



Climate change threats to cultural and natural heritage UNESCO sites in the Mediterranean

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Abstract

The study presents a time-dependent analysis of threats from man-made climate change at 244 UNESCO cultural and natural heritage sites in the Mediterranean. The hazards in our research are estimated by indices based on extremes of heat, fire weather conditions, heavy rainfall days, frost days, changes in mean sea level and aridity at each site. These indices were calculated from regional EUROCORDEX simulations, cover the period 1971–2100 and refer to two IPCC emission scenarios, namely RCP4.5 and RCP8.5. A combined threat index was next calculated, as explained in the text, together with its synergy with local exposure geophysical threats, such as seismicity, topography and proximity to forests and seas. All indices related to man-made climate change show an overall increasing trend from present to the end of the twenty-first century. Some of these increasing trends are intensified after the 2030s and 2040s, except for the case of the days with frost. As the global warming evolves, in both IPCC scenarios studied, the combined threat to the majority of UNESCO sites studied increases. Notable is the amplification of the threat at sites vulnerable to seismic activity and to other local or regional topography and geophysical regional characteristics. 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. Based on the proposed combined threat index, for the worst-case scenario (RCP8.5) 35 monument sites fall within the “high hazard” and 12 sites fall under the category “extreme hazard”.

Keywords Heritage sites · Climate change · Extreme weather and climatic events · Heritage preservation

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1 Introduction

According to the recent IPCC report (IPCC, 2021), there is high certainty that anthropogenic global warming is progressing faster than estimated before. The Mediterranean region, one of the cradles of global civilization, is included among the most vulnerable regions to climate change for the decades to come. Therefore, cultural and natural heritage in this part of the world, which contains 244 UNESCO heritage sites, is expected to be at risk from man-made climate change in the decades to come. That reason provided the driving force to proceed with further research on the additional threat that man-made global warming has on our natural and cultural heritage sites, a topic that has not yet been included in the latest IPCC report.

Historically, at the International Conference entitled “Climate Change Impacts on Cultural Heritage—Facing the Challenge”, held in Athens, Greece, on 21–22.06.2019, the initiative “Addressing climate change impacts on cultural and natural heritage” was launched. The initiative was supported by a number of international institutions, including the UN Framework Convention on Climate Change (UNFCCC), the UN Educational, Scientific and Cultural Organization (UNESCO), the World Meteorological Organization (WMO), the International Council on Monuments and Sites (ICOMOS), the UN Sustainable Development Solution (UN SDSN), the Group of Earth Observations (GEO), Europa Nostra, the University of Kent and the Academy of Athens. Until COP26 (2021), more than 100 UN member states had expressed their support to the Greek initiative. The UN Secretary-General included the Greek proposal in the “Report on the 2019 Climate Action Summit and the Way Forward in 2020” among the most ambitious initiatives. The initiative aims to support the protection of cultural and natural heritage from the impact of climate change by mainstreaming this protection into climate change policies and/or processes, in line with the Paris Agreement objectives and commitments and the UN SDGs, taking into account policies and recommendations by UNESCO, WMO and other international organizations.

It should be pointed out here that man-made climate change has already been recognized as an additional threat to the monuments among a number of other threats, including the effects of air pollution, invasive species and war aggression (Veillon, 2014; Leissner et al., 2015; ICOMOS, 2019). Moreover, several recent studies indicate that climate change can be one of the most significant threats in the years to come in view of the accelerating destabilization of our climate (Zerefos, 2019; Day et al., 2020; Zerefos et al., 2022; Bonazza et al., 2022). Particularly for the natural heritage sites, climate change has already become the most prevalent threat as stated in the latest International Union for Conservation of Nature (IUCN) World Heritage Outlook (Osipova et al., 2020). In view of the pollution abatement efforts globally, the importance of pollution as a threat is slightly decreasing, with a few exceptions worldwide. In contrary, climate change is an emerging important hazard, particularly when synergistic effects amplify the threat (e.g. Bonazza et al., 2009; Brimblecombe et al., 2010; Grøntoft, 2011).

Most heritage monuments are expected to be vulnerable to climate change, considering their old age (Berenfeld, 2008). In addition, reparations with new and modern materials can be detrimental to their authenticity. The same applies to the replacement of whole systems, such as existing rainwater drainage pipes with wider ones that can cope with more intense rainfall (Cassar, 2005) or with the reinforcement of old walls and roofs in order to sustain the increased wind and snow loads (Haugen & Mattsson, 2011) due to climate change. Conservation costs will also increase due to the acceleration of climate change-related damage (Grøntoft, 2011), as well as air conditioning costs for indoor collections

and museums (Cassar, 2005). Some monuments may be at extreme risk, most notably those in danger of inundation by sea level rise and storm surge (Camuffo et al., 2014; Cassar, 2005).

Hydrometeorological extreme events linked to man-made climate change represent an additional risk to heritage (Sardella et al., 2020). According to Bonazza et al. (2021), a general increase in lengthy periods (e.g. 5 days) of heavy precipitation in the future, under RCP8.5 scenario, is associated with a high likelihood of flooding risk at cultural sites. At building level, an additional high degree of vulnerability is the result of maintenance plan lacking strategy to abate susceptibility of structures to water impact. Also, according to ICOMOS (2019), long-term transformation of regions to drier (aridity) conditions alters cultural landscapes and culturally important species may be lost. Wildfires are an additional growing threat to natural and cultural heritage to which they may cause material loss, deformation and increase of the probability of cracking or splitting in built structures (ICOMOS, 2019). Several parameters should be monitored for each heritage site depending not only on the change of climatic factors but also on its properties, such as the masonry materials and structure.

Sardella et al. (2020) and Cacciotti et al. (2021) 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. The HERACLES EU project 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) (Padeletti et al., 2019). Bonazza et al. (2018) presented an overview of existing knowledge, at European and international level, on safeguarding cultural heritage from the effects of natural disasters and threats caused by human action, including extreme climate change events. The study underlines the existing research gaps related to the establishment of an integrated methodology for the comprehensive modelling of the impacts of disasters on heritage and to the development of a pathway for the management of a multi-risk assessment.

Multi hazard risk assessment in natural-hazard-prone regions is necessary for the design and optimized implementation of disaster risk reduction and resilience-enhancing strategies (Sevieri et al., 2020). The Mediterranean area falls within this type of regions. Cultural heritage assets require special consideration because of their physical vulnerability as a result of the material degradation due to ageing, the possible presence of structural modifications and local repair and/or partial or total reconstructions over time (D'Ayala, 2014; Despotaki et al., 2018). The incorporation of climate change in such an analysis is indeed challenging (Ravankhah et al., 2019).

In this study, we examine the evolution of days with extreme weather events at 244 cultural and natural heritage UNESCO sites in the Mediterranean.¹ The countries to which belongs the heritage sites are listed alphabetically: Albania, Algeria, Bosnia and Herzegovina, Croatia, Cyprus, Egypt, France, Greece, Israel, Italy, Jordan, Lebanon, Libya, Malta, Montenegro, Morocco, Palestine, Portugal, Slovenia, Spain, Syrian Arab Republic, Tunisia and Turkey. Out of the 244 UNESCO sites, 244 sites are characterized as cultural heritage, 11 sites as natural heritage, while 6 sites are mixed.

¹ More information about the latitude/longitude, elevation, the country and the category (cultural or natural or mixed) is provided for each site in supplementary material.

In this work, we propose a set of six extreme climate indices that represent possible climatic hazards at the selected sites during the period 1971–2100. The indices have been calculated from a large ensemble of high-resolution model results based on 21 regional climate models. The list of hazards in our research includes heat waves, the fire weather index, the days with heavy rainfall and with frost as well as changes in mean sea level and in aridity at each site as described in the following paragraph. These indices were calculated from regional EUROCORDEX simulations, cover the period 1971–2100 and refer to two emission scenarios, namely RCP4.5 and RCP8.5. A combined threat index was next calculated, as explained in the following paragraphs, including the synergy with local geophysical properties, such as topography, proximity to forests and seas and earthquake probability. The latter has been estimated at each site using the extracted intensity measure type of the maximum expected peak ground acceleration value in “g” (PGA), from the most up to date European Seismic Hazard Model (ESHM20), representative of a rock type site with $V_{s30}=800$ m/s² and with probability of exceedance 0.2103% in 1 year and mean return period of 476 years (Danciu et al., 2021).

