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RESEARCH

Applied climatology for heritage

Peter Brimblecombe[1,2] · **Jenny Richards**[3,4]

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Abstract
The protection of heritage from a changing climate has been of increasing interest over the last few decades, which creates a need for a systematic approach to the impacts of climate on tangible and intangible heritage. We present heritage climatology as an applied, interdisciplinary field of science that examines aspects of climate that affect heritage and provides data, statistics, well-tuned climate parameters and projections that can aid interpreting past changes and future management of heritage. It must consider the impact of extreme events, cyclic processes and the gradual accumulation of damage. Climate threats to heritage need to be represented at the appropriate temporal and spatial scales, and transferred using dose–response functions such that they can be interpreted in terms of management decisions yet be resistant to errors from both the representation of the climate threat and its translation into policy.

1 Introduction

The application of climatology to practical settings is vital for understanding and managing activities that are important to humans. The growth of applied climatology is apparent in a wide range of fields, including aviation (Quantick 2001), agriculture (Hollinger 1994) and the built environment (Bitan 1988), providing operational descriptions and scientific studies of relevant climates. For more than two decades increased concern about the effect of potential changes in climate on heritage (Colette 2013; EC 2022) has been evident from key agencies, such as the UNEP World Heritage Centre or the European Commission.

Heritage is defined by the World Heritage Centre as "…our legacy from the past, what we live with today and what we pass on to future generations. Our cultural and natural heritage are both irreplaceable sources of life and inspiration" [https://whc.unesco.org/en/about/]. While established forms of applied climatology such as urban and building climatology might include many forms of cultural heritage (e.g. historic cities, stately houses), they often represent a narrow set of climate processes that focus on the building, and for example the need to achieve a comfortable environment and ensure energy efficiency (Bitan 1988). This seems insufficient to represent the breadth of the heritage environment that includes rural and urban areas, archaeological sites and modern structures, and at scales from whole landscapes to microclimates in rooms, display cases and painting frames (Loli and Bertolin 2018; Lony et al. 2009). There is a need to engage with a wider set of climate processes to represent the heritage context.

Research interest in heritage protection in the 1980s focussed on the effects of pollution (acid rain) on historic buildings. However, as the levels of aggressive pollutants decreased in major cities there was a shift to studying the effects of a changing climate on material heritage Sabbioni et al. 2008), which have long been noted (Schaffer 1932; Winkler 1966). Research on the effects of climate on heritage was initially fostered by the European Commission through the STEP (Science and Technology for Environmental Protection) projects of the late 1980s (O'Brien et al. 1995) through to Framework Programmes such as Noah's Ark, Climate for Culture (Sabbioni et al 2008; Leissner et al. 2015). The research increasingly highlighted the relationship between climate factors and deteriorative processes, such as salt weathering (McCabe et al. 2013; Grossi et al.

✉ Peter Brimblecombe
p.brimblecombe@uea.ac.uk

Jenny Richards
jennifer.richards@sjc.ox.ac.uk

[1] Department of Marine Environment and Engineering, National Sun Yat-Sen University, Kaohsiung, Taiwan

[2] School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK

[3] John's College, Oxford University, Oxford OX1 3JP, UK

[4] School of Geography and the Environment, Oxford University, Oxford OX1 3QY, UK

2011; Godts et al. 2022), frost damage (Grossi et al. 2007; Richards and Brimblecombe, 2024) and sea level rise (Vousdoukas et al. 2022; Li et al. 2022). Research into the effects of climate, especially climate change, on heritage grew rapidly (Fatorić et al. 2017; Sesana et al. 2021)[20,21]. This has resulted in a large body of work that assesses environmental effects on both tangible and intangible heritage (Higgins 2022; Dembedza et al. 2022; Aktürk et al. 2021), although the latter can seem under-represented (Adger wt al. 2011).

While climate and weather have always interacted with heritage, the rate, magnitude and type of process involved are altered by climate change. Recently, the IPCC (Intergovernmental Panel on Climate Change) has raised public awareness, thus framing climate impacts on heritage in international policy (Pörtner et al. 2022). However, emerging heritage climate research has tended to neglect specific details of the roles played by climate, with ~ 40% of the studies in this subject area not mentioning specific climate drivers and ~ 60% lacking a time scale (Orr et al. 2021). Furthermore, research has typically focussed on weather observations or models of a changing environment, commonly expressed in terms of potential risk rather than representing long-term damage. This means heritage climate research can lack practical applicability and has rarely been able to handle the propagation of errors into management decisions (Richards et al. 2023).

