical and biological processes of the soils, as well as water penetration and soil moisture. The aforementioned measurable parameters lead to structural damage of heritage, to the loss of integrity and abandonment of authentic historic meaning of damaged monuments and, especially in the urban fabric, they can be combined with atmospheric pollutants, putting heritage in jeopardy.

Also, cultural heritage sites in coastal regions are threatened by the risks of sea-level rise (SLR) and of storm surges, while natural hazards such as floods, landslides, earthquakes, volcanoes, and fire can also worsen the situation with devastating impacts on cultural heritage assets [18]. The most severe losses due to climate change are likely to occur at the coast; Rowlands [19] refers to it as the 'battlefront'. Coastal heritage includes land-based sites, intertidal sites, an underwater or submerged sites including wrecks. The main threats are sea level rise (SLR), storm events, and increased wave energy, leading to greater flooding, coastal erosion, coastal squeeze, and saline intrusion [20]. As coastal erosion and SLR progresses, more monuments will find themselves within this extreme environment [21]. Climate change is responsible for an increase in the freeze/thaw cycle in northern Europe, extreme heat and droughts in the Mediterranean region, the overall decrease in summer precipitation in Europe, and an increase in winter storms and heavy precipitation events in the Atlantic region. In addition, cultural heritage sites in coastal regions are particularly at risk of sea-level rising (SLR) and the occurrence of storm surges while natural hazards such as floods, landslides, earthquakes, volcanoes, and fire can also have devastating impacts on cultural heritage assets [18].

Materiality and conservation

With respect to building materials, they can provide information on the effect of climate change, like stone buildings, which are less influenced than wooden constructions, as they present differences in humidity levels, which cause physical changes, or even structural damage. The type and magnitude of damage created on a building by climate change depends on the building material and its state of conservation, on the surrounding urban or rural landscape, and on the geometry of the building, which is essential in determining the degree of exposure of architectural surfaces to (and shelter from) climate parameters, such as rain, wind, and solar radiation [22]. Climate change poses an important issue

while understanding that the inherent outstanding universal value of heritage may disappear due to environmental and socio-economic impacts. Ageing buildings must remain relevant to the contemporary use and challenges while adapting to survive climate change [13]. Environmental and biological changes affect ecosystem functioning and the provision of ecosystem goods and services with significant consequences on human livelihoods. Therefore, socio-economic activities like agriculture, fishery or tourism are also being impacted, for instance, through changes in freshwater supply [11]. In 2005, a study was conducted by the World Heritage Centre among all State Parties to the World Heritage Convention to assess the impacts of change in weather pattern on World Heritage sites. The collected responses reveal that climate change had an impact on 72% of the natural and cultural heritage sites in the sampled countries [11]. In the specific context of the Convention, climate change increases many concerns that are significant for the future implementation of the Convention. Heritage sites are inscribed on the World Heritage List if they meet at least one criterion of outstanding universal value and also fulfil the conditions of integrity [23]. At present, if a site is threatened by severe and specific danger/both determined and potential/it can be listed in the List of World Heritage in Danger. The Convention also observes that if a property loses the characteristics which approved its inscription on the World Heritage List, it can be removed from the list [11]. According to the 2030 Agenda (United Nations, 2015) and, specifically, with the Sustainable Development Goal 11 (SDG 11), countries have pledged to 'make cities and human settlements inclusive, safe, resilient and sustainable' [24]. According to Brandi (1963), cultural heritage has a value for the message it holds, and not for its material consistency; to be more accurate, he distinguished a marble from a quarry as something that 'was subjected to a radical transformation to be a vehicle of an image' [25].

Assessments of the sensitivity of heritage to the effects of climate change are largely dependent upon past experience of weathering and conservation science [26]. The largest research project completed to date is the European Union-funded Noah's Ark project. In this project, predictions from regional climate models were used to produce maps for future heritage climatology, for example wet-frost cycles [27]. By combining those predictive maps with existing knowledge of deterioration mechanisms, Noah's Ark created a series of predictive maps, of damage and risk, for heritage materials. Noah's Ark action includes scientific laboratories engaged in research on cultural heritage in the context of climate change,

together with an international insurance company and a private company specialising in the recovery from environmental disasters [28]. The continent's monumental heritage has to be treated as a whole. It is important to take into account innovative techniques of data analysis for the heritage at risk, such as virtual reality technology to create a simulated environment [29]. Another action in Europe is 'Sustainable Heritage', regarding issues related to climate change and cultural heritage [28]. The research had better incorporate the fact that climate change is subtle and occurs over long timescales, which means that different parts of Europe will experience different changes in climate over varying timeframes [5].

Stone conservation studies can require large data sets but with limited access to samples [28]. So, the need of alternative, minimally invasive or non-destructive techniques (NDT) is essential and therefore the permeability of stone is only related to porosity in instances where the stone has uniform types of pores and pore sizes. Effective porosity is an index property of rock as it is considered a key parameter relating to rock strength, permeability and durability [28].

Meanwhile, intangible factors are also influenced, as populations are forced to migrate, leading to the break-up of communities and the abandonment of property, with the eventual loss of rituals and cultural memory [11]. There are also intangible pieces of heritage, such as works of art, poems and lyrics which are included in the deterioration of monuments because of weather conditions [13]. Intangible heritage also includes memory, history and the societies and communities associated with the tangible cultural heritage [30]. The 'lived experience of culture', the 'identity', 'belonging', and 'sense of place' together with the values, traditions, and cultural practices need to be taken into consideration to determine the acceptability of the climate change adaptation solution [31].

Concerning the aforementioned information, there are three major threats: effects on historic building materials, effects on biodeterioration and the response of materials to extreme events. Brimblecombe et al. [32] estimate that the development of a vulnerability Atlas for monuments involves the assessment of the damage both to objects as a whole, as well as to individual materials and details. The summary of the results obtained on specific damage typologies embraces the climate science in a broader context of European cultural heritage encouraging sustainable movements. Therefore, selected materials should be studied according to the frequency of their use in built heritage, the availability of measurement of the response to risks and of the damage functions and the sensitivity to climatic factors. Sabbioni et al. [10]

developed an Atlas depicting the impacts of climate change on cultural heritage in Europe using different climate change scenarios. The Atlas provides an assessment of the potential risks of a range of climatic stressors on cultural heritage, bringing together the outcomes of previous research focusing on individual climate risks [33, 34].

There are studies about programmes and applications (e.g. EnergyPlus for the simulation of the hygrothermal environment of historic building weathering degradation, particularly in combination with rain and wind, strong winds, heavy rains, floods and landslides) for the observation, documentation and scenarios of future behaviours of climate parameters showing the effects of climate change [32]. One of the most important and measurable effects of the climate change which is used in the aforementioned programmes, is the temperature rise, as it is scientifically unequivocal that the world has warmed and thus society, governments and industry require actionable information at the local level to make informed decisions [35]. Of course, all this forms a useful database to document in order to evaluate the risks for the study and composition of the most adequate management of every case, including the model of mitigation and adaptation of heritage.

Changes in environmental parameters that control physical effects, such as freezing and thawing, thermal shock, or changes in humidity, are critical for the conservation and durability of materials. They can result in exfoliation, powdering, detachment, or worsening crack formation and deformation, causing decay with consequently loss of cultural value [33]. In spite of the worldwide awareness of the effects of climate change, research investigating and quantifying its impact on cultural heritage is still limited, and even more so at a scale relevant to decision-making, thereby making it difficult to incorporate climate change into preservation frameworks and management practices from government policy level down to the practice in the field [33].

Methodological frameworks

In the literature review, there is a significant void regarding the impacts of climate change on cultural heritage and resources located at various continents and disciplines. There has been obtained a wide range of research methods representing natural and social science discipline, but there is need for future studies focused on adaptation planning options for heritage sustainability; the opportunities and tools of implementing the practices of adaptation and preservation should be more efficiently verified [36].

As cultural heritage consists of different types of properties, which relate to a variety of settings, including

important works of art, monuments, sites, large historic areas and landscapes, the development of a framework involves methodological inspection, survey and documentation of the resource's historical setting, of the social, cultural and economic functions as well as of the physical environment [37]. According Sabbioni et al. [5], the structure of the guide for mitigating and adapting cultural heritage to changing climate related to the following steps:

1. Understanding the vulnerability of materials to climate,
2. Monitoring change, especially on decadal and even century-long time scales,
3. Modelling and projecting changes in heritage climate at high spatial and temporal resolution, estimating the reliability of the results
4. Developing tools to manage cultural heritage in a changing climate,
5. Preventing damage by developing long term strategies.

The aforementioned steps refer also to the promotion of a long-term risk assessment, followed by the re-evaluation of cultural environments [38].

Furthermore, it has also been stated that humanity should accept the loss of some of our heritage [10]. UNESCO, for its part, underlined that not all cultural heritage can be saved and that some sites might be abandoned because of the consequences of extreme events. Heritage work needs to become familiar with embracing loss with the search of creative and empowering ways to accomplish adaptation. The adaptive defence for the protection of heritage (hard coastal defence, new flood defences designed for the integrity of historical buildings, alteration of agricultural and forestry practices resulting from changes in crop, stock or species viability) could pose a risk to buried archaeological sites, traditional farm buildings and historic landscapes. Hitherto, heritage and climate change have had clear impacts on the history of our species, and they are bound to shape our ongoing cultural evolution, determining contemplation of the perception and the communication of the change, especially through time and space [9].

Although climate change and its effects on heritage is a subject of universal concern, at this certain point the research focuses on European assets. Europe is a continent with a great variety of monuments of any historic period and the data collected present geographical concentration of a place with controversial climate instances. Due to climate change, there are biological, chemical, and physical mechanisms leading to the degradation of Europe's assets. With respect

to the region of study, this fact includes increase in the freeze-thaw cycle in northern Europe, extreme heat and droughts in the Mediterranean region, the overall decrease in summer precipitation in Europe, increase in winter storms and heavy precipitation events in the Atlantic region. Sardella et al. [6] and Cacciotti et al. [39] proposed a web GIS tool to map climate change risk-prone areas in Europe and in the Mediterranean basin and proposed the need for the development of a methodology of heritage vulnerability ranking. At this point, we just mention the tool the HERACLES EU project; which presented responsive systems/solutions for effective resilience of cultural heritage against climate change effects, demonstrating the effectiveness of the project holistic approach at three heritage pilot sites: two in Crete (Greece) and one in Gubbio (Italy) [40].

As for the particular pieces of heritage located in Europe, the hydro-meteorological parameters relevant to changing impacts on cultural heritage include: extreme precipitation events (a difficult parameter to predict, yet critically important in terms of predicting storm damage), saturation of soils and water loading on roofs and other architectural elements. Research suggests that summers may have less precipitation [41, 42] altering the range of relative humidity cycles. Documented facts about stone show that it is especially vulnerable to relative humidity cycles and a wet-frost occurs when porous stone is saturated by significant rainfall, only to have a freezing event on the following day. Another conclusion coming from measurements is that increasing temperatures and lower rainfall rates in future summers imply increased evaporation and a reduction in soil moisture content [32].

At the following table (Table 1) we can see the collected publications of the main subject of this review, which have already been mentioned, taking into account the year and the general topic, with the number of citation in the text, respecting the chronological order of the publications.

The necessary relationship of mitigation-adaptation with heritage

First and foremost, the observation of the environmental factors affected by climate change is important, starting from the visual inspection on materials (e.g. fungal growth and pest damage). Secondly, the strategy for climate change should be based on risk assessment, adaptation measures, and monitoring effects of climate change on historic buildings with evidence of decay [43]. For the better understanding of the current conditions of climate change, the creation of climate maps, heritage climate maps, damage maps and risk maps could be helpful [26]. Mitigation deals with

Table 1 Table of the impact of natural and anthropogenic hazards on heritage

Natural and Anthropogenic factors	Impact on heritage
Increased coastal erosion and tidal flooding due to sea -level rise	Potential loss or damage to archaeological sites and structures
Flood events?an increased trend	Damage to historic buildings and structures which are not designed to withstand prolonged immersion and drying, encouraging the growth of damaging micro-organisms, such as moulds
Flooding,?particularly the eroding effect of rapid flowing water	Archaeological sites and monuments may be at risk
Water penetration and soil moisture	Potential greater salt mobilisation and consequent damaging crystallisation on decorated surfaces through drying
Changes to the hydrological, chemical and biological processes of the soils	Degradation of the preserved buried archaeological remains
Cracking and heaving of soils	Loss of stratigraphical integrity
Atmospheric pollutants because of urbanization, technology and globalization	Heritage damage and degradation?specifically combined with climate change

measures and activities, such as reducing GHG emissions or enhancing the sinks of such gases, while adaptation refers to any adjustments in a system in response to the actual or projected climatic stimuli, including changes in socio-environmental processes, perceptions, practices, and actions to reduce potential damages or to take advantage of new opportunities that may arise [18]. Mitigation has traditionally been given more attention in climate change research and policy than adaptation [18]. Adaptation can be defined as ?the decision-making process and the set of actions undertaken to maintain the capacity to deal with current or future predicted change? [44]. The focus on climate change mitigation in the 1990s and early 2000s has shifted (in the face of failure to address runaway carbon emissions), with policies and practices at a global level increasingly emphasising the need for adaptation.