2 Data and methodology

In order to investigate the impact of climate and weather extremes on the 244 UNESCO Heritage Sites, six climate change hazard indices were selected throughout the study period 1971–2100. The proposed six indices represent estimates of man-made climate hazards and are listed here:

1. The number of extreme hot days per year (TX_{37}) is defined as the number of days per year with a maximum air temperature higher than 37 °C
2. The number of days per year with extreme forest fire risk, FWI45, is the number of days per year with a Fire Weather Index exceeding 45 (Good et al., 2008; Moriondo et al., 2006; Van Wagner, 1987). This index allows assessing the future risk for the destruction of the sites or of the quality of their surrounding environment by wildfires. The calculation of the Canadian Fire Weather Index was performed using the package CFFDRS of R statistical computing software using as input the daily values of maximum temperature, minimum relative humidity derived by absolute humidity and maximum temperature, precipitation and wind speed (Van Wagner, 1987).
3. The number of days per decade with extreme precipitation. PR99 is defined here as the number of days per decade exceeding the 99th percentile of precipitation daily totals on days with at least 1 mm of precipitation, during the 1971–2000 reference period.
4. The aridity index, AI, is a measure of the dryness of the climate at a location calculated by the ratio between precipitation and potential evapotranspiration. Its use was proposed to identify sites where the environment will suffer severe degradation due to aridity. This is one of the greatest risks for natural Heritage Sites, as well as for cultural monuments, threatening the quality of the surrounding environment and often the monuments themselves and the sufficiency of their water resources (Heathcote et al., 2017; Kempiak et al., 2017).

AI is calculated using the mean monthly temperature at 2 m, T_m , and precipitation, P_m . For each year, two empirical factors (I , a) are calculated as follows (Thorntwaite, 1948):

$$I = \sum_{m=1}^{12} T_m / 5 \quad (1)$$

$$\alpha = 0.000000675 * I^3 - 0.000077 * I^2 + 0.01792 * I + 0.49239 \quad (2)$$

and used to calculate monthly potential evapotranspiration:

$$PET_m = 1.6 * (10 * T_m / I)^\alpha \quad (3)$$

Finally, the AI is calculated as

$$AI = \sum_{m=1}^{12} (P_m) / \sum_{m=1}^{12} (PET_m) \quad (4)$$

5. The number of frost nights, TNO, i.e. the number of days per year with a minimum temperature below 0 °C, is an important index describing damage to building materials (Kočí et al., 2014; Calle & Van Den Bossche, 2017).
6. The mean sea level rise, SLR, was calculated at the coastal UNESCO sites. The inundation of monuments by sea level rise or by storm surge is the hardest threat to deal with and may cause the abandonment and destruction of a site (Cassar, 2005). SLR was calculated from the extreme sea level (ESL) dataset of the Large Scale Integrated Sea-level and Coastal Assessment Tool (LISCOAST) program developed by the Joint Research Center (JRC) of the European Commission.

The six hazard indices were next calculated using input from the ensemble of 21 simulations of the EURO-CORDEX program (<https://euro-cordex.net/>) for the years 1971–2100 based on two emission scenarios, namely RCP8.5 (Riahi et al., 2011) and the intermediate RCP4.5 (Thomson et al., 2011). Each simulation consists of a global climate simulation and a dynamical downscaling over Europe, with a combination of Earth system models (ESMs) and regional climate models (RCMs), as shown in Table 1. The spatial resolution of the regional simulations is 11 × 11 km. The parameters were calculated from the results of the 21 simulations using the nearest-neighbour method for spatial interpolation and averaging the results over all simulations. The use of climate data estimated from a large ensemble of individual models assures the validity of the climate change hazard indices projected in the decades to come. In addition, regional climate modelling provides more spatially detailed and accurate results that are more suitable to climate change analyses in complex topography. Such complexity can be found for example in Venice and in the complex topography of the northern Mediterranean countries. Under this downscaling analysis, the results presented in this study add significant value and more detail to the IPCC estimates in the Mediterranean region, customized at each UNESCO site.

Table 2 presents the corresponding hazard indices along with a non-exhausting list of their associated impacts. The impacts are various and may be referring to the materials and structure of the sites, to the general landscape and its characteristics or to the ecosystems biodiversity in the case of natural heritage sites. The indices have been constructed based on the research work by UNESCO (2007), Carroll & Aarrevaara, 2018; ICOMOS, 2019; Sardella et al. (2020), Sesana et al. (2021) and Zerefos et al. (2022).

Table 1 Description of RCM and ESM models used in each simulation

Simulation	RCM	ESM
CNRM-CERFACS-CNRM-CM5_CLMcom-CCLM4-8-17	CLM4	CNRM-CM5
CNRM-CERFACS-CNRM-CM5_CNRM-ALADIN53	ALADIN53	CNRM-CM5
CNRM-CERFACS-CNRM-CM5_KNMI-RACMO22E	RACMO22E	CNRM-CM5
CNRM-CERFACS-CNRM-CM5_SMHI-RCA4	RCA4	CNRM-CM5
ICHEC-EC-EARTH_CLMcom-CCLM4	CLM4	EC-Earth
ICHEC-EC-EARTH_DMI-HIRHAM5	HIRHAM5	EC-Earth
ICHEC-EC-EARTH_GERICS-REMO2015	REMO2015	EC-Earth
ICHEC-EC-EARTH_KNMI-RACMO22E	RACMO22E	EC-Earth
ICHEC-EC-EARTH_SMHI-RCA4	RCA4	EC-Earth
IPSL-IPSL-CM5A-MR_IPSL-INERIS-WRF331F	WRF331F	IPSL-CM5A-MR
IPSL-IPSL-CM5A-MR_SMHI-RCA4	RCA4	IPSL-CM5A-MR
MOHC-HadGEM2-ES_CLMcom-CCLM4-8-17	CLM4	HadGEM2-ES
MOHC-HadGEM2-ES_DMI-HIRHAM5	HIRHAM5	HadGEM2-ES
MOHC-HadGEM2-ES_KNMI-RACMO22E	RACMO22E	HadGEM2-ES
MOHC-HadGEM2-ES_SMHI-RCA4	RCA4	HadGEM2-ES
MPI-M-MPI-ESM-LR_CLMcom-CCLM4-8-17	CLM4	MPI-ESM-LR
MPI-M-MPI-ESM-LR_MPI-CSC-REMO2009	REMO2009	MPI-ESM-LR
MPI-M-MPI-ESM-LR_SMHI-RCA4	RCA4	MPI-ESM-LR
NCC-NorESM1-M_DMI-HIRHAM5	HIRHAM5	NorESM1-M
NCC-NorESM1-M_GERICS-REMO2015	REMO2015	NorESM1-M
NCC-NorESM1-M_SMHI-RCA4	RCA4	NorESM1-M

Last but not least comes the threat of the possible synergy from the seismicity in a site if applicable. In order to investigate the synergistic effect of earthquake activity, we have selected as an index of the seismic hazard the expected peak ground acceleration (PGA) extracted from the most updated “2020 Euro-Mediterranean Seismic Hazard Model (ESHM20)” (Danciu et al., 2021). In particular, PGA values were extracted from the ESHM20 model, in terms of the arithmetic mean PGA value expected with probability of exceedance 0.2103% in 1 year in a time interval of 476 years on rock soil characterized with $V_{s30} = 800 \text{ m/s}^2$. A scale of five categories was proposed for the extracted PGA values as: level 0 – $\text{PGA} < 0.05 \text{ g}$, level 1 – $0.05 \text{ g} < \text{PGA} < 0.10 \text{ g}$, level 2 $0.10 \text{ g} < \text{PGA} < 0.2 \text{ g}$, level 3 $0.2 \text{ g} < \text{PGA} < 0.35 \text{ g}$ and level 4 $\text{PGA} > 0.35 \text{ g}$. That seismicity index has been next assigned to each one of the 244 UNESCO sites under study.