Consequently, it seems both important and timely to explore the relationship between climate and heritage more systematically. A key challenge in examining the climate threat to heritage is establishing relevant climate variables and layout indices that reflect the threat (Giglio et al. 2024). Twenty years ago, the Noah's Ark project realised that climate metrics need to be carefully chosen to represent particular threats imposed on material heritage (Sabbioni et al. 2008). Such ideas evolved into the notion of heritage climatology, which represents specific drivers of damage (Brimblecombe 2010; 2023); a concept that has gradually been more widely adopted (Casati et al. 2015; Heron et al. 2014; Kuchař et al. 2024; Menendez 2018; Sardella et al. 2020; Sass et al. 2022). As changes imposed by a shifting climate relate to the very background upon which our lives play out, it is now time for defining the concept of heritage climatology to make it more readily applicable to a wide range of heritage.

2 Gradual processes and extreme events

Heritage can be affected by a variety of pressures including: (i) one-off or sudden events i.e., impulses such as storm or flood; (ii) longer term processes that may impose cycles of change e.g. daily or seasonal and (iii) cumulative processes where change accrues over time e.g. sand abrasion or water erosion. The effect of these can be amplified through synergies, feedback loops or thresholds, resulting in changes in risk to heritage, even from small changes in climate.

2.1 Impulses and extreme events

The impact of extreme weather events, such as flooding or storms on heritage commonly features in public discourse in their immediate aftermath. Such high-profile events often captivate the public imagination, so can lead to appeals for funding and resources to support work for repair, restoration or future protection. The Florence floods of 1966 drew special attention to the extent of damage to cultural property, and as a result transformed the approach taken to protecting cultural heritage (Conway and Conway 2018). However, extreme events remain a challenge for heritage conservation e.g., there have been numerous floods at other historic sites (Arrighi 2021); in drier regions, sandstorms can be of concern in Africa (Colette 2013) and Asia (Zhang et al. 2022), while in recent years wildfires and lightning strikes have been catastrophic to flammable heritage (Mallinis et al. 2016; Tantra and Brimblecombe, 2022). Furthermore, other extreme events such as fungal growth or insect infestations can be caused by changing environmental conditions (Querner et al. 2022).

2.2 Cyclic processes

Damage to materials can be driven by cyclic processes. These can occur over a range of timescales, including regular daily or annual changes in temperature or humidity. For example, thermal cycles can induce dimensional change in materials, such as metal or stone. When surfaces are exposed to direct sunlight, the surface temperatures of coarse-grained materials such as granite or calcite can reach 75 °C (Al-Omari et al. 2014; Bonazza et al. 2009; Freire-Lista et l. 2016), leading to significant, repeated thermal stress in the material. Organic materials, such as wood or paper, are likely to change dimensions with variations in humidity (Menart ET AL 2011). Over multiple cycles, such changes can cause warping, or where there are multiple layers (e.g. paint on wood) cracking can occur, as the surface layer does not change in the same way as the support (Grøntoft and Stoveland 2023).

2.3 Cumulative processes

Many processes impose damage in a manner that accumulates over time. The dose, D, experienced by heritage can be considered as the product of some intensity related parameter (I), such as concentration or depositing flux, integrated over time (t) perhaps simplified as:

$D = It$

As the accumulation of this dose can be slow, changes can be subtle and pass unnoticed unless specifically monitored. This was evident in exposure to pollutants, where the slow build-up of surface deposits on stone was not noticeable from one day to the next, but over time led to substantial blackening and surface recession (Viles and Gorbushina 2003; Bonazza et al. 2007). Such findings have similarly been found for climate related processes, e.g. the cumulative impact of sediment laden wind resulting in material loss through abrasion (Pineda and Iranzo 2017; Richards et al. 2020).

2.4 Amplification of processes

Small increases in temperature may often be insufficient to cause a substantial change in the rate of damage to materials. However, when these small changes are close to zero, they can cause increases in the number of freeze–thaw cycles (Richards and Brimblecombe 2024). Similarly, small changes in relative humidity can cause large changes in the number of salt weathering cycles, when the shift in relative humidity affects the number of transitions between salt crystals and brines in porous stone (Grossi et al. 2011; Oguchi and Yu 2021). Changes in temperature and humidity can also amplify biological processes, enhancing rates of fungal or lichen growth on buildings (Basu et al. 2020; Cozzolino et al. 2022), or numbers of insects, birds and rodents (Qu et al. 2014; Querner et al. 2022). Thus, subtle changes in environmental conditions can be amplified and present an altered risk of damage. An understanding of both the climate and heritage processes is required if such subtle interactions are to be effectively understood.