Cassar [45] summarised the adaptation measures suggested by the UN Educational, Scientific and Cultural Organization (UNESCO) and by the International Council On Monuments and Sites (ICOMOS), who recommend increasing research, knowledge, education, engagement, the upgrading of management plans?including risk assessments?and monitoring procedures to increase the resilience of the sites. The formation of a climate change mitigation-adaptation strategy for heritage, presupposes a base of climate-induced decay variables, describing mechanical, chemical, and biological decay on several building materials and structures, which should be in accordance with their protection status. In particular, some variables offer valuable material to review the effects of climate change, as hygroscopic materials, such as wood, which will gain and release moisture during changes in relative humidity (RH) and temperature (T) [43]. The changes of these factors lead to swelling and shrinkage, which may be cause of permanent damage. Parameters

like *type* of building, specific site-related factors, available indoor and outdoor climate data, observed damages and suitability for other work packages are reviewed and are transferred into a Climate for Culture database which has several layers of information [46].

Furthermore, there is a variety of the effects of climate change, either depending on locality, or on the cultural and natural sections of life, estimating adaptability as a vital characteristic of heritage management. Climate change is an ongoing universal fact to be managed, with effects on society, economy and environment, including cultural heritage, promoting the need of adaption of historic assets so as to become more resilient [13]. ?he concept of adaptive capacity refers to the quality of adaptation of a cultural system to the altering conditions of climate change. However, this feature lacks the necessary investigation in the field of cultural heritage management and, meanwhile, climatic changes have potentially serious implications for the historic environment, which is itself non-renewable. The efficient heritage management of mitigation-adaptation strategy takes into account the resilience and the adaptive capacity of the studied heritage. It is important to act proactively and design specific strategies for the adaptation of cultural and natural sites to climate change [18]. Of course, the specific damage by climate change on heritage depends on a variety of additional variables and parameters, e.g. the construction materials, state of conservation, surrounding landscape, topography, etc. These variables have been detected as follows: Geographic information (Latitude, Longitude, Elevation, Country), Heritage categorization (Cultural (C), Natural (N), Mixed (C/N)), Geographic characteristics (Approximate distance from coast, Proximity to coast, Proximity to forest or other dense vegetation, Changes in the extreme climate indices relevant to the reference period and the future projected period under scenarios, Geophysical data

(more specifically the peak ground acceleration), Coastal flooding hazard sub-index, as well as the Seismic hazard index [47]. Although the preservation of cultural heritage sites is a priority, reduction of the environmental impact of the building system must also be considered during the early design stages. Certain studies have demonstrated that approximately 20.0% of the global environmental impact is related to the manufacture, construction, demolition and end use of building materials in conventional buildings, where the operational stage has higher impacts [48]. The methodologies and the means that should be taken into consideration are the following: (i) parameterisation-simulation-optimisation, (ii) light weight, (iii) industrialised processes, (iv) quick assembly, (v) quick disassembly, (vi) reversibility and (vii) reuse/recycling; these tools and particularly *reversibility* (International Council on Monuments and Sites, 2003), are essential to proper heritage intervention [48].

The selected management of successful strategies to address climate change impacts will depend on an informed assessment of the risks [49]. In order to understand how the impacts matrix applies to an individual site, and crucially to identify for decision makers what are likely to be the key impacts, a site assessment is necessary. UNESCO recommends the use of a coupled human-environment vulnerability analysis for site level assessments [30]. This requires evaluating the exposure (E), sensitivity (S), and adaptive capacity (AC) of the site to the likely impacts of climate change. The difficulty is to foresee how researchers can grapple successfully with researching an unquantified resource, preserved in poorly understood environmental conditions, that faces an uncertain level of climatic change [50].

Strategic actions of mitigation and adaptation

Many historic buildings, sites and landscapes have already experienced and survived significant climatic changes in the past and may demonstrate considerable resilience in the face of future climate change. In order to adapt to a changing climate and to limit further changes, it is likely that these heritage assets will be irreparably damaged and the cultural, social and economic benefits they provide will also be lost, due to poorly designed adaptation and mitigation responses. The non-renewable character of historic features and the potential for their damage and loss should, therefore, always be taken into account when adaptation and mitigation responses are being planned and executed.

Moreover, energy efficiency of traditional buildings and monuments is fundamentally important and it can be upgraded by positively promoting management. More specifically, thick walls and small windows of many

vernacular buildings provide them with a high thermal mass that keeps them warmer in the winter and cooler in the summer. Every reasonable alteration to the existing building stock can mitigate climate change, especially combined with the fact that historic building materials are often more durable than contemporary replacements and more cost-effective in energy terms [13]. In terms of climate change, the changes that have to be applied to a building, the cautious selection and determination should be certainly assured, along with the longevity of the building, as well as the health and comfort of the occupants, ensuring reversibility wherever possible.

In the field of cultural heritage, mitigation can involve improving the energy efficiency of historical buildings, for instance, while building a sea wall to protect coastal heritage sites from storm surges and SLR is an example of adaptation to climate change risks. The pursuit of heritage adaptation has been noted by Sabbioni et al. [5], through the development of guidelines for adapting the European cultural heritage to climate change impacts, which were later adopted by the Italian Strategic Agenda. These included strategies for both physical adaptation and for adjusting management practices. Examples of the latter include improving the monitoring, maintenance, and preparedness to floods and landslides at cultural heritage sites [18]. Some best practice examples in managerial and decisional adaptation to climate change are: the increase of fundraising, the open access to knowledge and its dissemination, the engagement of stakeholders (scientist, heritage, experts, owners, communities, tourists) the promotion of monitoring and maintenance, the upgrade of management plans, the attention to the update of regulations and guidelines and the projection of future climate scenarios to reduce future risks. Sesana et al. [18] present the suggested 'managerial and decisional' adaptations inspired by the aforementioned practices as follows:

- Financial resources
- Knowledge of climate change impacts on cultural heritage
- Dissemination of information
- Engagement with stakeholders (e.g., communities and decision-makers)
- Monitoring and maintenance
- Inclusion of climate change in management plans
- Preservation of values
- Regulations and guidelines for adaptation
- Mitigation strategies

The suggested 'practical' adaptations included the following:

- Building coastal defences, roofs, and shelters
- Improving drainage system
- Moving the heritage site
- Avoiding maladaptation such as the inappropriate use of certain building materials and developing new materials compatible with the historic environment
- Improve or strengthen monitoring and
- Digital recording of cultural heritage

Digital heritage can be defined as one of the unique resources of human knowledge which contains cultural, scientific, technical and other types of information created using digital means [28]. A project of virtual reality also enables the interested visitors and users to experience and enjoy this rare and unique community without causing further degradation of the socio-cultural and architectural fabric, caused by uncontrolled mass-tourism [28]. Briefly, the benchmarking of best practice examples of practical adaptation to climate change should include (1) Knowledge, education, communication, and awareness; (2) Management, regulations, governance, and drivers; (3) Economic factors; (4) Cultural values; (5) Health and safety concerns; (6) Time; this means that economic resources are important as the accessibility to financial resources allows each community to fund adaptation efforts. but other solutions like public engagement, collaboration, and communication are also important and decision-making should not be influenced only by the need for finance [18]. Also, apart from economic resources there are additional parameters of great importance, such as technology and the up-to-date implementation techniques for the adaptive strategy and the alarming systems, as well as infrastructure for the response to the changing environmental conditions.

Moving from reactive to proactive adaptation is essential to increase the resilience of cultural heritage sites to future changes in climatic conditions, including extreme weather events [14]. There are two modes of adaptation; the reactive and the proactive. Reactive adaptation is in response to the impact of a climatic event that has already been experienced, for instance a severe storm, landslide, or flood, and often results in short-term planning that aims at returning to conditions as they were prior to the event in question, without necessarily aiming to increase the resilience of the site to future events. Proactive (or anticipatory) adaptation takes place before the occurrence of a climatic event and can be in response to projected changes in climate. This means that proactive adaptation allows more time for consultation, discussion of alternatives and long-term planning. Adaptation will possibly be limited if the safeguarding of authenticity, integrity and value of cultural heritage is taken into account [18]. This is the concept of proactive

planning, with efficiency of heritage interpretation and consideration of its vulnerability to the threats of climate change. In this way, the main aim is to protect the uniqueness of each heritage and simultaneously actions regarding adaptation could be a helpful and additional tool and not the only priority for heritage salvage.

The sufficiency and integrity of a strategy of mitigation-adaptation should certainly consider the 'lived experience of culture?', the 'identity?', 'belonging?', and 'sense of place?' together with the values, traditions, and cultural practices, so as to determine the acceptability of the climate change adaptation solution. All this could be summarized into four main categories of adaptation measures: technological, behavioural, managerial, and policy [18]. Indirect consequences like fragmentations of populations, loss of intangible features [48] declining in visitor numbers, and disruption of socio-economic activities [49]. Climate change is likely to affect cultural diversity and socio-cultural interactions by forcing communities to change their work habits and ways of life [52] to compete for resources or to migrate elsewhere [52] under the different type of climate-driven disasters like desertification, flooding or sea-level rise [54]. The impacts of climate change on the loss of social community [55] traditional knowledge, cultural identity [29] or natural and socio-economic systems.

Overall, awareness of climate change impacts and hence greater dissemination along with the raising awareness of this issue to local communities via increasing the community engagement and the support from the wider community are important components for successful adaptation to climate change. While there may be a lack of specific monitoring at cultural heritage properties, the utilization of research from other fields can be of great value. Reports on shifts in agricultural practices, forestry, or population densities, for example, are often carried out by environment agencies and are relevant to the archaeological values in the landscape [54]. The collection of these data is important for the heritage virtues, as Phillips [57] investigated the adaptive capacity to climate change at cultural heritage sites and identified access to information, authority, resources, cognitive factors, leadership, and learning capacity as the key determinants.

At the following table (Table 2), one could examine the presented publication regarding the year of publication and the topic, respecting the numbered reference in the present study. The publications are presented in chronological order.