As mentioned before, the current study is proposing a set of six extreme climate indices that represent possible man-made climatic hazards at the UNESCO sites during the period 1971–2100 in the Mediterranean. All six hazard indices are presented in Figs. 1, 2, 3, 4, 5 and 6 in the next paragraph both in a linear scale as well as grouped in five categories of a chromatic scale according to the intensity of the expected hazard. The five colour categories have been selected to represent five successive groups ranging in intensity from no hazard up to extreme hazard at a given site. In Figs. 1, 2, 3, 4, 5 and 6, these groups are shown as *N*, *L*, *M*, *H* and *X* corresponding to the Arabic numbers 0, 1, 2, 3 and 4 and implying no hazard, low hazard, moderate hazard, high hazard and extreme hazard, respectively. In calculating these indices, we took

Table 2 Climate change-related hazard indices and indicative impacts on cultural and natural heritage monuments

Climate change hazard	Climate index	Abbreviation (units)	Indicative impacts
Extreme heat	Number of days with maximum temperature higher than 37 °C	TX ₃₇ (days/year)	<p><i>Indicative Impacts on Cultural Heritage</i></p> <p>Thermoclastic deterioration from repeated expansion and shrinkage (e.g. earthen materials, building facades)</p> <p>Structural deterioration or degradation of buildings and structures (e.g. increased crystallization of salts to increase rates of structural cracking)</p> <p>Metal rust accelerated</p> <p>Increased rate of chemical decay of materials</p> <p>Increased need for environmental controls (e.g. A/C equipment) in facilities/house collections</p> <p>Wood/brick new fauna—pests</p> <p><i>Indicative Impacts on Natural Heritage</i></p> <p>Global extinctions</p> <p>Heat stress, decline or local disappearance of some plant or animal species</p> <p>Coral reefs bleaching</p> <p>Lengthening of plants growing season</p> <p>Plant and animal ranges shifting poleward and upward in elevation</p> <p>Changes in the capacity to grow traditional crop varieties/animal husbandry or lower crop yields</p>
Wildfires	Number of days with Fire Weather Index higher than 45 (extreme forest fire risk days)	FWI ₄₅ (days/year)	<p><i>Indicative Impacts on Cultural Heritage</i></p> <p>Loss or damage of structures</p> <p>Heat fracturing/alterations</p> <p>Damage from ash</p> <p>Discoloration/colour change caused by smoke and/or heat</p> <p>Physical damage from firefighting efforts</p> <p>Danger of destruction of cultural resources during creation of firebreaks</p> <p>Damage to exterior decorations, marbles, statues etc</p> <p>Burning tree roots damaging below-ground structures and artefacts</p> <p>Pressure to change character defining features to fire resistant alternatives</p> <p><i>Indicative Impacts on Natural Heritage</i></p> <p>Loss or damage of landscapes</p> <p>Danger of destruction of cultural/natural resources during creation of firebreaks</p> <p>Pressure to change character defining features to fire resistant alternatives</p> <p>Changes in vegetation density and composition</p> <p>Loss of soil fertility due to high heat</p>

Table 2 (continued)

Climate change hazard	Climate index	Abbreviation (units)	Indicative impacts
Extreme precipitation/flooding/landslides	Number of days with precipitation higher than the 99th percentile of the reference period (1971–2000) (extreme wet days)	PR ₉₉ (days/year)	<p><i>Indicative Impacts on Cultural Heritage</i></p> <p>Wood/Brick/Stone erosion and/or chemical dissolution</p> <p>Increased rusting/ corrosion of metals</p> <p>Increased damage and erosion from tourist footfall at high visitation heritage sites under wet conditions</p> <p>Humidity/Wetting damage (e.g. paintings, archival, paper, book/photo collections)</p> <p>Increased hail damage to roofs, windows and decorative elements</p> <p>Damages or complete loss by the force of flood water, debris and sediments</p> <p>Sewage overflow leading to contamination</p> <p>Movement of artefacts/structures and loss of context (during or post-flood)</p> <p>Site erosion from overflow and new flood channels (especially at riverine and estuarine sites)</p> <p>Increased risk of subsidence (during or post-flood)</p> <p>Increased risk of fungal/insect attack</p> <p>Loss of buildings located on slopes or burial due to landslides</p> <p><i>Indicative Impacts on Natural Heritage</i></p> <p>Decline/disappearance of some vegetation species</p> <p>Decreased soil fertility from erosion, waterlogging, leaching</p> <p>Increased risk of fungal/insect attack</p> <p>Site erosion from overflow and new flood channels (especially at riverine and estuarine sites)</p>
Aridity	Aridity index	AI (-)	<p><i>Indicative Impacts on Cultural Heritage</i></p> <p>Damage to wooden, paper, textile and organic objects from drying due to lower relative humidity</p> <p>Increase in dry salt deposits near masonry and porous stone, which hydrate and infiltrate during infrequent rain events causing spalls and fractures</p> <p>Destabilization of wetland or waterlogged sites</p> <p>Loss of stratigraphic integrity due to crack/heave damage in drier soils</p> <p><i>Indicative Impacts on Natural Heritage</i></p> <p>Water stress may inhibit growth or result to disappearance of some vegetation species</p> <p>Loss of stratigraphic integrity due to crack/heave damage in drier soils</p> <p>Soil infertility and increased erosion</p> <p>Challenges to current irrigation practices</p>

Table 2 (continued)

Climate change hazard	Climate index	Abbreviation (units)	Indicative impacts
Frost	Number of days with minimum temperature lower than 0 °C (frost nights)	TN ₀ (days/year)	<i>Indicative Impacts on Cultural Heritage</i> Effects of wet frost on porous materials Damage to foundations due to increased frost heave action Structural damage to roofs Stone/brick freeze–thaw damage <i>Indicative Impacts on Natural Heritage</i> Decline/disappearance of vegetation species susceptible to frost heaving
Sea level rise	Sea level rise	SLR (m)	<i>Indicative Impacts on Cultural Heritage</i> Flood damage or total submergence of coastal sites and artefacts/structures Increased erosion of sites due to encroaching water levels, wave action Deterioration/corrosion/rusting of artefacts, materials (e.g. porous materials/iron) and infrastructure due to salt water intrusion and increased wet/dry cycles exposure Damage to or overwhelming of drainage systems, leading to associated building damage Damage to or loss of historic buildings and districts (e.g. cracking, destabilization) and associated infrastructure <i>Indicative Impacts on Natural Heritage</i> Disturbance/exposure/burial due to stronger wave action Damages to underground archaeology <i>Indicative Impacts on Natural Heritage</i> Decline/disappearance of some species Soil infertility due to waterlogged, anaerobic conditions Erosion of coastal sites and landscapes Soil infertility from soil erosion and saltwater intrusion, loss of topsoil, released contaminants

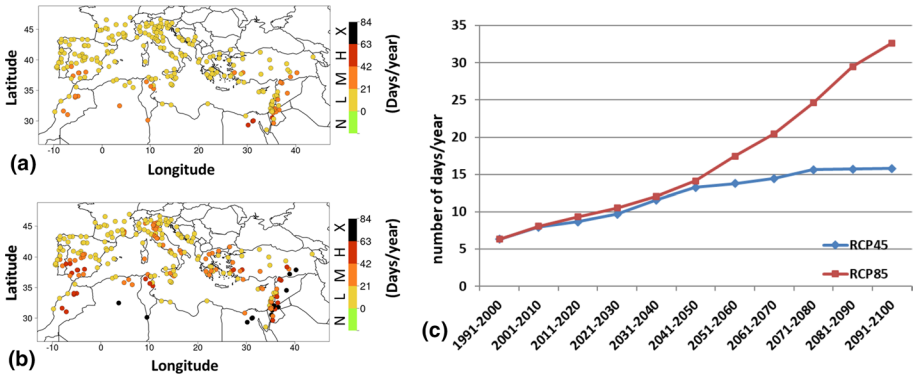


Fig. 1 Difference between the number of days per year with max air temperature > 37 °C from the reference 30-year period (1971–2000) to the future period 2071–2100 based on 21 regional climate simulations under two IPCC emission scenarios RCP4.5 (a) and RCP8.5 (b). A five-class colour scale runs parallel to the linear scale to characterize each group from no threat (N), low (L), moderate (M), high (H) up to extreme threat (X) from man-made climate change at each UNESCO site. c To the right shows the time series of decadal mean number of days with Tmax > 37 °C, averaged over all UNESCO sites under the two emission scenarios throughout the period 1991–2100