3 Heritage climatology

The need for a heritage climatology has been strongly felt for several decades in research projects looking at the long-term climate impacts on outdoor materials and monuments. Classical meteorological descriptions of climate are not sufficient to capture processes of interest to heritage researchers (Sass et al. 2022; Brimblecombe et al. 2006; 2008). As reported as culture under climatic threat, in the *EC Research-Environment Newsletter* of 2007, there was a realisation that "we would have to develop our own cultural heritage climatology" (Brimblecombe 2010). There is now sufficient work to demonstrate how heritage climatology has the potential to be widely applicable in a range of heritage and environmental contexts (Richards and Brimblecombe 2023).

Traditional climate metrics, such as maximum and minimum temperature, total rainfall and average relative humidity, can provide a broad sense of the climate experienced by heritage. However, such metrics rarely represent the specific drivers that are of interest or concern to those managing heritage, which may need to capture the frequency or cumulative total of occurrence, or the number of times when set thresholds have been crossed (Brimblecombe and Richards 2023a). The development of metrics specific to heritage contexts (Fig. 1) can provide a flexible and adaptable approach for evaluating the interactions between heritage and climate, reflecting the diversity of challenges facing heritage and its context. They can be applied to both immovable (sites and buildings) and movable heritage (objects and artefacts), as well as intangible heritage, such as pilgrimage (Brimblecombe et al. 2023) and sport (Brammer et al. 2014; Richards 2024), although parameterisation for such cases is less common.

Heritage climate metrics can combine multiple parameters to provide a single metric that can better represent a threat to heritage (see Fig. 1a) e.g., wind velocity and precipitation can be combined to describe driving rain that can penetrate porous materials. However, heritage climate metrics can be developed to have multiple representations of a given process e.g., frost damage, known to cause weathering to historic materials such as stone and brick, is commonly determined by counting the number of times the temperature crosses the freezing point (Ingham 2005). However, there are other ways to consider representing this threat e.g., deep freezing ($T_{min} < -5$ °C) is also important as it can cause moisture deep within the material to freeze, meaning that damage occurs not only at the surface. Furthermore, frost damage can also be enhanced when rainfall saturates a porous material, which then freezes. Considering these three metrics for frost can provide a more nuanced understanding of damage processes in an area compared with considering only the number of freeze–thaw cycles (Richards and Brimblecombe 2024).

For climate metrics to be relevant to heritage, they need to operate at the appropriate spatial and temporal scales (Richards and Brimblecombe 2023). Sites and objects are typically small compared to the resolution of climate models. This has often led to calls among heritage scientists for data to be produced at fine resolutions (Sardella et al. 2020). High resolution modelling approaches (e.g. computational fluid dynamics[49] can establish the climate of a particular facade or the microclimate of a moulding are at a very hight resolution. In contrast, observations taken from meteorological stations provide data at a specific location, which might be some distance from the heritage. Consequently, it appears useful to install weather stations at heritage sites. In addition, we also require an understanding of processes affecting heritage at regional and global scales to inform strategic