Risk assessment

Although there is an increasing interest in disaster management for cultural heritage, the threat of climate

Table 2 Table of publications which are the references of the present review study on climate change&heritage

Publication [with numbered citation]	Year	Topic
Brandi, C. <i>La Teoria del Restauro</i> ; Einaudi: Milan, Italy, 1963 [25]	1963	Cultural heritage
Tang, W., Davidson, C.I. (2004). <i>Erosion of limestone building surfaces caused by wind?driven rain: 2. Numerical modelling</i> . <i>Atmos. Environ.</i> 38, 5601?5609, https://doi.org/10.1016/j.atmosenv.2004.06.014 . [22]	2004	Material
Cassar, M., Pender, R. (2005). <i>The impact of climate change on cultural heritage: evidence and response</i> . In: Verger, I. (Ed.) (Proceedings) ICOM Committee for Conservation: 14th Triennial Meeting. (pp. pp. 610?616). James & James [13]	2005	Climate change&heritage
Woodside, R. 2006. <i>World Heritage and Climate Change: Developing a Framework for Assessing Vulnerability</i> . MSc Built Environment: Sustainable Heritage. University College London [8]	2006	Vulnerability approach
Colette, A. (2007). <i>Climate Change and World Heritage. Report on Predicting and Managing the Impacts of Climate Change on World Heritage and Strategy to Assist States Parties to Implement Appropriate Management Responses</i> ; UNESCO World Heritage Centre: Paris, France, 2007 [30]	2007	Heritage management
Periodic activity report, NOAA?S ARK GLOBAL CLIMATE CHANGE IMPACT ON BUILT HERITAGE AND CULTURAL LANDSCAPES (2007) cordis.europa.eu , https://cordis.europa.eu/docs/results/501/501837/124722791-6_en.pdf [27]	2007	Climate change&heritage
Sabbioni, C., Bonazza, A., Messina, P. (2007). <i>Cambiamenti climatici e patrimonio culturale. Contributi sugli effetti dei cambiamenti climatici sul patrimonio costruito e sul paesaggio culturale</i> , Istituto di Scienze dell'Atmosfera e del Clima, pp. 805?808 [34]	2007	Climate change&heritage
Laoui, ?, (2007). <i>Centre for the Assessment of Natural Hazards & Proactive Planning</i> , National Technical University of Athens, Sub Project DISMA DISaster MAnagement GIS with emphasis on cultural sites, TECHNICAL REPORT: Volume II [35]	2007	Heritage management
Sabbioni, C., Cassar, M., Brimblecombe, P., Lefevre, R.A. (2008). <i>Vulnerability of cultural heritage to climate change, European and Mediterranean Major Hazards Agreement (EUROPA)</i> . Council of Europe, Strasburgo, 2008; Sabbioni, C., Cassar, M., Brimblecombe, P., Lefèvre, R.-A. (2009). <i>Vulnerability of cultural heritage to climate change. Pollution Atmospherique</i> . pp. 157?169 [5]	2008	Vulnerability approach
Grossi, C.M., Bonazza, A., Brimblecombe, P., Harris, I.; Sabbioni, C. (2008). <i>Predicting twenty?first century recession of architectural limestone in European cities</i> . <i>Environ. Geol.</i> 2008, 56, 455?461, https://doi.org/10.1007/s00254-008-1442-6 [17]	2008	Material
National Trust, 2005a; Caffrey and Beavers, 2008; Edwards and O?Sullivan, 2007; Cuffe Fitzgerald, 2010; Murphy et al., 2009; Rowlands (2008) [19]	2008	Climate change&heritage
Pearson, M. (2008). <i>Climate change and its impacts on Australia's cultural heritage. Historic Environment</i> , 21 [20]	2008	Climate change&heritage
Sabbioni, C., Brimblecombe, P., Cassar, M. (2010). <i>The atlas of climate change impact on European cultural heritage. Scientific analysis and management strategies</i> , Anthem Press, London [10]	2010	Climate change&heritage
Shanahan, B., & McNeary, R. (2010). <i>Landscapes of memory in the heartland of Connacht, Ireland</i> . In L. Lévêque, M. Ruiz del Árbol, & L. Pop (Eds.), <i>Patrimoine, Images, Mémoire des Paysages Européens</i> (pp. 163?176). L?Harmattan [21]	2010	Cultural and natural heritage
Interdisciplinary Committee on Climate Change Impact Assessment (CCISC), Bank of Greece (2011). <i>The environmental, economic and social impacts of climate change in Greece</i> , ISBN 978?960-7032?49-2 [16]	2011	Climate change
Brimblecombe, P., Grossi, C.M., Harris, I. (2011). <i>Climate Change Critical to Cultural Heritage</i> . In Fort, Alvarez de Buergo, Gomez-Heras, Vasquez-Calvo (Ed.). <i>Heritage, Weathering and Conservation</i> . (pp.195?205). London: Taylor & Francis Group [32]	2011	Heritage management
Huijbregts, Z., Kramer, R.P., Martens, M.H.J., Van Schijndel, A.W.M.; Schellen, H.L. (2012). <i>A proposed method to assess the damage risk of future climate change to museum objects in historic buildings. Build. Environ.</i> 2012, 55, 43?56 [26]	2012	Risk assessment
Intergovernmental Panel on Climate Change (IPCC). <i>Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part b: Regional aspects; Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change</i> ; Agard, J., Schipper, E.L.F., Birkmann, J., Campos, M., Dubeux, C., Nojiri, Y., Olsson, L., Osman-Elasha, B., Pelling, M., Prather, M.J., et al., Eds.; Cambridge University Press: New York, NY, USA, 2014; rconomipp. 1757?1776 [31]	2014	Climate change&heritage
Trevor Letcher (ed.). (2015). <i>Climate Change: Observed Impacts on Planet Earth</i> , Book, 2nd Edition, 634 p, Elsevier, ISBN 978?0-444?63,524-2, (??? 21?35, 37?77, 241?269, 271?293, 309?324, 419?447, 449?463, 465?489, 547?583, 585?594), (Ebook- central) https://ebookcentral-proquest-com.proxy.eap.gr/lib/eapgr/detail.action?docID=4003861 [12]	2015	Climate change
Harvey, D., & Perry, J. (Eds.). (2015). <i>The Future of Heritage as Climates Change: Loss, Adaptation and Creativity</i> (1st ed.). Routledge. https://doi.org/10.4324/9781315724164 [14]	2015	Climate change&heritage
United Nations. <i>Transforming OurWorld: The Agenda 2030 for the Sustainable Development</i> ; A/RES/70/1; United Nations: New York, NY, USA, 2015 [24]	2015	Heritage management
Tuija MIKKONEN. (2016). <i>Cultural Environment as a Resource in Climate Change Mitigation and Adaption</i> [38]	2016	Mitigation & adaptation
Hambrecht, G., Rockman, M. (2017). <i>International Approaches to Climate Change and Cultural Heritage, American Antiquity</i> , 82(4), 627?641. https://doi.org/10.1017/aaq.2017.30 [1]	2017	Climate change&heritage

Table 2 (continued)

Publication [with numbered citation]	Year	Topic
Hambrecht, G.; Rockman, M. International Approaches to Climate Change and Cultural Heritage. <i>Am. Antiq.</i> 2017, 82, 627?641 [1]	2017	Climate change&heritage
United Nations Educational, Scientific and Cultural Organization Convention concerning the protection of the world cultural and natural heritage, World Heritage Committee, 41 Session, Krakow, Poland 2?12 July 2017 [23]	2017	Heritage management
Fatori?, S., Seekamp, E. Are cultural heritage and resources threatened by climate change? A systematic literature review. <i>Climatic Change</i> 142, 227?254 (2017). https://doi.org/10.1007/s10584-017-1929-9 [36]	2017	Climate change&heritage
Monthly summaries of precipitation, relative humidity and soil moisture, <i>climate.copernicus.eu</i> , https://climate.copernicus.eu/monthly-summaries-precipitation-relative-humidity-and-soil-moisture [42]	2017	Climate change indices
Gavalas M. Severe Weather: The New Challenge for the Planning of Greek Islands. <i>Proceedings.</i> 2018; 2(11):669. https://doi.org/10.3390/proceedings2110669 [3]	2018	Climate change
Sesana, E.; Gagnon, A.S.; Bertolin, C.; Hughes, J. (2018). Adapting Cultural Heritage to Climate Change Risks: Perspectives of Cultural Heritage Experts in Europe. <i>Geosciences</i> , 8, 305. https://doi.org/10.3390/geosciences8080305 [18]	2018	Climate change&heritage
Padeletti, G., HERACLES Consortium Staff. (2019). Heritage Resilience Against Climate Events on Site?HERACLES Project: Mission and Vision. In: Moropoulou, A., Korres, M., Georgopoulos, A., Spyarakos, C., Mouzakis, C. (eds) <i>Transdisciplinary Multispectral Modeling and Cooperation for the Preservation of Cultural Heritage. TMM_CH 2018. Communications in Computer and Information Science</i> , vol 961. Springer, Cham, https://doi.org/10.1007/978-3-030-12957-6_26 [40]	2019	Heritage management
Sesana, E., Bertolin, C., Gagnon, A.S., Hughes, J.J. (2019). <i>Mitigating Climate Change in the Cultural Built Heritage Sector.</i> <i>Climate</i> 2019, 7, 90 [33]	2019	Heritage management
Dastgerdi, A.S.; Sargolini, M.; Pierantoni, I. (2019). Climate Change Challenges to Existing Cultural Heritage Policy. <i>Sustainability</i> 2019, 11, 5227. https://doi.org/10.3390/su11195227 [11]	2019	Climate change&heritage
Sardella A., Palazzi E., Hardenberg J., Carlo del Grande, De Nuntii P., Sabbioni C. and Bonazza A. (2020). Risk Mapping for the Sustainable Protection of Cultural Heritage in <i>Extreme Changing Environments, Atmosphere</i> 2020, 11, 700; https://doi.org/10.3390/atmos11070700 [6]	2020	Heritage management
Figueiredo, R.; Romão, X.; Paupério, E. (2020). Flood risk assessment of cultural heritage at large spatial scales: Framework and application to mainland Portugal. <i>J. Cult. Herit.</i> 2020, 43, 163?174 [9]	2020	Heritage management
Dawson, T., Hambly, J., Kelley, A., Lees, W., Miller, S. (2020). Coastal heritage, global climate change, public engagement, and citizen science. <i>Proc. Natl. Acad. Sci. USA</i> 2020, 117, 8280?8286 [35]	2020	Climate change&heritage
Sesana, E.; Gagnon, A.S.; Ciantelli, C.; Cassar, J.; Hughes, J.J. Climate Change Impacts on Cultural Heritage: A Literature Review. <i>WIREs Clim. Chang.</i> 2021, 12, e710 [4]	2021	Climate change&heritage
Hajirasouli, A., Banihashemi, S., Kumarasuriyar, A., Talebi, S., Tabadkani, A. (2021). Virtual reality-based digitisation for endangered heritage sites: Theoretical framework and application, <i>Journal of Cultural Heritage</i> , Volume 49, 2021, Pages 140?151, ISSN 1296?2074, https://doi.org/10.1016/j.culher.2021.02.005 [29]	2021	Heritage management
Riccardo Cacciotti, Anna Kaiser, Alessandro Sardella, Paola De Nuntii, Milo? Drdác?y, Christian Hanus, Alessandra Bonazza, Climate change-induced disasters and cultural heritage: Optimizing management strategies in Central Europe, <i>Climate Risk Management</i> , Volume 32, 2021, 100,301, ISSN 2212?0963, https://doi.org/10.1016/j.crm.2021.100301 [39]	2021	Climate change&heritage
Mean precipitation- European Environment Agency (2021), <i>eea.europa.eu</i> , https://www.eea.europa.eu/data-and-maps/indicators/european-precipitation-2/assessment [41]	2021	Climate change indices
European Heritage Days 2022 shine a spotlight on ?Sustainable Heritage??Culture and Cultural Heritage?www.coe.int. (2022, September 7). Culture and Cultural Heritage. https://www.coe.int/en/web/culture-and-heritage/-/european-heritage-days-2022-shine-a-spotlight-on-sustainable-heritage- [28]	2022	Heritage management
Bonazza, A.; Bonora, N.; Duke, B.; Spizzichino, D.; Recchia, A.P.; Taramelli, A. (2022). Copernicus in Support of Monitoring, Protection, and Management of Cultural and Natural Heritage. <i>Sustainability</i> 2022, 14, 2501. https://doi.org/10.3390/su14052501 [7]	2022	Heritage management
Tringa, E.; Tolika, K. Analysis of the Outdoor Microclimate and the Effects on Greek Cultural Heritage Using the Heritage Microclimate Risk (HMR) and Predicted Risk of Damage (PRD) Indices: Present and Future Simulations. <i>Atmosphere</i> 2023, 14, 663. https://doi.org/10.3390/atmos14040663 [15]	2023	Heritage management

change increases the frequency and severity of the hazards of extremities, demanding adequate planning and mitigation actions. The method of risk assessment is related to firstly identifying the risks and then the recognition of agents of deterioration, which include the following, identified by Michalski [58]: physical forces;

criminals; fire; water; pests; contaminants; light, UV; incorrect temperature; and incorrect relative humidity. Therefore, these axes focus on the interpretation and the understanding of the risks and their magnitude, whose analysis reinforces the awareness of stakeholders so as they be prepared to obtain political and economic

Table 3 Additional table of publications of the references of this review

Publication [with numbered citation]	Year	Topic
Donnelly, A., Jones, M.B. & Sweeney, J. A review of indicators of climate change for use in Ireland. <i>Int J Biometeorol</i> 49, 1712 (2004). https://doi.org/10.1007/s00484-004-0215-5 [56]	2004	Climate change
Kjellstrom, T., Kovats, R.S., Lloyd, S.J., Holt, T., Tol, R.S.J. (2009). The direct impact of climate change on regional labor productivity. <i>Arch. Environ. Occup. Health</i> 2009, 64, 217?227 [52]	2009	Climate change
Black, R.; Bennett, S.R.G.; Thomas, S.M.; Beddington, J.R. (2011). Climate change: Migration as adaptation. <i>Nature</i> 2011, 478, 447 [53]	2011	Climate change
Kim, H.-E. Changing climate, changing culture: adding the climate change dimension to the protection of intangible cultural heritage. <i>Int. J. Cult. Prop.</i> 2011, 18, 259?290 [54]	2011	Climate change&heritage
Adger, W.N., Barnett, J., Brown, K., Marshall, N., O?brien, K. (2013). <i>Cultural dimensions of climate change impacts and adaptation</i> . <i>Nat. Clim. Chang.</i> 2013, 3, 112 [55]	2013	Heritage management
Phillips, H., (2015). <i>The capacity to adapt to climate change at heritage sites?The development of a conceptual framework</i> , Oxford Brookes University, Gypsy Lane, Oxford OX3 0BP, UK [57]	2015	Heritage management
Markham, A., Osipova, E., Lafrenz Samuels, K., Caldas, A. (2016). <i>World Heritage and Tourism in a Changing Climate</i> ; UNESCO Publishing: Paris, France [51]	2016	Climate change&heritage
Henderson, M., Seekamp, E. (2018). Battling the tides of climate change: The power of intangible cultural resource values to bind place meanings in vulnerable historic districts. <i>Heritage</i> 2018, 1, 220?238 [50]	2018	Heritage management

support [43], in order to continue to their incorporation to mitigation and adaptation (Table 3).