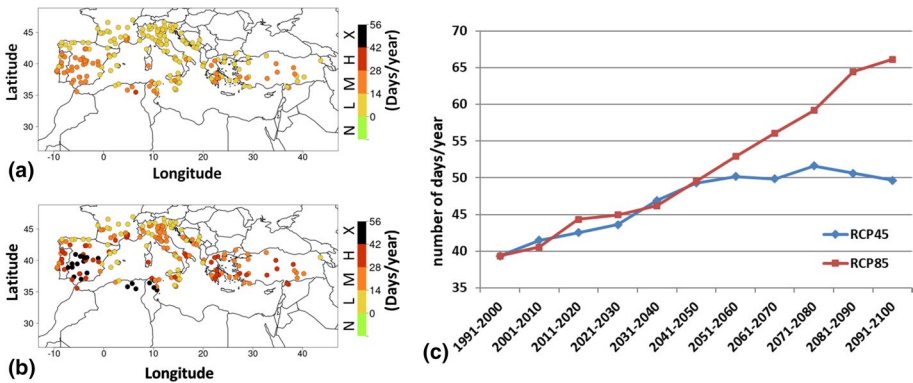


Fig. 2 Difference between the number of days per year with FWI > 45 during the reference 30-year period (1971–2000) and the future period 2071–2100 based on 21 regional climate simulations under two IPCC emission scenarios RCP4.5 (a) and RCP8.5 (b). A five-class colour scale runs parallel to the linear scale to characterize each group from no threat (N), low (L), moderate (M), high (H) up to extreme threat (X) from man-made climate change at each UNESCO site. c To the right shows the time series of decadal mean number of days with FWI > 45, averaged over all UNESCO sites under the same emission scenarios throughout the period 1991–2100

care of local environmental characteristics at each site such as elevation, geographical position, proximity to coast and/or to forest vegetation. The detailed description of the calculation methodology for these indices is provided in Appendix I. The grouping of hazards in five major categories allows an illustrative depiction for the geographical distribution of each hazard intensity and at the same time it provides a quantitative approach to produce an overall index as the sum of all six hazards. As shown in Fig. 8, the total hazard index from climate change is combined with a five-group scale

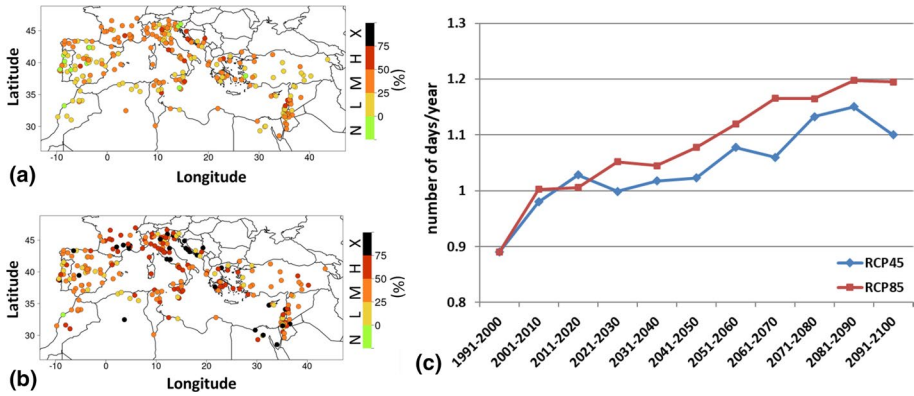


Fig. 3 Difference between the days per year with extreme precipitation during the reference 30-year period (1971–2000) and the future period 2071–2100 (in % of present (reference) period mean values) based on 21 regional climate simulations under two IPCC emission scenarios RCP4.5 (a) and RCP8.5 (b). A five-class colour scale runs parallel to the linear scale to characterize each group from no threat (N), low (L), moderate (M), high (H) up to extreme threat (X) from man-made climate change at each UNESCO site. c To the right shows the time series of decadal mean number of days with extreme precipitation, averaged over all UNESCO sites under the same emission scenarios throughout the period 1991–2100

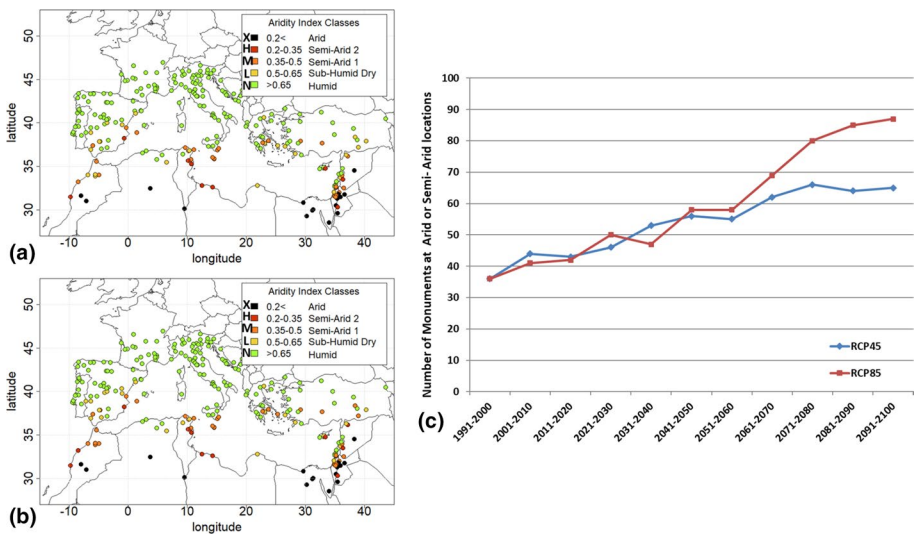


Fig. 4 Aridity index based on 21 regional climate simulations during the future period 2071–2100 under two IPCC emission scenarios RCP4.5 (a) and RCP8.5 (b). c To the right shows the time series of the number of threatened monuments per decade at Arid or Semi-Arid Locations under the same emission scenarios throughout the period 1991–2100

of seismicity hazard at each UNESCO site as described in the next paragraph. Finally, we propose a synergistic-combined heritage hazard index (HHI) to estimate the total threat from both man-made climate change and seismicity at each given site.

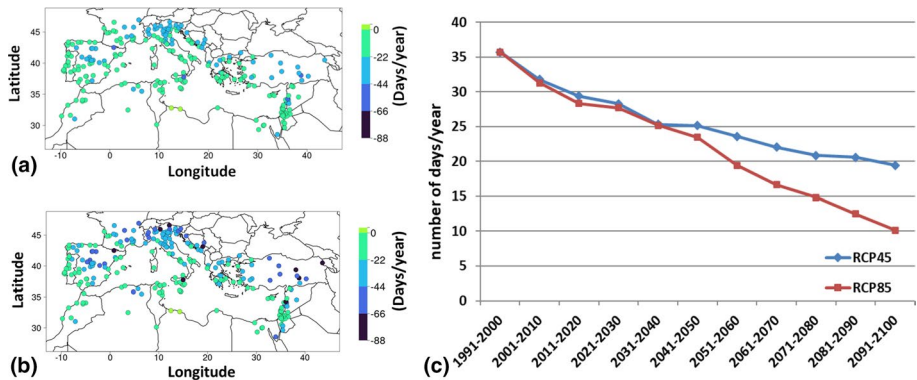


Fig. 5 Difference between the number of days per year with min air temperature below zero ($^{\circ}\text{C}$) from the reference 30-year period (1971–2000) to the future period 2071–2100 based on 21 regional climate simulations under two IPCC emission scenarios RCP4.5 (a) and RCP8.5 (b). c To the right shows the time series of decadal mean number of days with $T_{min} < 0$ $^{\circ}\text{C}$, averaged over all UNESCO sites under the same emission scenarios throughout the period 1991–2100

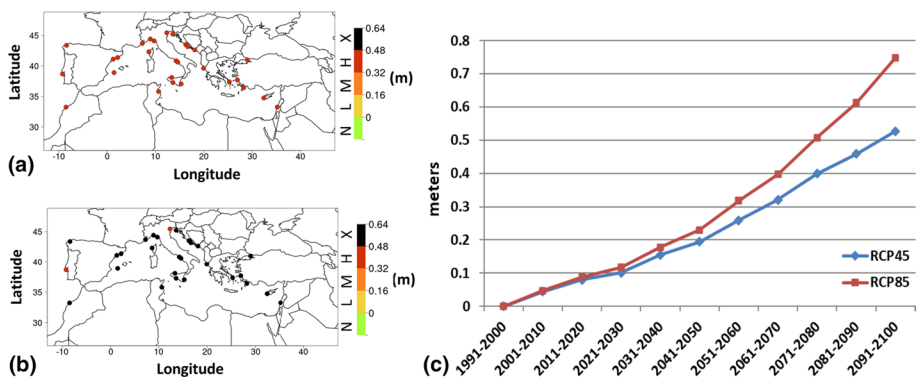


Fig. 6 Mean sea level rise from the reference 30-year period (1971–2000) to the future period 2071–2100, under two IPCC emission scenarios RCP4.5 (a) and RCP8.5 (b). A five-class colour scale runs parallel to the linear scale to characterize each group from no threat (N), low (L), moderate (M), high (H) up to extreme threat (X) from man-made climate change at each UNESCO site. c To the right shows the time series of decadal mean sea level rise averaged over all coastal Mediterranean UNESCO heritage sites under the same emission scenarios during the period 1991–2100

3 Results and discussion

In the following, we present the changes in various hazard indices that is expected to occur at the UNESCO sites due to man-made global warming. Figure 1 presents the number of hot days (TX_{37}). The change in TX_{37} between 1971–2000 and 2071–2100 is positive in all Mediterranean UNESCO sites and for both IPCC emission scenarios (Fig. 1, left). The increase at TX_{37} is quite strong, exceeding in some locations 50 days per year in the RCP8.5 scenario and 40 days per year in the RCP4.5, and it is higher in the south and at sites located far from the coast. The increase in TX_{37} is stronger in the RCP8.5 (Fig. 1, lower left) scenario than in the RCP4.5 (Fig. 1, upper left). The average TX_{37} for

all locations of the UNESCO heritage sites (Fig. 1, right) is shown to increase from about 6.5 days per year in the decade 1991–2000 to 14–15 days per year in 2041–2050 for both scenarios. After that decade, the rate of increase is marginal for the RCP4.5 (blue line) reaching 16 days per year in 2071–2080 and remaining steady after that decade. For the RCP8.5 scenario, the increase is stronger in the second half of the twenty-first century reaching 32 days per year in 2100. It should be noted that in warm and dry regions, such as the Mediterranean, there is a high risk of chemical degradation of the materials in the cultural sites (ICOMOS, 2019) which could be exacerbated due to climate change.

The number of days with extreme fire risk (FWI_{45}) is shown in Fig. 2. Sites that correspond to desert conditions have been excluded in this analysis. FWI_{45} is increased in the future period 2071–2100 for both scenarios relative to the reference period 1971–2000 (Fig. 2, left). An obvious dependence on latitude is evident in Fig. 2, with the highest FWI_{45} changes found in the southern sites, particularly in central and southern Spain and the north-western coast of Africa, with 50 more days with extreme fire risk for the RCP8.5 scenario and 30 more days for the RCP4.5. The average FWI_{45} over all sites (Fig. 2, right) is shown to generally increase in the twenty-first century for the RCP8.5 scenario. In 1991–2000, the average FWI_{45} is about 36 days per year and under the RCP4.5 scenario the increase is clear until the year 2050, when it exceeds 45 days per year, while in the second half of the twenty-first century it remains mostly constant with time. In the RCP8.5 scenario, the increase continues after the year 2050 at a steady rate reaching about 62 days per decade by the year 2100. The results of this study are in agreement with Sabbioni et al. (2010) predicting an increase in cultural heritage exposure to fire in the Iberian Peninsula.

Figure 3 shows the number of extreme precipitation days (PR_{99}) during the decades from 1991–2000 to 2091–2100. In most sites, PR_{99} is expected to increase in the future period, 2071–2100, for both scenarios, more strongly in the RCP8.5 scenario than in the RCP4.5 (Fig. 3, left). The spatial variability is rather remarkable. PR_{99} is more pronounced in France, Italy and most of the Adriatic coast where it ranges between 30 and 60% in most of the sites for the RCP4.5 scenario and between 40 and 80% for the RCP8.5. The average PR_{99} for all UNESCO sites (Fig. 3, right) is shown to generally increase throughout the twenty-first century although with fluctuations in the time series of its decadal values. The average value of PR_{99} is about 9 days per decade in 1991–2000 increasing to about 12 days per decade in the RCP8.5 scenario. These results may suggest increased risk of material degradation, of pluvial or fluvial flooding (about 100 heritage sites are located within a distance of 3 km from fluvial water systems, although generally a few of them are at a low elevation) and of landslides (depending on the topography).

The aridity index (AI) for the future period according to the two scenarios is presented in Fig. 4a and b. To the south of 40 °C, several sites are projected to become drier in the future, due to the northward expansion of the desert zone. In the northern regions, only a few sites become drier, but overall, the change is less pronounced, and the projected future conditions do not favour aridity. The changes are stronger in the RCP8.5 scenario than in the RCP4.5 in all the regions of the study. By the end of the twenty-first century, many sites, most notably in the Mediterranean south of the 40°N parallel, will experience arid or semi-arid conditions. Figure 4c shows the increasing number of monuments located at arid or semi-arid areas in the decades to come. That number of monuments at threat becomes more than double by the end of the twenty-first century. These results suggest possible loss in the effectiveness of water systems and structures, damage or loss of forests and cultural landscapes, and damage to built structures due to cracking or splitting (ICOMOS, 2019). However, the future drier conditions indicate reduced corrosion of metals in south Europe (Grøntoft, 2011; Sabbioni et al., 2010; Sesana et al., 2021). Also, a future reduction in

the risk of some type of biological degradation may be expected (e.g. lower risk for fungal growth, decrease in lichen species richness) (Ariño et al., 2010; Sabbioni et al., 2010; Sesana et al., 2021).

The number of frost nights (TN_0) is projected to decrease in 2071–2100 relative to 1971–2000 (Fig. 5, left) in all UNESCO Mediterranean heritage sites and for both emission scenarios. The decrease is stronger in the RCP8.5 scenario (Fig. 5, left lower), exceeding -50 days per year in several sites in the Alps and the Pyrenees as well as in the highlands of central Spain and central and eastern Turkey, than in the RCP4.5 (Fig. 5, left upper), reaching up to -35 days per year in a few sites in the same regions. The decrease is most prominent far from the coast, in the high altitudes and in the north. Near the coastline, in low altitudes and in the south the change is negligible. The average TN_0 for all locations of the UNESCO heritage sites in the study area (Fig. 5, right) is projected to decrease from about 36 days per year at the end of the twentieth century to 20 days per year in the RCP4.5 Scenario (blue line) and to 10 days per year in the RCP8.5 Scenario (red line) at the end of the twenty-first century. The reduction is almost identical in the two scenarios until the year 2040 (about 12 days per year) after which the decrease in the RCP4.5 scenario decelerates, whereas in the RCP8.5 the rate of decrease remains steady. These results are indicative of a significant decrease in frost damage, which has been discussed in Sesana et al. (2021) for archaeological sites and historical buildings in Europe but for the far north. However, a possible increase in the population of certain pests due to lack of killing freeze, may represent a negative impact of climate change.