Daly [59] claimed that the approach followed by heritage decision-making should dedicate on the embodiment of cultural heritage significance or values assessment into climate change vulnerability or risk assessment. The aforementioned tools are connected with the necessary heritage management policy, including the allowed transformation of heritage before the loss of its heritage benefits or the assessment of the loss as a chance of the evolving heritage management [60].

Vulnerability approach

Because of the emergence of the multiple aspects of the effects of climate change, much attention has been given to the mitigation of its contributors and to the importance of vulnerability approach. The vulnerability assessment framework relates to the exposure to the hazard, which refers to the climatic conditions that can negatively impact on the cultural assets [61]. Thus, it is considered to be able to encompass all potential climate change related risks, such as gradual changes in temperature and relative humidity, as well as extreme events.

Vulnerability is a function of the sensitivity of a system to changes in climate (the degree to which a system will respond to changes in climate, including beneficial and harmful effects), adaptive capacity (the degree to which adjustments in practices, processes or structures can be moderated to offset the potential for damage or take advantages of opportunities created by a given change in climate) and of the degree of exposure to climatic hazards; a vulnerability approach explores the key

concepts and variables of vulnerability, which include hazard, exposure, sensitivity and adaptive capacity [8]. Furthermore, this approach is related to a World Heritage context, with application assessments. Following the ?bottom-up? vulnerability-driven approach usually involves assessing both past and current climate vulnerability of a heritage case with specific identity, applications and methods and how these might be adapted to climate change. Vulnerability in this context is defined as the degree to which a system is susceptible to, or unable to cope with, the adverse effects of climate change, including climate variability and extremes [8]. The identification of the climate data of the historic community, including thermal risk assessment under climate change, (shading characteristics on the focused zone) as well as the responses to adaptation risk (heat stress hazard, user?s exposure) are factors of assuming the local vulnerability [62].

Natural processes have often been ignored in previous assessments of vulnerability and the inclusion of geological hazards such as landslides and groundwater flooding in vulnerability assessments is limited [63]. Also, there are barriers regarding institutional (e.g., lack of political commitment), technical (e.g., lack of technical expertise), and financial factors (e.g., lack of funding) [18]. Management plans and decision-making strategies of heritage should include climate change. This means that stakeholders need to mitigate against the impacts of current changes in climate, including changes in the frequency and intensity of extreme events, but also require awareness of the potential impacts of climate change. Moreover, the mentioning of stakeholders refers to multidisciplinary groups of diverse backgrounds and specializations, including anthropologists, archaeologists,

architects, conservation scientists, geologists, biologists, heritage site managers and coordinators, sustainability officers, and urban planners [18]. Also, adaptive capacity is an important component to consider in the overall assessment of vulnerability, as it determines the extent to which a community can alter its sensitivity to climate change risks and it depends on a number of determinants, including access to information and technology, availability of skilled people and economic resources [64]. Moreover, vulnerability and adaptive capacity are often considered to be negatively correlated: the higher the adaptive capacity of a system, the lower is its vulnerability to climate change. Adaptive capacity at the sites is dynamic, as it is influenced by changes in the management of the site and legislation [33].

Urban areas and climate change data

In a more general context, urban areas are affected by the climatic conditions and the weather and therefore so does the cultural heritage of the urban web. Prohibitions and relative measurements of lock-down of the COVID-19 pandemic, created an interesting basis to assess the levels of pollution, according the data collected by the Observatory of Athens. In a synopsis, the period between March 23 to the end of April 2020, when the traffic restraint measures were implemented in the context of preventing the spread of the COVID-19 pandemic, there was a reduction in greenhouse gas concentrations in the city of Athens, up to 43% in the case of carbon dioxide [16]. However, at a regional level, both greenhouse gases seem to continue their increasing rate.

It is important to mention that in dense urban areas climate change is not profoundly related to the cultural context of the effects of climate change and focusing mostly on physical deterioration and designation issues [14]. Site managers and management systems have a central role in conservation and take decisions which seek to manage change and retain heritage significance, balancing different challenges, such as the need for economic viability [57]. However, research regarding the adaptation and the management of sites for climate change seems inefficient. Likewise, the capacity of current management systems that forecast preparation for the consequences of climate change needs process and amelioration. Reactive planning is important for the recovery of culture, after the effects of any extreme phenomenon. Meanwhile, tolerate heritage management needs also the evolution of proactive planning [65]. In 2006, the UK Climate Impacts Programme (UKCIP) developed a tool for considering the current weather and its impacts called the LCLIP -Local Climate Impacts Profile [66]. This tool uses the vulnerability to current weather as a good starting point

for the better understanding of the impacts of a future climate. This action reinforces the preparedness of the heritage protection, especially when combined with the experiences from past climatic events, as they may provide useful insights into the constraints and barriers to adaptation to future climate change [57].

Innovative initiatives such as the Adaptive Capacity Wheel, seem very significant. This specific tool is settled on the dimensions of variety, learning capacity, room for autonomous change, leadership, availability of resources and fair governance [67]. It examines the influence of institutions to encourage the adaptive capacity of society to respond to climate change. This happens through a certain method aiming to develop quantitative measures of adaptive capacity in order to develop indicators. The key determinants include the learning capacity, the encouragement of autonomous change, the access to resources and the promotion of leadership. The research composed of case studies of cultural heritage sites with vulnerability to climate change, with documented impacts from severe weather events in the last five years for particular places. In particular, the selected sites were: Ironbridge Gorge in Shropshire, Fountains Abbey and Studley Royal in Yorkshire, and Blenheim Palace in Oxfordshire, where interviewees were selected using snowball sampling, including site owners and land managers, local authority planning and conservation officers, conservators and archaeologists. The quantitative data from the questionnaire responses was analysed statistically and the qualitative data (interview transcripts and documentary sources) was analysed using coding, using an inductive approach, looking for common themes in the respondents' answers, providing useful material at a national and international level review [57].

Extreme weather phenomena; the region of Mediterranean and the case of Greece

Research and future projections calculate that Mediterranean region presents vulnerability to climate change impacts. From the findings of literature review (e.g. Tringa et al. [15]), seems as evident that the future ideal temperature conditions will increase, posing new adaptation challenges to the structural monuments under a much warmer climate. This means that crisis management and long-term strategies must be planned in order to properly manage heritage assets in a changing climate, with important concern to the monitoring for ameliorations. The latter is of great importance, as the increase in the future ideal temperature and RH (relative humidity) conditions may generate expansions of the materials and their architectural structures, which can cause serious stress and cracks in the monuments [15].

The Mediterranean basin is a region of frequent cyclonic activity, associated in many cases with precipitation extremes, driven by local factors such as orography and latent heat release at the sea surface [67]. Droughts are of great importance mainly in coherence with socio-economic implications and this is the reason that they are widely studied by using the length of dry spells, such as the index of maximum number of Consecutive Dry Days (CDD). Looking at summer CDD pattern, it is obvious the high values, reaching 90 days, that appear in south west coasts of Iberian Peninsula, coasts of Libya and Egypt, Middle East, Aegean Islands and western coasts of Turkey significant positive trends were revealed for the index of maximum number of consecutive dry days, especially for stations in southern regions, particularly on the islands. Nastos and Zerefos [68] found statistically significant (confidence level of 95%) negative trends, mainly in the western region of Greece, while insignificant positive trends for CDD appear almost all over the country with emphasis in the southeastern region. CDD obtain maxima in the Cyclades Islands and the southeastern Aegean Sea, while minima are found in the northwestern Greece [69].

In particular, the detection and estimation of alarm of the Consecutive Dry Days according to the findings of Nastos and Zerefos [68] indicate that Consecutive Dry Days obtain maxima in the Cyclades Islands and the southeastern Aegean Sea, while minima are found in the northwestern Greece. On the contrary, the longest Consecutive Wet Days are observed in western Greece and western part of Crete Island and the shortest in the eastern continental Greece and in the majority of the Aegean Sea. Besides, increased dryness linked with higher temperatures and decreased precipitation have contributed to changes in drought and this threatens particularly the islands of the Aegean Sea and for Cyprus, showing a general future drought and desertification for the southern Mediterranean region. Furthermore, desertification-related scenarios reveal a tendency towards drier climatic conditions in the eastern Mediterranean [8]. Anomalies in precipitation, including dry winter-time conditions over southern Europe and the Mediterranean and wetter-than normal conditions over northern Europe and Scandinavia since 1980, are also linked to the behaviour of NAOI (North Atlantic Oscillation Index-see appendix 1). The observed downward trend in precipitation over Greece is principally linked to a rising trend in the hemispheric circulation modes of the NAOI. The pattern of the mean annual CWD within the examined period (1958–2007) shows that the longest CWD appear in western and north-western Greece and western Crete. On the other hand, the shortest CWD exist in eastern

continental Greece and in the majority of the Aegean Sea [66].

As far as Mediterranean region is concerned, studies show that it is particularly vulnerable to climate change, due to intense warming and drought, in particular during the summer season [70, 71]. The region of Greece is widely characterized by the 'humid' class, from which there is a progressive shift towards the 'sub-humid' and 'semi-arid' classes appeared in the eastern Crete Island, the Cyclades complex, the Evia and Attica, that is mainly the eastern Greece. The most significant change appears during the period 1991–2000 [69].

The Aridity Index (AI) classifies the type of climate in relation to the water availability and it is a climatic index, which can be used for monitoring and prediction of drought. The collection and procession of meteorological data, such as air temperature, precipitation and evapotranspiration compose the method of its calculation. During the decade 1951–1960, almost the whole area of Greece is classified as 'wet', except the central/eastern Crete Island, which are classified as 'sub-humid'. Over the next years, however, areas of the eastern Crete Island, Cyclades Islands complex, Evia Island and Attica basin, that is mainly the eastern Greece, shift gradually to 'sub humid' climate zone. Especially, during the last decade of the study period 1991–2000, the greater part of Crete Island, Cyclades Islands complex, eastern Attica, central/southern Evia Island and western Halkidiki area have shifted to the 'semi-arid' climate zone [72].

A decrease in precipitation has been observed within the eastern Mediterranean and Greece [68, 69, 72]. The increase of air temperature in Greece, especially during summertime [67], leads to increased evapotranspiration and hence to drier conditions, explained by lower AI values. The implications of drought include the influence of the growth of natural vegetation. In the coming years, the adverse prevailing climatic conditions during the growing seasons of annual crops lead to uncovered lands, creating favourable conditions for increased runoff and erosion, which provoke desertification of land over the last under study decade 1991–2000 [72].

The study of rain intensity trends is a good tool for policy makers, in order to estimate, among other factors, the erosion and the desertification that appear as a consequence of the climatic change in the eastern Mediterranean Sea. In the region of Greece, the frequency of heavy precipitation events has increased over most land areas, observed with warming and increases of atmospheric water vapour. The trend analysis revealed that statistically significant (95% confidence level) positive trends of the mean annual rain intensity—mainly within the summer season, appear

in the wider area of Athens (very likely attributed to an enhanced UHI effect), the northern coastal areas of Crete Island, the Cyclades complex and the north-eastern sub-regions of Greece [73].

In the study of Kapsomenakis et al. [74], which is about threats of climate change for 244 UNESCO cultural and natural heritage sites in the Mediterranean region, it is presented that the majority of heritage sites were categorized as vulnerable with an increasing threat rate from man-driven global warming and extreme events. A previous study of Ravankhah et al. [75], which was about the impacts of climate change on the historic center of Rethymno in Greece, it was highlighted that it is necessary to define both past and future risks due to climate change for cultural heritage risk assessment and adequate management. Also, in the area of study, it is assumed by research findings that the risk of thermoclastism (due to seasonal fluctuations) is projected to increase in the Mediterranean region because of climate change [10, 76], notably for the widely used marble [5].

For the better approach of the example of a Mediterranean country, we also mention that extreme precipitation events seem to alarmingly appear in Greece. Nastos and Zerefos [66] collected daily precipitation totals recorded at 21 meteorological stations of the Hellenic National Meteorological Service for a 45-year period (1957–2001) for the study of precipitation assessment. For the northern, southern, western, eastern and central regions of Greece, a representative station is selected for the analyses, which were the following: Ioannina for western (1), Iraklio for southern (2), Mikra for northern (3), Mytilini for eastern (4) and Athens (National Observatory of Athens) for central (5) region. According to the stations' data, the extreme precipitation events appear during winter months in the western and eastern regions, and mainly during autumn in the rest of the country. Moreover, the fitted gamma distributions to the daily precipitation totals with respect to the 45-year period (1957–2001) reveal that high figures of the scale parameter appear in the western, eastern and southeastern Greece, while low ones appear mainly in the central continental Greece [64].

Also, literature presents the implementation of some projects of risk assessment and heritage evaluation in the region of interest of this paper. Ravankhah et al. [73] approached a proposed hazard assessment framework in the case of the Historic Centre of Rethymno, a city on the northern coast of the island of Crete in Greece. The main project is called the STORM (Safeguarding Cultural Heritage through Technical and Organisational Resources Management) project (STORM 2016–2019) which claims an innovative methodology to assess and manage risks related to natural hazards [75]. This

project was applied to five cases of heritage in the Historic Centre of Rethymno, aiming to identify, analyze, and prioritize the hazards that have the potential to cause damage. According to Ravankhah et al. [75] the procedure is based on climate model projections, GIS spatial modelling and mapping, all of which conclude in a hazard analysis matrix. These analysis levels enhance the interpretation, understanding and dissemination of multiple hazards with the stakeholders. The study also suggests a classification of the detected natural hazards (sudden- and slow-onset) and in the meantime it considers their future variances because of climate change [75]. The final classification list is capable of applying on different heritage types and assets in a variety of environmental conditions. In that case study of Rethymno, the combination of wind, salt, wind-driven rain, moisture and the whole external maritime environmental conditions have a severe impact on the stones, the metallic elements, the mortar joints of the fortress walls and the plaster of the buildings [75]. The exposure of the subject heritage to the altering weather conditions leads to decay and degradation. So, the analysis and prioritization of hazards can be enabled by GIS models, maps and future climate projections in order to design a multi-criteria risk assessment.

Phenomena such as tornadoes, waterspouts and funnel clouds occur mostly at the complex inland terrain of Greece along with the Ionian Sea at the west and the Aegean Sea at the east. More specifically, northwest Peloponnesus and north parts of Crete Island (south Aegean Sea) seemed to be the favourable areas for tornado development, with numerous tornado events (especially waterspouts) observed over western and northern parts of central Crete and not over eastern parts. The monthly variability reveals a tornado tendency of occurrence during autumn and winter while the maximum appears in November and December followed by October and September. Also, tornado development mostly happens between 05:00 and 16:00 UTC [77].

At this point, the amplification of the threat at sites vulnerable to seismic activity and to other local or regional topography and geophysical regional characteristics seems notable. Our conclusion is that the majority of heritage sites in the Mediterranean are vulnerable to an increasing rate of threats from man-made global warming and extreme events. Seismic activity is magnifying these threats only at the sites in which that additional hazard applies [47].

The Mediterranean region presents tourist interest as there are many archaeological sites, where there should be identified a framework for spatial planning to meet the challenges of reducing the effects of climate change and there are studies of protection policies in heritage sites

of this place, such as the research of Asprogerakas et al. in Greece [78]. It is already known that archaeological sites convey the learning and transfer of the knowledge into social contexts and experiences [79]. The research focused on Greece includes starts with the indexing of the legislative and institutional framework and related policy documents and studies regarding the directions and actions of preventive and repressive character and afterwards the evaluation of the directions and actions identified. It is interesting that the actions related to spatial planning in particular for for Sea level rise and Soil Erosion risks are more than the ones that are about archaeological sites in general. Thus, it is clear that cultural heritage protection and adaptation needs further research [78]. The study of Asprogerakas et al. analyse the prevention and adaptation of archaeological sites in their natural environment with cultural and tourist interest regarding four types of climate-related risks, floods, forest fires, sea level rise and soil erosion [78]. Moreover, Chalkidou et al. [80] used special tools of future projections and noted that the effect of SLR is expected to be intensified in Greece and Italy between 2050 and 2100, while France, Cyprus, Slovenia and Malta are expected to present a constant number of additional coastal flooded land. In particular, four UNESCO World Heritage Sites with significant danger from Sea Level Rise are located in Greece and Italy: the island of Delos, the Medieval City of Rhodes, Pythagoreion and Heraion of Samos in Greece and the Amalfi Coast in Italy [80].

While the general provisions of the European framework are adapted to the country's particularities, responsibilities are not clearly addressed and combined with the relatively low applicability and specialization of the scope, there is a significant risk for inertia, as the monitoring seems weak and as research reveals, especially in the Mediterranean region [78]. Especially in the Mediterranean Sea, mitigation measures should follow a more holistic approach considering the threat of Sea Level Rise, since the coastal archaeological sites are usually located near settlements and they are the fundamentals of the identity of the place, the tourism growth, the employment opportunities and the economic system [80]. Unfortunately, scientists have questioned the salvation of all coastal monuments from the erosion and flooding threats, because of lack of time, resources and technical solutions, in the time of consistent climate change consequences [80].

Theory

Heritage awareness and sustainability

The impact of climate change on heritage can also be used as a means to both reflect on the nature of heritage, but also to interpret anthropogenic change. It

is important to notice the relationship between tourism and climate change, in which the former is both affected by the latter and at the same time it contributes to it. Additionally, heritage tourism is not only affected by such change but given its role within tourism, also contributes to climate change, especially due to the contribution of transport to the emissions in getting to and from heritage sites [80]. Climate change is increasingly recognised as a major threat to the sustainability of tourism, as heritage tourism may be affected and meanwhile it may provide an opportunity to both respond to and interpret the implications of climate change. Cultural heritage sites can be particularly sensitive to severe weather events and to climatic changes, both due to direct impacts on built structures, archaeology and designed landscapes, but also due to changes in visitor behaviour and the potentially adverse implications of adaptive measures on heritage significance [57].

The influence of climate change extends to a range from the formation of community identities to the economic support coming from heritage tourism. So, it is important to research the practices of diverse communities and representatives so as to help monitor, adapt to, mitigate against, and communicate about climate threats to cultural heritage, leading to adequate management and action of stakeholders both global and national scale [32].

Nowadays, sharing of information and knowledge is vital and could be described as easily accessible, with the sharing of knowledge accomplished via professional networks or public outreach, as well as via the creation of applications for smartphones and mobile devices which facilitate the monitor of the situation of monuments (photos, location GPS and description). So, the baseline data and adaptive responses in diverse areas, ranging from the effects of climate change on heritage and approaches to management and mitigation seem to be forwarded to public engagement in monitoring and decision making [32]. Today's technology provides valuable information about the history of heritage assets. For example, academies, museums and plaster cast galleries conserve historical plaster casts in the Mediterranean Area, which represent precious references to assess the process of decay during the time elapsed from the reproduction of the monuments, until their current state or until the moment of their relocation to museums [82]. Models of high-resolution designed by 3D tools and technologies can show differential data of the morphometric loss of surface material, such as: (i) different exposition related to cardinal orientations, (ii) elevation from ground level (vertical factor) and (iii) geometric index (complexity of stone) [82].

The increasing concern over climate change effects, led to the evidence that humans might be directly responsible

for the emergence of this phenomenon. The sustainability of natural and socio-economic systems is irregularly exacerbated by changes in weather pattern which would lead to unbalancing social and environmental conditions. Also, there are indirect consequences like fragmentations of populations, loss of intangible features, declining in visitor numbers, and disruption of socio-economic activities. The forcing of communities to change their work habits and ways of life, to compete for resources or to migrate elsewhere, under the different type of climate-driven disasters like desertification, flooding or sea-level rise are aspects of the affected cultural diversity and socio-cultural interactions by climate change [14].

The protection of cultural heritage is related to developing climate-resilience policies, because the sustainability of landscape requires the reflected definition of heritage. The latter is a composition of characteristics of the territory. Resilience is defined as 'the amount of change a system can undergo and still retain the same function and structure while maintaining options to develop' [44]; it is also understood as a system's 'elasticity', which describes a condition in which the system as a whole has the capacity to self-organise, learn and absorb change [44].

Stakeholders should initiate a debate about the concept of cultural heritage as the primary step in the development of climate-resilience policies for heritage sites, while climate change is transforming the social, economic, and political dynamics across different geographies. For climate activists and heritage policy-makers, increasing their understanding of priority actions, engagement of local communities and collaboration with scientists and scholars on the intersections is of great importance to diminish the additional stress on cultural heritage sites [11].

There is a lack of peer-reviewed publications specifically focusing on approaches and methods required to cope with the challenge of climate change, and this is particularly the case in the field of cultural heritage [33]. A collaborative and interdisciplinary approach between academics, public institutions and the managers of the sites is required for the identification of the values to be preserved and the potential impacts of climate change, so as to increase managers' alerted activity and to strengthen the resilience of sites to climatic stressors. In order to address the challenges of climate change for the management of cultural heritage, a vulnerability assessment is required so that heritage managers are aware of climate change impacts for their incorporation into preservation frameworks and management plans [33].

Local and global aspect

Local communities represent an important issue of cultural heritage, as they are part of a diversity of heritage and they are loyal to the preservation of local identities. Therefore, the present and future generations create the sequence to the local cultures, which are the basic components of the global diversity and thus their interpretation should be combined with the climate processes, the natural climate variability and the projection of the response of forcing agents (e.g., greenhouse gases and aerosols) [10]. The need for further development of damage functions and for identification of extreme climate indices specifically devised to quantify the impact on heritage assets, as well as the generation of future projections with high spatial resolution, should be considered of paramount importance [37]. It is evident that heritage and its preservation strongly refer to communities and to the strengthening of regional cultural identities, with an emphasis on family values and local traditions, with high population growth [1]. This emphasis is significant considering that family is the first fundamental community of every new member of society and it has great role of transmitting heritage virtues and knowledge of cultural recognition. The plethora of local communities demonstrates the needed adaptation to a methodology of management and protection of the effects of climate change on heritage. This consists of synergies of education, literature, questionnaires, site visits, regional and policy workshops so as to pursue efficient assessments [13]. Furthermore, it was found that it is misleading to believe that adaptation is solely a local response as it requires significant resources and often support from national government. Governments can also implement regulations to encourage adaptation and the way it is informed and implemented [33].

Simultaneously, 'local' is connected to a greater range as there is a necessity to develop national policies for the mitigation of the effects of climate change, to strengthen accurate warning systems as well as adaptation policies for the natural environment and vernacular construction. This obligation of the state must be transformed into mitigation strategies, while developing national policies to improve sustainable production, endorsing renewable energy sources, and in the same time implementing programmes of adaption to new conditions. The longevity and survival of the ancient heritage sites, especially those in isolated locations, have been gradually threatened over the past decades, due to the globalization and subsequent socio-cultural changes [28].

An instance of connecting local heritage with the interest and awareness is the Mediterranean region, where climate change and its effects are already a basic subject of global research. As far as the effect of the

increase in the sea level and its thermal content is concerned, there is an explanation about the region of the Mediterranean and especially its eastern basin, is particularly sensitive to climate change. Its location is characterized as the cultural crossroad and also the core of atmospheric processes, influenced by both tropical and polar gas mass systems, depending on weather conditions.