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The sea level rise (SLR) for the coastal UNESCO heritage sites is shown in Fig. 6. A rise in the sea level is projected at all sites and for both scenarios (Fig. 6, left). For the RCP4.5 scenario (Fig. 6, upper left) the rise from the reference period, 1971–2000, to the future period 2071–2100 ranges between 0.3 and 0.55 m and for the RCP8.5 (Fig. 6, lower left) between 0.45 and 0.75 m. The strongest sea level rise is projected for the northern sites of the Atlantic coast in both scenarios, while significant values are also evident at the Aegean Sea, the Adriatic coastline and the Gulfs of Genoa and Venice. The time series of the decadal average sea level change for all Mediterranean UNESCO sites (right) indicates a relatively smooth and monotonous increase for both scenarios. In the RCP4.5 scenario, the average sea level rise for all sites increases up to 0.2 m until 2041–2050, reaching up

Fig. 7 Seismic hazard index (SHaz) in terms of the expected peak ground acceleration (PGA, based on Danciu et al., 2021) at all southern European and Turkey UNESCO Heritage Sites (see text for explanation of the proposed index shown on a colour scale to the right)

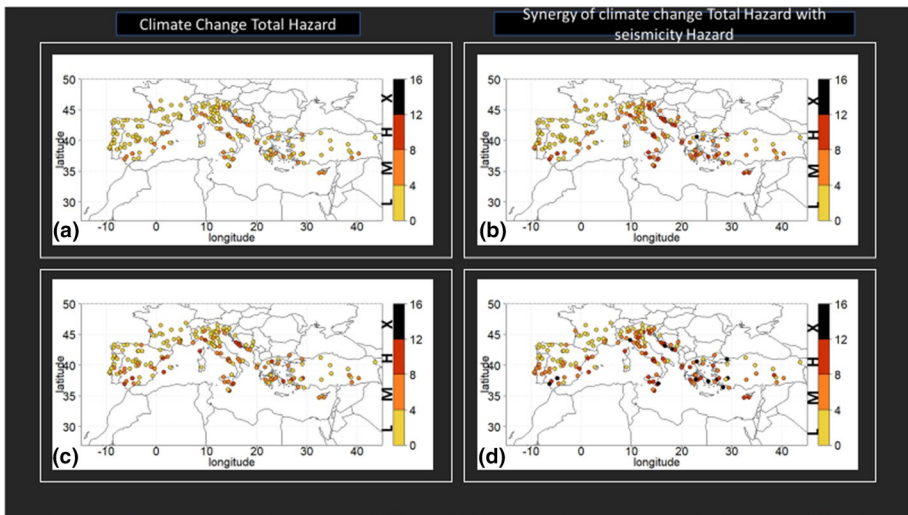
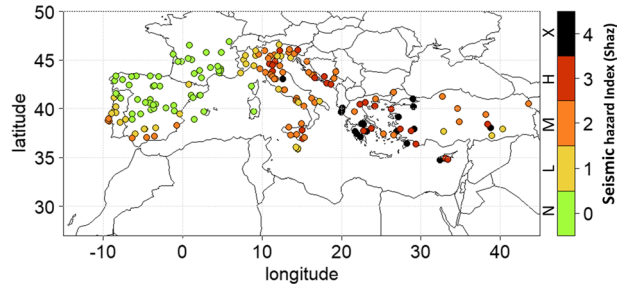


Fig. 8 The climate change total hazard (left) under the two IPCC emission scenarios RCP4.5 (a) and RCP8.5 (b). c and d show the synergy of climate change total hazard to the left with the seismicity hazard. A five-class colour scale runs parallel to the linear scale to characterize each group from no threat (N), low (L), moderate (M), high (H) up to extreme threat (X) from man-made climate change at each UNESCO site. At sites vulnerable to seismicity the total climate hazard is enhanced (see examples in Fig. 10)

to 0.5 m by 2091–2100. In the RCP8.5 scenario, the increase rate of the average sea level rise is accelerating throughout the twenty-first century and by 2091–2100 the rise exceeds 0.7 m.

Figure 7 presents the seismic hazard (SHAZ) in terms of the expected peak ground acceleration (PGA) at the UNESCO Heritage Sites, as it was extracted from the most updated ESHM20 model (Danciu et al., 2021). A maximum PGA value in “g” was extracted for each site from the ESHM20 model using web services and python scripting (<http://efehrcms.ethz.ch/en/web-services/>). It represents the arithmetic mean PGA value expected at the selected site, with probability of exceedance 0.2103% in one year for an average time return period of 476 years. The site is assumed on rock soil characterized with $V_{s30}=800$ m/s². An index scale of five categories was assigned for the extracted PGA values as: level 0 – $PGA \leq 0.05$ g, level 1 – $0.05 < PGA \leq 0.10$ g, level 2 $0.10 < PGA \leq 0.2$ g, level 3 $0.2 < PGA \leq 0.35$ g and level 4 $PGA > 0.35$ g. It is important to note that Italy, Greece and Turkey are characterized in general by high earthquake

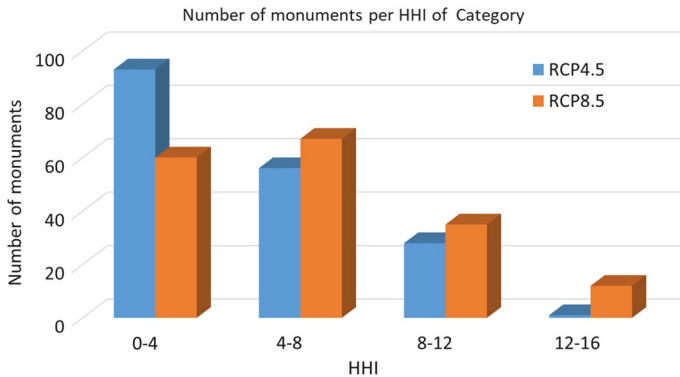


Fig. 9 Number of UNESCO sites under four classes of Hazards ranked from low (0–4), to moderate (4–8), to high (8–12) and to extreme Hazard based on HHI under the two IPCC emission scenarios RCP4.5 (blue) and RCP8.5 (orange)

hazard as clearly shown in Fig. 7, which is a result from our general approach to demonstrate the seismic hazard on all selected sites.

Figure 8 presents the climate change total hazard (CCTHaz, to the left) under the two IPCC emission scenarios RCP4.5 (a) and RCP8.5 (b). Figure 8c and d shows the synergy of climate change total hazard combined with the seismic hazard. This is done through the equation²:

$$\text{HHI} = \text{CCTHaz} + \sqrt{(\text{CCTHaz}) \times (\text{SHaz})} \quad (5)$$

A five-class colour scale runs parallel to the linear scale to characterize each group from no threat (N), low (L), moderate (M), high (H) up to extreme threat (X) from man-made climate change at each UNESCO site.

As we can see from Fig. 8, under the RCP4.5 scenario, the majority of heritage sites are under low or moderate climate change hazard (Fig. 8, a). The sites that are at higher hazard are mostly at coastal areas. The risk increases considerably under the RCP8.5 scenario at all heritage sites studies (Fig. 8, b). This is more evident for the monuments located in the southern European countries where the fire risk is more enhanced considering also the desert landscape of the North African coastal countries. To the right of Fig. 8 is shown the amplification of climate hazard at places which are vulnerable also to seismic hazard (Fig. 8c and d). The above results are indicative of a comparatively higher total risk at the heritage sites located in countries at the centre and east of southern Europe (Italy, Greece, Dalmatia, western Turkey and Cyprus).