Actually, climate models concerning the Mediterranean region configure that with the extension of the endotropical zone, the southern part of the country will be influenced with increasing rate by the tropical gas masses [16]. Particularly when it comes to locality, measurements are significant proof of the process and course of climate change. In Greece, for example, there is an extremely extensive and unique in network of about 700 terrestrial measuring stations (meteorological stations, GPS seismographs, accelerometers, tidal radars, radars, antennas, magnetometers, etc.) covering the entire Greek, from Attica to Kastellorizo, Gavdos and Antikythera, as there is also a specialized center of collection, analysis and distribution of satellite data coming from a large number of satellite webs -polar orbit, geostatic and low orbit [16]. The stations provide precious information, such as the increase of extreme phenomena in 2012, according to the data retrieved by all stations for that year, and the following year there was a significant decrease. This may be due either to the El Nino phenomenon or to the intense weather fronts or to the Fukushima disaster (2011), as huge quantities of radioactivity were released in the atmosphere with unknown impact on the climate, like the similar event occurred in 1986 with the explosion at Chernobyl, when the following year (1987) the deadliest heatwave of modern history occurred in Greece.

The history of local heritage is of great interest. For instance, in Roman times, the trade of white and coloured marbles was really evolved, so that precious and rare stones from Aegean, Asia Minor, Egypt and North Africa were imported in the centre of the Empire to be used in architectural creations. Theatres were among the most precious constructions in Roman times, as a part of the society and this is why this study shares special mention to this heritage type. The unique decoration of the theatres reflected the importance of the customer and families involved in its construction [82]. The trade and the use of marble in central Italy in Roman times was discussed in the paper by Taelman et al. [84], taking in consideration as a case study the Urbino Roman theatre, which represents an outstanding example of the Western Mediterranean architecture [83]. Also, contemporary needs for the proper function of heritage, demand special

and discrete constructions, as the case of study of Roman Theatre in Italica, Spain, with the study of a reversible addition regarding lighting and electroacoustic elements which improve the stage use [48].

As far as a local aspect is concerned, for centuries now, the works of Greek architects have inspired the world in their unique manner of applying insightful meaning to the purpose of their structures, which are incorporated into the surrounding environment in a manner of devotion to Mother Nature [85]. This explains the reference of this country as a unique part of the Mediterranean region with heritage in jeopardy due to the evident and eminent threats of climate change. The amphitheatre at Delphi as a national monument in Greece -currently on the World Heritage List of ancient structures identified by UNESCO, is an instance with mountainous landscape which is capable of enhancing the quality of sound transmitted by air, which influences the work of artists who exhibit performances on the orchestra [85]. More specifically, research presents that the heavy concentration of olive trees as the main vegetative cover in Delphi provides insight into how the particular environment helps in minimization of dust carried over to the theatre orchestra and cavea, restricting the dust carried from far and beyond because of the climate fluctuation and protecting the limestone fabric of the theatre, significantly impacting the original quality of the stone from its rudimentary stages, after the construction of the theatre [85].

Results and discussion

Heritage management

The awareness of the effects of climate change on cultural heritage is vital so as to enable the principal cultural heritage stakeholders? owners and curators of historic buildings and collections, public policy-makers and national heritage organizations? to deal with both catastrophic climate impacts and more pervasive and subtle long-term effects [32]. At this point, the role of heritage management in correlation with stakeholders should be mentioned, as they compose an adequate number of groups for documenting the ways in which management systems experience the changing conditions and the processes of decision making, which may accommodate adaptation or provide means of enhancing the capacity to adapt [57]. Of course, the research and the interpretation of the aforementioned factors are combined with consultation with regional and local heritage experts, managers, advisers and custodians, showing that the key policy is described by cooperation, funding, research and education [13]. Adaptation and appropriate politics are essential for the management

of heritage. Firstly, structural and qualitative transformations in the ways society makes decisions have to be accomplished, regarding the nature of the issues (ontologies and consequences), and responses (processes, policies, and possibilities). In addition, the review of the actions of institutions, while facing of the risk of climate change on cultural heritage should be scrutinized and sensitively evaluated, especially in Europe, where the adaptive potential should be relatively high because of well-developed political, institutional and technological support systems.

The twentieth century faced a revolution in the sector of material science and building techniques. Fuel burning, the cement industry, and many other issues have caused an increase in CO₂ release to the atmosphere that is greater than that in the natural cycle. Many other factors are related to climate change, such as rising sea levels, precipitation, and others [86]. The knowledge of materials and experience have to be adapted with an appropriate mode to reduce greenhouse gas emissions by decreasing fossil fuel use, increasing energy efficiency and exploiting low carbon technologies and renewable energy sources [13]. So, the day-to-day decision making should be harmonically combined with the long-term planning, according to the conditions of the place and the diversity of local necessities. All the necessary data has to be taken into consideration, regarding local morphology, weather, economic activities and natural, cultural and architectural environments, with the involvement, of all stakeholders on a local scale [3]. The greatest challenge of planning is the mix of spatial planning, environmental and cultural protection and economic development. At the same time, the aforementioned pillars of planning should be combined with the integration of climate change factors, and in particular with the extreme weather phenomena, aiming to sustainability and resilience of a particular region of study, e.g. Greek islands. The quite serious phenomenon of locality focuses on region's particular entity, which includes vulnerability to climate change effects, such as the case Greek islands [3]. Efficient heritage management should be organized into different scales: national (e.g., implementation of regulations), regional (e.g., engagement of population), local (e.g., updating management plans), or done autonomously (e.g., improve regular maintenance and repairs). Simultaneously, it takes into account the diversity of typologies of cultural heritage, the different geographical locations of heritage assets and the context in which they are located, and the climatic conditions to which they are exposed. This takes into account and comes additionally to the state of decay

and the different materials, geometry, and age that characterize cultural heritage assets [18].

The influence on tourist travel patterns shows the role of climate, environment, risk and security, determining heritage tourism prone to climate change. Moreover, research shows that by 2030 the impacts of energy-efficiencies on emissions reduction are potentially to be more than halved and that the reduction in the potential gains in energy efficiencies over the period to 2035 are to be cut by more than 35%. There should be an assessment of where emissions occur, respecting the role of the place, as well as an identification of where further growth occurs, possibly in combination with an evaluation of the underlying reasons for this growth [74]. The new forms of carbon governance, combined with behavioral and structural change in tourism consumption with respect to where and how people travel, will lead to absolute reductions in emissions [81, 83].

To sum up, the aims of the relationship of heritage tourism and climate change are the awareness to action on climate change and the willingness to contribute further to the costs of heritage conservation and protecting the heritage resources [81].

Dissemination

Dissemination describes the communication and information sharing to managers, stakeholders and to the public and local communities [32]. So, there is need to strengthen the monitoring and the maintenance as well as to increase the risk-preparedness and the transmission of know-how (intangible cultural heritage), in the context of adaptation of cultural heritage to climate change [19]. More specifically, Bonazza [87] accentuated that by 2020 the following actions should have taken place for the effective application of adaptation techniques:

- Dissemination of existing knowledge and unique know-how
- Adoption of continuous environmental monitoring, promoting sustainability
- Collection of data to support the national and local decision-making process
- Execution of routine maintenance for the decrease of invasive interventions of restoration
- Prioritize, organize and conduct the needed actions in relation to the state of conservation of heritage in response to climate changes and with continuous detection of environmental conditions
- Understanding the environmental, economic and social context of the heritage assets under risk

As long as the former steps are obtained or at least considered, heritage management could accomplish the promotion and communication of different strategies for long-term financing of maintenance actions in order to verify the existence and efficiency of resources for the heritage sustainability [64]. Moreover, Sesana et al. [18] used the tool of semi-structured interviews for the collection of data relevant to the degree of awareness. The interviews were conducted in three European countries: the UK, Italy and Norway. The interviews focused on the following four questions: (1) is adaptation of cultural heritage to climate change possible? (2) Are you aware of any example(s) of management methodologies to mitigate the impacts of climate change on cultural heritage? (3) Are you aware of best practice examples in adapting cultural heritage to climate change? (4) What are the determinant factors for implementing adaptation of cultural heritage to climate change? [18]. The best practice examples in managerial and decisional adaptation to climate change were as follows: to increase fundraising, increase the production of knowledge and its dissemination, engage those involved with the heritage (owners, communities, tourists) in adaptation, promote and strengthen monitoring and maintenance, upgrade management plans to include climate change, strengthen regulations and guidelines, keep working on mitigating climate change to reduce future risks [18]. Great attention has to be given to the consequence of the selected strategy, as adopting wrong solutions can lead to a reduction of the multiple values associated with cultural heritage. For instance, decreasing the aesthetic and architectural value of a cultural heritage resource can decrease the interest of tourists with a subsequent decrease in economic and social values or, equally, leading to disinterest of local communities from protecting the heritage site [18].

The dissemination of information should be characterized as clear, concise, easily accessible and open to the potential exploitation of new technologies to approach different stakeholders. The heritage knowledge needs to be shared not only on best practice for adapting cultural heritage to climate change, but also on the maladaptive actions that should be avoided and limited because they increase further the vulnerability of cultural heritage to climate change [17].

Conclusion

According to the data collected regarding the effects of climate change on cultural and natural heritage and especially the results of the information presented on this study, it is assumed that heritage management is essential for the interpretation and protection of the cultural assets. In order to accomplish it, the hazards of each case should be monitored and evaluated applying

risk assessment and vulnerability approach. In this way, stakeholders could understand the extent of the threats to the cultural identity -either of the heritage, or of the whole- landscape, so as to structure the ideal heritage management for each property.

Also, dissemination of the results of the relevant research is a pillar of heritage management as well, as the multidisciplinary approach is vital. Diverse scientific sectors and stakeholders should collaborate aiming to the pure motive of the heritage protection, its adaptation to the ongoing climate change and the mitigation of the adverse effects, where this would seem applicable. This research discusses the focus on the collected data and the creation of an inventory of the heritage categories which have been studied and adequately managed, in order to discover the areas with little or hardly any information. Thus, there is lack of information respecting the preservation and management of heritage assets incorporated into the landscape with their exposure to the climatic conditions. Moreover, it is accentuated that there are restricted data and lack of gathered information about the landscape and the climatic conditions, the effects of climate change and the dynamics of heritage with characteristics of an open-air type, such as the ancient Greek theatre, which is aforementioned as monument in jeopardy.

Overall, the efficiency of stakeholders' awareness should be organized so as to obtain political and economic support, as well as consistency of management of cultural heritage with regard to adaptation to climate change risk [43]. Stakeholders can share and digitize heritage information. Their motivation for the preservation of culture from the effects of climate change can structure interesting scopes and future openings. These are about greater knowledge sharing, more communication to the general public (local, regional, national, and international), monitoring and prioritization of threatened sites, allocation of more resources by funding agencies, universities, governmental and nongovernmental organizations, as well as private foundations toward projects dealing with the effects of climate change on cultural heritage [32].

Guidelines offering adaptation strategies for cultural heritage management have been produced, aiming to assist heritage stakeholders, owners and curators of historic buildings and collections, public policy-makers and national heritage organizations to deal with future climate change pressures [5]. Furthermore, adaptation can be attained through small steps and at different scales: national (e.g., implementation of regulations), regional (e.g., engagement of population), local (e.g.,

updating management plans), or done autonomously (e.g., improve regular maintenance and repairs) [45].

The mitigation and adaptation strategies should be focused on the balance of damage limitation, keeping as priority the sustainability and the rational energy consumption. Research should be converted into practice with the formation of protocols and directives of heritage stakeholders, coming from local to global backgrounds. Action measurements and behaviour policies are urgent and they should promote immediate unity, harmony and optimization of the existing climate services and accurate warning systems for climate change-related disasters of the region of study at any given timeframe, including supportive observations from relevant national infrastructures [16]. Future research is needed for the understanding of materials vulnerability, the monitoring of change, the modelling and the projecting of climate behaviour, the cultural heritage management and the desired prevention of damage [5]. The particularities of each piece of heritage design the sustainable balance between conservation and energy improvement, as accomplished by specific case studies, respecting their unique characteristics. Therefore, the contemporary use of the monument (representing any kind of heritage) is assessed to be pursued with the adequate respect to the creator's original concept.

Calculating the data of current impacts of climate change, due to the uncertainty arising from the future evolution of climate change impacts on heritage, communities and states had better adopt a 'no regrets' or 'low regrets' approach to regulatory and grant-aid activities, basing the decisions on the best available information [13]. The contribution of heritage interpretation, protection and management can help mitigate the effects of climate change, structuring a global heritage network involved in research and offering incentives to improve the quality of the future, respecting the past [13].

It has already been highlighted that the framework of adaptive capacity is of great significance. It is focused predominantly on a local level, although national level factors will influence these local determinants, and assessing certain determinants e.g. policy context and leadership may involve a consideration of national level factors. The determinants of adaptive capacity, the meaning and the actions of this theory are crucial to heritage management. The key determinants of adaptive capacity to affect the capacity to adapt to climate change, are cognitive factors, leadership, learning capacity, access to information, authority and resources [57].

A multidisciplinary approach would be useful so as to concentrate on evolving the cultural heritage concept,

which is about bridging the existing gaps and redefining cultural heritage from a dynamic and territorial planning point of view, not only for its protection against climate change, but also for the emergency preparedness and disaster risk reduction. So, the priorities are the synthesis of existing information, transdisciplinary research, inventory, monitoring and delivery of relevant information to managers and stakeholders to support decision-making [11].

Overall, cultural sustainability has to be amplified through a strategic action plan, constituting a policy based on documentation, organization, assessment and monitoring of the pathology of the monuments and the sensibility against climate change. This venture should seek local, national and international guidance. For this reason, UNESCO created a cultural initiative, enlightening the importance of climate Science and Knowledge [88], based on the following pillars:

- Climate-based UNESCO Climate Change Adaptation Forum
- Climate Change Education for Sustainable Development Program
- Global Climate Change Field Observatory of UNESCO sites

Proposals of weather information projects are also recommended, expressing ways of illustrating extreme events and how they can affect a community, of knowledge transmission across generations and of scientific understanding. Thus, the aforementioned factors should be approached through the understanding of humanity's dependence on nature. It should be accentuated that a commitment to less destructive behaviours is indispensable, reflecting natural and cultural sustainability. In the study of heritage (both natural and cultural) there is unity of time, as there is a linkage between past, present and future. It is noted that there is a tendency for 'discounting the future': that is, successively reducing the importance ascribed to future events and conditions, merely because of their futurity? [89].

Heritage work needs to move beyond the sites, buildings, art, specimens, and 'old stuff' that museums and other organizations look after, into a realm of ever-changing 'wicked' problems. 'Nature bats last,' as the saying goes, and climate change would suggest 'She is already standing at the plate' [10]. Also, future studies should continue the recognition of the importance of the subject of the current review from a broader point of view, concerning the global approach and not only European countries [36].

Multidisciplinary opinions about the climate change risks and the perspectives of heritage are basic leads for the interpretation of this relationship, as stakeholders of diverse backgrounds can evaluate the difficulties and the opportunities. Thus, the adaptation of cultural heritage to climate change could be formed through a combination of better understanding of what needs to be provided and prioritized for adaptation to take place and in its strategic planning [18]. Further research is needed for the creation of tailor-made management plans for each kind of heritage, taking into account the particularities of the landscape which structure the uniqueness of the identity.

Appendix

The North Atlantic Oscillation (NAO) index

The North Atlantic Oscillation (NAO) index is based on the surface sea-level pressure difference between the Subtropical (Azores) High and the Subpolar Low. The positive phase of the NAO reflects below-normal heights and pressure across the high latitudes of the North Atlantic and above-normal heights and pressure over the central North Atlantic, the eastern United States and western Europe. The negative phase reflects an opposite pattern of height and pressure anomalies over these regions. Both phases of the NAO are associated with basin-wide changes in the intensity and location of the North Atlantic jet stream and storm track, and in large-scale modulations of the normal patterns of zonal and meridional heat and moisture transport, which in turn results in changes in temperature and precipitation patterns often extending from eastern North America to western and central Europe. (North Atlantic Oscillation (NAO), Teleconnections, National centres for Environmental Information, [https://www.ncdc.noaa.gov/teleconnections/nao/#:~:text=The%20North%20Atlantic%20Oscillation%20\(NAO,High%20and%20the%20Subpolar%20Low\).](https://www.ncdc.noaa.gov/teleconnections/nao/#:~:text=The%20North%20Atlantic%20Oscillation%20(NAO,High%20and%20the%20Subpolar%20Low).)

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Author contributions

M.P.N. organized a review for the effects of climate change on heritage, as it seems that this study still needs to be further analyzed. The present review is considered a valuable contribution to the research of heritage science.

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No datasets were generated or analysed during the current study.

Declarations

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References

- Hambrecht G, Rockman M. International approaches to climate change and cultural heritage. *Am Antiq*. 2017;82(4):627-41. <https://doi.org/10.1017/aaq.2017.30>.
- Gavalas M. Severe weather: The new challenge for the planning of greek islands. *Proceedings*. 2018; 2(11):669. <https://doi.org/10.3390/proceedings2110669>
- Sesana E, Gagnon AS, Ciantelli C, Cassar J, Hughes JJ. Climate change impacts on cultural heritage: a literature review. *WIREs Clim Chang*. 2021;12:e710.
- Sabbioni C, Cassar M, Brimblecombe P, Lefevre RA. Vulnerability of cultural heritage to climate change, European and Mediterranean Major Hazards Agreement (EUROPA). Council of Europe, Strasburgo, 2008
- Sabbioni C, Cassar M, Brimblecombe P, Lefèvre R-A. Vulnerability of cultural heritage to climate change. *Pollut Atmos*. 2009. pp. 157-169
- Sardella A., Palazzi E., Hardenberg J., Carlo del Grande, De Nuntis P., Sabbioni C. and Bonazza A. Risk mapping for the sustainable protection of cultural heritage. *Extreme Chang Environ Atmos* 2020;11:700. <https://doi.org/10.3390/atmos11070700>
- Bonazza A, Bonora N, Duke B, Spizzichino D, Recchia AP, Taramelli A. Copernicus in support of monitoring, protection, and management of cultural and natural heritage. *Sustainability*. 2022;2022(14):2501. <https://doi.org/10.3390/su14052501>.
- Woodside, R. 2006. World Heritage and Climate Change: Developing a Framework for Assessing Vulnerability. MSc Built Environment: Sustainable Heritage. University College London
- Figueiredo R, Romão X, Paupério E. Flood risk assessment of cultural heritage at large spatial scales: framework and application to mainland Portugal. *J Cult Herit*. 2020;2020(43):163-74.
- Sabbioni C, Brimblecombe P, Cassar M. The atlas of climate change impact on European cultural heritage. Scientific analysis and management strategies. London: Anthem Press; 2010.
- Dastgerdi AS, Sargolini M, Pierantoni I. Climate change challenges to existing cultural heritage policy. *Sustainability*. 2019;2019(11):5227. <https://doi.org/10.3390/su11195227>.
- Trevor Letcher (ed.). Climate change: observed impacts on planet earth, Book, 2nd Edition, 2015. 634 p, Elsevier, ISBN 978-0-444-63524-2 (??). 21-35, 37-77, 241-269, 271-293, 309-324, 419-447, 449-463, 465-489, 547-583, 585-594) (Ebook- central) <https://ebookcentral-proquest-com.proxy.eap.gr/lib/eapgr/detail.action?docID=4003861>
- Cassar M, Pender R. The impact of climate change on cultural heritage: evidence and response. In: Verger, I. (Ed.) (Proceedings) ICOM Committee for Conservation: 14th Triennial Meeting. James & James 2005, pp. 610-616.
- Harvey D, Perry J. (Eds). The future of heritage as climates change: loss, adaptation and creativity (1st ed.). Routledge. 2015. <https://doi.org/10.4324/9781315724164>
- Tringa E, Tolika K. Analysis of the outdoor microclimate and the effects on greek cultural heritage using the heritage microclimate risk (HMR) and

- Predicted Risk of Damage (PRD) indices: present and future simulations. *Atmosphere*. 2023;14:663. <https://doi.org/10.3390/atmos14040663>.
16. Interdisciplinary Committee on Climate Change Impact Assessment (CCISC), Bank of Greece. The environmental, economic and social impacts of climate change in Greece, 2011. ISBN 978-960-7032-49-2
 17. Grossi CM, Bonazza A, Brimblecombe P, Harris I, Sabbioni C. Predicting twenty-first century recession of architectural limestone in European cities. *Environ Geol*. 2008;2008(56):455?61. <https://doi.org/10.1007/s00254-008-1442-6>.
 18. Sesana E, Gagnon AS, Bertolin C, Hughes J. Adapting cultural heritage to climate change risks: perspectives of cultural heritage experts in Europe. *Geosciences*. 2018;8:305. <https://doi.org/10.3390/geosciences8080305>.
 19. National Trust, 2005a; Caffrey and Beavers, 2008; Edwards and O'Sullivan, 2007; Cuffe Fitzgerald, 2010; Murphy et al., 2009; Rowlands 2008
 20. Pearson M. Climate change and its impacts on Australia's cultural heritage. *Hist Environ* 2008;21
 21. Shanahan B, McNeary R. Landscapes of memory in the heartland of Connacht, Ireland. In: Lévêque L, Ruiz del Árbol M, Pop L, editors. *Patrimoine, Images, Mémoire des Paysages Européens*. L'Harmattan; 2010. p. 163?76.
 22. Tang W, Davidson CL. Erosion of limestone building surfaces caused by wind-driven rain: 2. Numerical Model *Atmos Environ*. 2004;38:5601?9. <https://doi.org/10.1016/j.atmosenv.2004.06.014>.
 23. United Nations Educational, Scientific and Cultural Organization Convention concerning the protection of the world cultural and natural heritage, World Heritage Committee, 41 Session, Krakow, Poland 2?12 July 2017
 24. United Nations. Transforming our world: the agenda 2030 for the sustainable development; A/RES/70/1; United Nations: New York, NY, USA, 2015
 25. Brandt CL. Teoría del Restaura. Milan: Einaudi; 1963.
 26. Huijbregts Z, Kramer RP, Martens MHJ, Van Schijndel AWM, Schellen HL. A proposed method to assess the damage risk of future climate change to museum objects in historic buildings. *Build Environ*. 2012;2012(55):43?56.
 27. Periodic activity report, Noah's ark global climate change impact on built heritage and cultural landscapes. [cordis.europa.eu](https://cordis.europa.eu/docs/results/501/501837/124722791-6_en.pdf). 2007. https://cordis.europa.eu/docs/results/501/501837/124722791-6_en.pdf
 28. European Heritage Days 2022 shine a spotlight on ?Sustainable Heritage? - Culture and Cultural Heritage? [www.coe.int](https://www.coe.int/en/web/culture-and-heritage/-/european-heritage-days-2022-shine-a-spotlight-on-sustainable-heritage). Culture and Cultural Heritage. 2022. <https://www.coe.int/en/web/culture-and-heritage/-/european-heritage-days-2022-shine-a-spotlight-on-sustainable-heritage>
 29. Hajirasouli A, Banihashemi S, Kumarasuriyar A, Talebi S, Tabadkani A. Virtual reality-based digitisation for endangered heritage sites: theoretical framework and application. *J Cult Herit*. 2021;49(2021):140?51. <https://doi.org/10.1016/j.culher.2021.02.005>.
 30. Colette A. Climate Change and World Heritage. Report on predicting and managing the impacts of climate change on world heritage and strategy to assist states parties to implement appropriate management responses; UNESCO World Heritage Centre: Paris, France, 2007
 31. Intergovernmental Panel on Climate Change (IPCC). Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part b: Regional aspects; Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Agard, J., Schipper, E.L.F., Birkmann, J., Campos, M., Dubeux, C., Nojiri, Y., Olsson, L., Osman-Elasha, B., Pelling, M., Prather, M.J., et al., Eds.; Cambridge University Press: New York, NY, USA, 2014; rconomipp. 1757?1776.
 32. Brimblecombe P, Grossi CM, Harris I. Climate change critical to cultural heritage. In: Fort, Alvarez de Buergo, Gomez-Heras, Vasquez-Calvo (Ed.). *Heritage, Weathering and Conservation*. London: Taylor & Francis Group, 2011, pp. 195?205.
 33. Sesana E, Bertolin C, Gagnon AS, Hughes JJ. Mitigating climate change in the cultural built heritage sector. *Climate*. 2019;2019(7):90.
 34. Sabbioni C, Bonazza A, Messina P. Cambiamenti climatici e patrimonio culturale. Contributi sugli effetti dei cambiamenti climatici sul patrimonio costruito e sul paesaggio culturale, Istituto di Scienze dell'Atmosfera e del Clima, 2007, pp. 805?808.
 35. Dawson T, Hambly J, Kelley A, Lees W, Miller S. Coastal heritage, global climate change, public engagement, and citizen science. *Proc Natl Acad Sci USA*. 2020;2020(117):8280?6.
 36. Fatori? S, Seekamp E. Are cultural heritage and resources threatened by climate change? A systematic literature review. *Clim Change*. 2017;142:227?54. <https://doi.org/10.1007/s10584-017-1929-9>.
 37. Laoupi ?. Centre for the assessment of natural hazards & proactive planning, national technical University of Athens, Sub Project DISMA DISaster Management GIS with emphasis on cultural sites, TECHNICAL REPORT: Volume II. 2007
 38. Mikkonen T. Cultural Environment as a Resource in Climate Change Mitigation and Adaption. 2016
 39. Cacciotti R, Kaiser A, Sardella A, De Nuntiis P, Drdác?y M, Hanus C, Bonazza A, Climate change-induced disasters and cultural heritage: optimizing management strategies in Central Europe, *Climate Risk Manag*, Volume 32, 2021, 100301, ISSN 2212-0963, <https://doi.org/10.1016/j.crm.2021.100301>.
 40. Padeletti G, HERACLES Consortium Staff. Heritage Resilience Against Climate Events on Site - HERACLES Project: Mission and Vision. In: Moropoulou, A., Korres, M., Georgopoulos, A., Spyarakos, C., Mouzakis, C. (eds) *Transdisciplinary Multispectral Modeling and Cooperation for the Preservation of Cultural Heritage*. TMM_CH 2018. Commun Comp Inform Scivol 961. Springer, Cham. 2019. https://doi.org/10.1007/978-3-030-12957-6_26
 41. Mean precipitation- European Environment Agency. [eea.europa.eu](https://www.eea.europa.eu). 2021. <https://www.eea.europa.eu/data-and-maps/indicators/european-precipitation-2/assessment>
 42. Monthly summaries of precipitation, relative humidity and soil moisture, climate.copernicus.eu, <https://climate.copernicus.eu/monthly-summaries-precipitation-relative-humidity-and-soil-moisture>
 43. Betolin C (Ed.) *Preservation of Cultural Heritage and Resources, Threatened by Climate Change*, Switzerland: MDPI, 2019. [https://www.mdpi.com/journal/geosciences/special issues/Preservation.Cultural.Heritage](https://www.mdpi.com/journal/geosciences/special%20issues/Preservation.Cultural.Heritage). Climate.Change
 44. Nelson D, Adger W, Brown K. Adaptation to environmental change: contributions of a resilience framework. *Ann Rev Environ Resour*. 2007. <https://doi.org/10.1146/annurev.energy.32.051807.090348>.
 45. Cassar M. Sustainable heritage: challenges and strategies for the twenty-first century. *Apt Bull J Preserv Technol*. 2009
 46. Bokova I. UNESCO climate change initiative. 2009
 47. Kapsomenakis J, Douvis C, Poupkou A, Zerefos S, Solomos S, Stavraka T, Melis NS, Kyriakidis E, Kremlis G, Zerefos C. Climate change threats to cultural and natural heritage UNESCO sites in the Mediterranean. *Environ Dev Sustain*. 2022. <https://doi.org/10.1007/s10668-022-02677-w>.
 48. Gómez de Cózar J-C, Martínez AG, López Í-A, Alfonsea M-R. Life cycle assessment as a decision-making tool for selecting building systems in heritage intervention: Case study of Roman Theatre in Itálica, Spain, *J Clean Prod*. 2019. ISSN 0959-6526, <https://doi.org/10.1016/j.jclepro.2018.09.169>
 49. Daly C. Climate change and the conservation of archaeological sites: a review of impacts theory. *Conserv Manag Archaeol Sites*. 2011;13(4):293?310. <https://doi.org/10.1179/175355212X13315728646058>.
 50. Henderson M, Seekamp E. Battling the tides of climate change: The power of intangible cultural resource values to bind place meanings in vulnerable historic districts. *Heritage*. 2018;2018(1):220?38.
 51. Markham A, Osipova E, Lafrenz Samuels K, Caldas A. World heritage and tourism in a changing climate. Paris, France: UNESCO Publishing; 2016.
 52. Kjellstrom T, Kovats RS, Lloyd SJ, Holt T, Tol RSJ. The direct impact of climate change on regional labor productivity. *Arch Environ Occup Health*. 2009;2009(64):217?27.
 53. Black R, Bennett SRG, Thomas SM, Beddington JR. Climate change: Migration as adaptation. *Nature*. 2011;2011(478):447.
 54. Kim H-E. Changing climate, changing culture: adding the climate change dimension to the protection of intangible cultural heritage. *Int J Cult Prop*. 2011;18:259?90.
 55. Adger WN, Barnett J, Brown K, Marshall N. Cultural dimensions of climate change impacts and adaptation. *Nat Clim Chang*. 2013;2013(3):112.
 56. Donnelly A, Jones MB, Sweeney J. A review of indicators of climate change for use in Ireland. *Int J Biometeorol*. 2004;49:1?12. <https://doi.org/10.1007/s00484-004-0215-5>.
 57. Phillips H. The capacity to adapt to climate change at heritage sites?The development of a conceptual framework, Oxford Brookes University, Gypsy Lane, Oxford OX3 0BP, UK, 2015.
 58. Michalski S, Pedersoli Jr JL. The ABC Method: a risk management approach to the preservation of cultural heritage, Canadian Conservation Institute, Canada, 2016. ISBN 978-0-660-04134-6