Figure 9 presents the number of UNESCO sites under four classes of hazards ranked from low (0–4), to moderate (4–8), to high (8–12) and to extreme hazard, based on HHI under the two IPCC emission scenarios RCP4.5 (blue) and RCP8.5 (orange). For the worst-case scenario (RCP8.5), 35 monument sites fall within the “high hazard” and 12 sites fall under the category “extreme hazard”. Figure 10 shows examples of decadal enhancement of synergistic hazard when combining the Climate Change Hazard

² See also Appendix.



Fig. 10 Examples of decadal enhancement of synergistic hazard when combining the climate change total hazard (left column) with the seismic hazard. The synergy hazard is shown in the right column at 5 selected vulnerable UNESCO sites in the MED under two emissions scenarios RCP4.5 (blue) and RCP8.5 (orange). Dot lines correspond show the hazard indices averaged over all UNESCO sites in the MED

(left column) with the seismic hazard. The synergy hazard is shown in the right column at five selected vulnerable UNESCO sites in the MED under two emissions scenarios RCP4.5 (blue) and RCP8.5 (orange). Dot lines correspond to the hazard indices averaged over all UNESCO sites in the MED.

4 Conclusions

A set of six climate-based indices and seismicity data are proposed together with a methodology to assess the hazard from the synergy of extreme weather in the future climate with or without seismic activity at 244 UNESCO cultural and natural heritage sites in the Mediterranean. The climate indices were calculated based on the results of an ensemble of 21 climate simulations for the period 1971–2100 according to two IPCC emission scenarios, namely the RCP4.5 and RCP8.5.

From these calculations, it appears that the climate hazards are expected to be enhanced in the future climate with negative impacts in locations where natural and cultural heritage exist. The main findings can be summarized as follows:

- Hot days are projected to increase under both emission scenarios, exceeding in some heritage sites 40 days per year under RCP4.5 and reaching up to 50 days per year under RCP8.5 scenarios. The largest increases are expected in the south and at sites distant from the coast.
- Extreme fire weather risk days will increase especially in central and southern Spain and in the north-western coast of Africa by 30 days per year (under RCP4.5) and 50 days per year (under RCP8.5). The average FWI₄₅ over most heritage sites is shown to increase as we move to the end of the twenty-first century.
- Days with extreme precipitation are projected to increase in most sites in the future period, 2071–2100, under both emission scenarios. The spatial variability of the changes is rather large; however, significant increases are more pronounced in France, Italy and in most of the Adriatic coast.
- By the end of the twenty-first century, under the RCP8.5 scenario, most heritage sites in the Mediterranean south of the 40°N parallel will experience arid or semi-arid conditions. The number of monument sites at threat doubles by the end of the twenty-first century.
- Frost nights are expected to severely decrease at all sites resulting to a general decrease in the frost damage for cultural heritage. Negative impacts are expected at natural heritage sites.
- Sea level is projected to rise between the reference period, 1971–2000, and the future period, 2071–2100, by 0.3–0.55 m under the RCP4.5 scenario and by 0.45–0.75 m under the RCP8.5. The strongest sea level rise is projected for the northern sites of the Atlantic coast in both scenarios, while significant increases are evident at the Aegean Sea, the Adriatic coastline and the Gulfs of Genoa and Venice.
- The seismic hazard in the northern Mediterranean sites was estimated from the peak ground acceleration (PGA) at the UNESCO Heritage Sites, as it was extracted from the most updated ESHM20 model (Danciu et al., 2021). It is important to note here that Italy, Greece and Turkey, are characterized in general by high earthquake hazard.
- The estimated man-made climate change hazard (i.e. the sum of all climate change hazards) in synergy with the seismic hazard magnifies the intensity of the threat. The sites that are at higher hazard are mostly at coastal areas. The hazard increases considerably under the RCP8.5 scenario at all heritage sites. This is more evident for the monuments located in the southern European countries such as Italy, Greece, Dalmatian coast, western Turkey and Cyprus.

- In ranking of threats, the number of monuments threatened by earthquakes represents 23% of the total, followed by about 20% of the monuments threatened by aridity and extreme precipitation (for the RCP8.5 scenario).
- Based on the HHI, for the worst-case scenario (RCP8.5) 35 monument sites fall within the “high hazard” and 12 sites fall under the category “extreme hazard”.

From the previous discussion, it has been shown that the majority of UNESCO cultural and natural heritage sites in the Mediterranean will be increasingly threatened by man-made climate hazards. In this context, it is important to act proactively and design specific strategies for the adaptation of cultural and natural sites to climate change (Sesana et al., 2018). 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. In this work, three types of indices have been proposed to describe individual climate hazards and the synergy of climate hazards with seismicity at each site. Under this view, the proposed indices depict climate change hazards on heritage and need to be considered as general but at the same time need to be customized at each cultural or natural site. Future work will include the customization of HHI at nine heritage sites to be defined by the nine Mediterranean countries (i.e. Croatia, Cyprus, France, Greece, Italy, Malta, Portugal, Slovenia and Spain) in an already declared collaboration in the framework of the 8th Summit of the Southern Countries of the European Union (EU MED 9) that was held in Athens, Greece, on 17 September 2021.

Appendix

Heritage hazard assessment methodology: a proposed heritage hazard index

A heritage hazard index (HHI) is introduced in the current paper to estimate the cultural and natural heritage synergistic hazard because of weather extremes and disasters as a result of climate change, and geological hazards (more specifically earthquakes). For this reason, specific data for each World Heritage Site have been collected based on information provided in the UNESCO web site (<https://whc.unesco.org/en/list/>), on the results of the 21 regional climate models ensemble and on the seismic hazard at the location of the 244 Mediterranean heritage sites. The data are presented in Supplementary to the paper and Appendix Excel file TableS1.xls and refer to the following:

- (1) Geographic information (Latitude, Longitude, Elevation, Country),
- (2) Heritage categorization (Cultural (C), Natural (N), Mixed (C/N)),
- (3) Geographic characteristics (Approximate distance from coast, Proximity to coast (yes if distance less than or equal to 3 km, no if distance greater than 3 km), Proximity to forest or other dense vegetation (yes if distance less than or equal to 1 km, no if distance greater than 1 km)),
- (4) Changes in the extreme climate indices relevant to the reference period (1971–2000) and the future period (2071–2100) under scenarios RCP4.5 and RCP8.5. More specifically,
 - Change in the number of extreme hot days (TX_{37}) between the future and reference periods (see also Fig. 1),

Table 3 Values of the extreme heat hazard sub-index according to the future relative change in TX_{37}

Relative change in TX_{37} (%)	Value of EHHaz	Qualitative characterization of EHHaz
Zero/negative TX_{37} relative change	0	No
$0 < \text{Relative change in } TX_{37} \leq +25$	1	Low
$+25 < \text{Relative change in } TX_{37} \leq +50$	2	Moderate
$+50 < \text{Relative change in } TX_{37} \leq +75$	3	High
$+75 < \text{Relative change in } TX_{37} \leq +100$	4	Extreme

Table 4 Values of the wildfires hazard sub-index according to the proximity to forest or other dense vegetation criteria set and the future relative change in FWI_{45}

Relative change in FWI_{45} (%)	Value of WFHaz	Qualitative characterization of WFHaz
Heritage not satisfying the proximity to vegetation criteria or zero/negative FWI_{45} relative change	0	No
$0 < \text{Relative change in } FWI_{45} \leq +25$	1	Low
$+25 < \text{Relative change in } FWI_{45} \leq +50$	2	Moderate
$+50 < \text{Relative change in } FWI_{45} \leq +75$	3	High
$+75 < \text{Relative change in } FWI_{45} \leq +100$	4	Extreme

- Change in the number of days with extreme forest fire risk (FWI_{45}) between the future and reference periods (see also Fig. 2),
 - Change in the number of days with extreme precipitation (PR_{99}) between the future and reference periods (see also Fig. 3),
 - Aridity index value for the future period (see also Fig. 4),
 - Change in the number of frost nights (TN_0) between the future and reference periods (see also Fig. 5),
 - Sea level rise (SLR) (see also Fig. 6).
- (5) Geophysical data, more specifically the peak ground acceleration (see also Fig. 7).

A hazard sub-index is assigned to each of the above-mentioned climate change hazards and associated indices, in addition to the seismic hazard index, according to the following description. The values of each climate change hazard sub-index and their sum and the values of seismic hazard index for each site are provided in Supplementary to the paper and this Appendix Excel file TableS1.xls for both RCP4.5 and RCP8.5 scenarios.

1. Extreme Heat Hazard Sub-index (EHHaz)

The values of the sub-index are presented in Table 3 and are dependent on the future relative change in TX_{37} estimated as a percentage of the future maximum change in TX_{37} over all studied sites.

2. Wildfires Hazard Sub-index (WFHaz)

Table 5 Values of the extreme precipitation hazard sub-index according to the future change in PR₉₉

Change in PR ₉₉ (%)	Value of EPHaz	Qualitative characterization of EPHaz
Change in PR ₉₉ ≤ 0	0	No
0 < Change in PR ₉₉ ≤ +25	1	Low
+25 < Change in PR ₉₉ ≤ +50	2	Moderate
+50 < Change in PR ₉₉ ≤ +75	3	High
+75 < Change in PR ₉₉	4	Extreme

Table 6 Values of the aridity hazard sub-index according to the aridity characterization in the future

AI characterization	Value of AHaz	Qualitative characterization of AHaz
Heritage that remains or become Humid (AI > 0.65)	0	No
Heritage that remains or become Sub-humid dry (0.5 < AI ≤ 0.65)	1	Low
Heritage that remains or become Semi-arid category 1 (0.35 < AI ≤ 0.5)	2	Moderate
Heritage that remains or become Semi-arid category 2 (0.2 < AI ≤ 0.35)	3	High
Heritage that remains or become Arid (0.06 < AI ≤ 0.2)	4	Extreme

Table 7 Values of the frost hazard sub-index according to the future relative change in TN₀

Relative change in TN ₀ (%)	Value of FHaz	Qualitative characterization of FHaz*
Zero TN ₀ relative change	0	No
0 < Relative change in TN ₀ ≤ -25	-1	Low
-25 < Relative change in TN ₀ ≤ -50	-2	Moderate
-50 < Relative change in TN ₀ ≤ -75	-3	High
-75 < Relative change in TN ₀ ≤ -100	-4	Extreme

*The characterization refers to hazard reduction

The hazard refers to sites characterized by a proximity to forest or other dense vegetation (i.e. distance less or equal to 1 km). The future relative change in FWI₄₅ is estimated as a percentage of the future maximum change in FWI₄₅ over all studied sites. The values of the sub-index are presented in Table 4.

3. *Extreme precipitation hazard sub-index (EPHaz)*

The hazard refers to extreme precipitation increases. The future change in PR₉₉ is estimated as a percentage of the reference period PR99. The values of the sub-index are presented in Table 5.

4. *Aridity hazard sub-index (AHaz)*

The values of the sub-index are presented in Table 6.

5. *Frost hazard sub-index (FHaz)*

Table 8 Values of the coastal flooding hazard sub-index according to the proximity to coast and elevation criteria set and the future relative SLR

Relative SLR (%)	Value of CFHaz	Qualitative characterization of CFHaz
Heritage not satisfying the proximity to coast and elevation criteria or sea level decrease/no change	0	No
$0 < \text{Relative SLR} \leq +25$	1	Low
$+25 < \text{Relative SLR} \leq +50$	2	Moderate
$+50 < \text{Relative SLR} \leq +75$	3	High
$+75 < \text{Relative SLR} \leq +100$	4	Extreme

Table 9 Values of the seismic hazard index according to the extracted peak ground acceleration (PGA) using the ESHM20 model

PGA (in g)	Value of SHaz	Qualitative characterization of SHaz
$0 < \text{PGA} \leq 0.05$ g	0	No
$0.05 \text{ g} < \text{PGA} \leq 0.1$ g	1	Low
$0.1 \text{ g} < \text{PGA} \leq 0.2$ g	2	Moderate
$0.2 \text{ g} < \text{PGA} \leq 0.35$ g	3	High
$\text{PGA} > 0.35$ g	4	Extreme

The values of the sub-index are presented in Table 7 and are dependent on the future relative change in TN_0 estimated as a percentage of the future maximum change in TN_0 over all studied sites.

6. Coastal flooding hazard sub-index (CFHaz)

The hazard refers to sites characterized by a proximity to coast (i.e. distance less or equal to 3 km) and an elevation less or equal to 20 m. The future relative SLR is estimated as a percentage of the future maximum SLR over all studied sites. The values of the sub-index are presented in Table 8.

7. Seismic hazard index (SHaz)

The index SHaz refers to the seismic hazard estimated at each southern European and Turkish site and remains constant with time. A maximum PGA value (in “g”, i.e. gravitational acceleration) was extracted for each site from the ESHM20 model using web services and python scripting (<http://efehrcms.ethz.ch/en/web-services/>). It represents the arithmetic mean PGA value expected at the selected site, with probability of exceedance 0.2103% in one year for time mean return period of 476 years. The site is assumed on rock soil characterized with $V_{s30} = 800 \text{ m/s}^2$. An index scale of five categories was assigned for the extracted PGA values as described in Table 9.

HHI is defined to consider the man-made climate change hazards and the seismic hazard (SHaz) at the location of each cultural and natural heritage site. The HHI value is calculated according to the following Eq. (6):

$$\text{HHI} = \text{CCTHaz} + \sqrt{(\text{CCTHaz}) \times (\text{SHaz})} \quad (6)$$

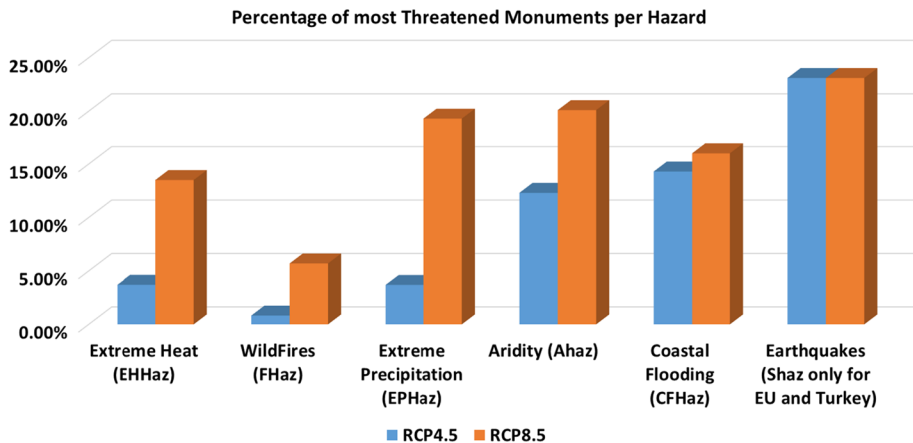


Fig. 11 Percentage of sites characterized by “high” and “extreme” hazard by each threat for the RCP4.5 and RCP8.5 emission scenarios

where $CCTHaz = \Sigma[Climate\ Change\ Hazards\ Sub-indices]$ (the man-made climate change hazards are the extreme heat, wildfires, extreme precipitation, aridity, frost and coastal flooding).

Supplementary Excel file TableS1.xls includes for each site in southern Europe and Turkey the values of the heritage hazard index (HHI) for both RCP4.5 and RCP8.5 scenarios.

Figure 11 shows the percentage of sites characterized by “high” and “extreme” hazard by each climate change threat for the RCP4.5 and RCP8.5 emission scenarios. About one quarter of the sites in South Europe and Turkey are characterized by significant seismic hazard. Under RCP4.5 scenario, the coastal flooding and aridity are important hazards for 14 and 12% of the sites in the Mediterranean area, respectively. In the case of RCP8.5 scenario, apart from aridity, extreme precipitation should be considered as a significant hazard for many sites in the Mediterranean area (20% for aridity and 19% for extreme precipitation). Coastal flooding is estimated to be high or extreme hazard for 16% of the sites.

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