59. Daly C. A framework for assessing the vulnerability of archaeological sites to climate change: theory development, and application. *Conserv Manag Archaeol Sites*. 2014. <https://doi.org/10.1179/1350503315Z.00000000086>.
60. Fatori'c S. and Egberts L., 2020 - Fatori'c S.; Seekamp, E. (2017) Securing the future of cultural heritage by identifying barriers to and strategizing solutions for preservation under changing climate conditions. *Sustainability* 2017, 9, 2143.
61. Intergovernmental Panel on Climate Change (IPCC), Annex II: glossary, in: K.J. Mach, S. Planton, C. Von Stechow, R.K.P.A.L.A.M. Writing Team (Eds.), *Climate change 2014: synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Geneva, Switzerland, 2014.
62. Huan K-T, Yang SR, Matzarakis A, Lin T-P. Identifying outdoor thermal risk areas and evaluation of future thermal comfort concerning shading orientation in a traditional settlement. *Sci Total Environ*. 2018;626(2018):567780.
63. Cigna F, Tapete D, Lee K. Geological hazards in the UNESCO world heritage sites of the UK: From the global to the local scale perspective. *Earth-Sci Rev*. 2018;2018(176):166794.
64. Smit B., Pilifosova O., (2001) Chapter 18: adaptation to climate change in the context of sustainable development and equity, In: J.J. McCarthy, O.F. Canziani, N.A. Leary, D.J. Dokken, K.S. White (Eds.), *Climate change 2001: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK
65. Quinlan KM. What triggers students' interest during higher education lectures? Personal and situational variables associated with situational interest. *Stud High Educ*. 2019;44(10):1781792. <https://doi.org/10.1080/03075079.2019.1665325>.
66. UK Climate Impacts Program (UKCIP) (2009) *Understanding Climate Change*. <http://www.ukcip.org.uk>
67. Gupta J, Bergsma E, Termeer CJAM, Biesbroek R, Brink M, Jong P, Klostermann J, Meijerink S, Nooteboom S. The adaptive capacity of institutions in the spatial planning, water, agriculture and nature sectors in the Netherlands. *Mitig Adapt Strat Glob Change*. 2015;21(6):1721. <https://doi.org/10.1007/s11027-014-9630-z>.
68. Nastos PT, Zerefos CS. Spatial and temporal variability of consecutive dry and wet days in Greece. *Atmos Res*. 2009;94:616728.
69. Nastos PT, Kapsomenakis J, Douvis, K.C. Analysis of precipitation extremes based on satellite and high-resolution gridded data set over Mediterranean basin. *Atmos Res*. 2013;131(2013):46759. <https://doi.org/10.1016/j.atmosres.2013.04.009>.
70. Tolika K, Anagnostopoulou C, Maheras P, Vafiadis M. Simulation of future changes in extreme rainfall and temperature conditions over the greek area: a comparison of two statistical downscaling approaches. *Glob Planet Chang*. 2008;63:132751.
71. Barcikowska MJ, Kapnick SB, Krishnamurthy L, Russo S, Cherchi A, Folland CK. Changes in the Future Summer Mediterranean Climate: Contribution of Teleconnections and Local Factors. *Earth Syst Dynam*. 2020;11:161781.
72. Nastos P, Politi N, Kapsomenakis J. Spatial and temporal variability of the Aridity Index in Greece. *Atmos Res*. 2011;119(2013):140752. <https://doi.org/10.1016/j.atmosres.2011.06.017>.
73. Gouvas MA, Sakellariou NK, Kambezidis HD. Estimation of the monthly and annual mean maximum and mean minimum air temperature values in Greece. *Meteorol Atmos Phys*. 2010;110:14379. <https://doi.org/10.1007/s00703-010-0111-y>.
74. Kapsomenakis J, Douvis C, Poupkou A, Zerefos S, Solomos S, Stavraka T, Melis NS, Kyriakidis E, Kremlis G, Zerefos C. Climate change threats to cultural and natural heritage UNESCO sites in the Mediterranean. *Environ Dev. Sustain*. 2022
75. Ravankhah M, de Wit R, Argyriou AV, Chliaoutakis A, Revez MJ, Birkmann J, ?uvela-Aloise M, Sarris A, Tzigounaki A, Giapitsoglou K. Integrated assessment of natural hazards, including climate change's influences, for cultural heritage sites: the case of the historic centre of Rethymno in Greece. *Int J Disaster Risk Sci*. 2019;10:343761.
76. Camuffo D. *Microclimate for cultural heritage: measurement, risk assessment, conservation, restoration, and maintenance of indoor and outdoor monuments*, 3rd ed.; Elsevier: Amsterdam, The Netherlands, 2019; ISBN 978-0-444-64106-9.
77. Nastos PT, Matzarakis AP. Variability of tropical days over Greece within the second half of the twentieth century. *Theor Appl Climatol*. 2008;93:75789.
78. Asprogerakas E, Gourgiotis A, Pantazis P, Samarina A, Konsoula P, Stavridou K. Corrigendum: The gap of cultural heritage protection with climate change adaptation in the context of spatial planning. The case of Greece. *IOP Conf Ser Earth Environ Sci*. 2021, 899, 012022, <https://doi.org/10.1088/1755-1315/899/1/012022>
79. Fatori' S, Seekamp E. Knowledge co-production in climate adaptation planning of archaeological sites. *J Coastal Conserv*. 2019;23(3):689710.
80. Chalkidou S, Georgiadis C, Roustanis T, Patias P. A methodology for identifying coastal cultural heritage assets exposed to future sea level rise scenarios. *Appl Sci*. 2024;14:7210. <https://doi.org/10.3390/app14167210>.
81. Hall CM. Heritage, heritage tourism and climate change. *J Herit Tour*. 2016;11(1):179. <https://doi.org/10.1080/1743873X.2015.1082576>.
82. Coletti C. Climate change threats to stone cultural heritage: state of the art of quantitative damage functions and new challenges for a sustainable future. *Heritage*. 2024;7:3276790. <https://doi.org/10.3390/heritage7060154>.
83. Antonelli F, De Bonis A, Miriello D, Raneri S, Silvestri A. Geosciences for cultural heritage: an overview. *J Cult Herit*. 2020;43(2020):338741. <https://doi.org/10.1016/j.culher.2020.01.001>.
84. Taelman D, Delpino C, Antonelli F, Marble decoration of the Roman theatre of Urvinum Mataurense (Urbino, Marche region, Italy): an archaeological and archaeometric multi-method provenance study, <https://doi.org/10.1016/j.culher.2019.03.009>
85. Ghosh S, Pillai RH, Roy A, Murali RA, Vardhan V. A simulation study of dust transport on an ancient amphitheatre: The Delphi example. *J Cult Herit*. 2017. <https://doi.org/10.1016/j.culher.2016.10.009>.
86. Hegazi YS. Resilience adaptation approach for reducing the negative impact of climate change on coastal heritage sites through machine learning. *Appl Sci*. 2022;2022(12):10916. <https://doi.org/10.3390/app122110916>.
87. Bonazza A. Cultural Heritage in the Italian National Strategy for Adaptation to Climate Change, International Workshop cultural heritage facing climate change: experiences and ideas for resilience and adaptation, 2017
88. Climate Change, *UNESCO*, unesco.org, retrieved on January 2022
89. Bartolini N, DeSilvey C. Landscape futures: decision-making in uncertain times, a literature review. *Landsc Res*. 2021;46(1):8724. <https://doi.org/10.1080/01426397.2020.1861228>.

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