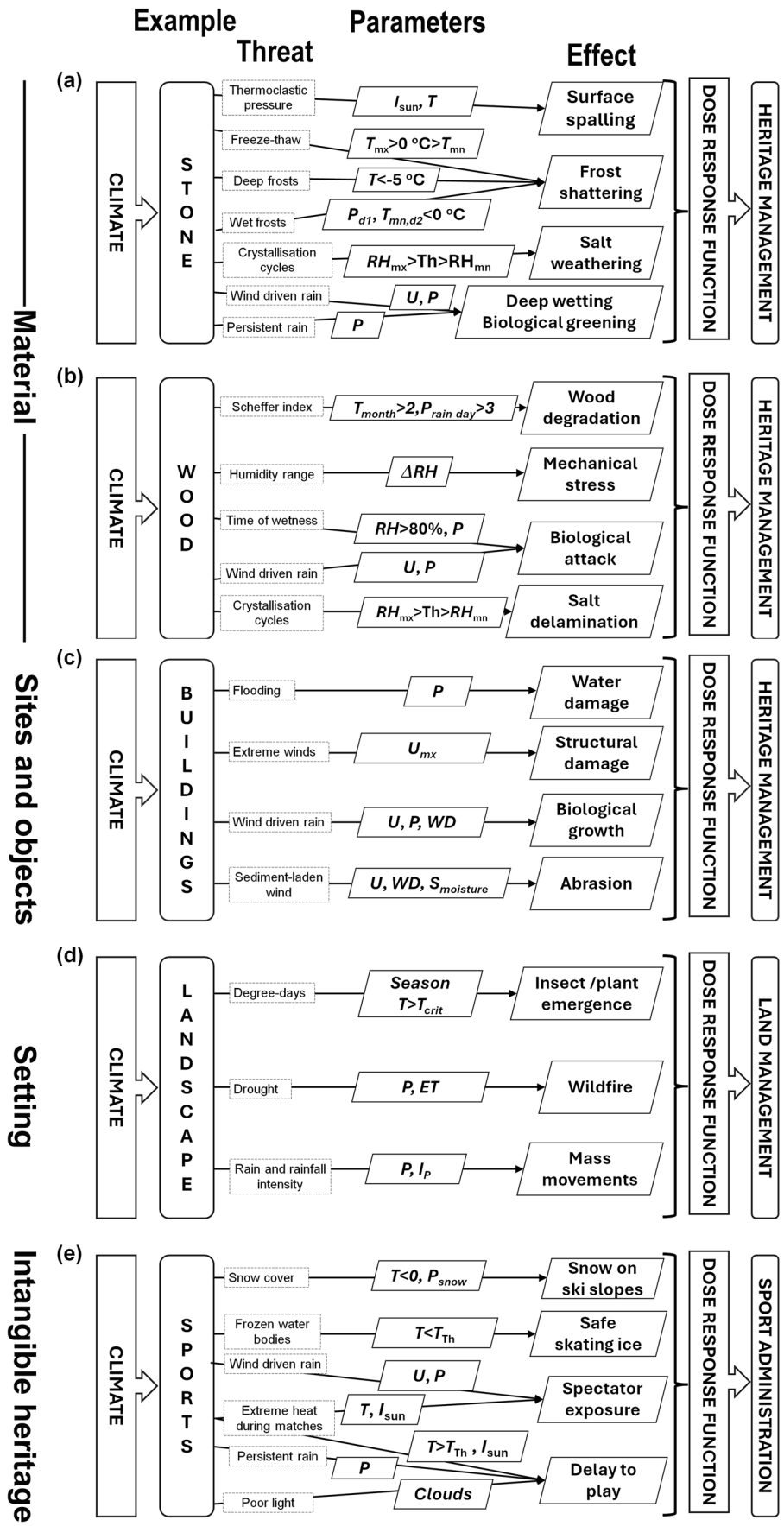


Fig. 1 Examples of types of heritage and the threats they face (**a**) stone as a material, (**b**) wood as a material, (**c**) buildings as an example of a site, (**d**) landscape as a setting, with other examples of settings being indoor galleries or buried archaeology and (**e**) sport as an example of intangible heritage. The parameters are given in more detail in Table 1

Table 1 Details for the threats shown presented as examples in Fig. 1

(a) Stone	
Thermoclastic pressure	occurs through stresses in stone surfaces that typically due to intense solar radiation (I_{sun}) and cool at night (T) is alternately heated and cooled, causing surface spalling [Bonazza er al. 2009]
Freeze–thaw	number of cycles that induce stress as pore water in stone freezes and thaws as minimum temperatures (T_{mn}) move from somewhat below 0 ºC to maximum temperatures (T_{mx}) above 0 ºC [Richards and Brimblecombe 2024]
Deep frosts	as the number of days below -5 °C that account for freezing to penetrate deep into the materials, which captures the "frost cracking window", ~ -3 and -10 °C [Richards and Brimblecombe 2024]
Wet frosts	are taken to occur when it rains ($P_{d1} > 0.2$ mm) on Day 1 followed by Day 2 with minimum temperature ($T_{mn,d2}$) below 0 °C [Richards and Brimblecombe 2024]
Crystallisation cycles	where relative humidity cycles across a relative threshold (Th) characteristic of a particular salt within the stone [Grossi et al. 2011]
Wind driven rain	which drives water deep into porous stone. Typically expressed as a function of precipitation (P) and wind velocity (U)
Persistent rain	which continues over long periods maintaining a wet surface e.g. consider a prolonged period of wetness to be ≥ 4 days of rainfall ≥ 0.2 mm [Brimblecombe and Richards 2023]
(b) Wood	
Scheffer index	which represents the threat to timber with the formula $\Sigma(\mathrm{Tm}-2)(\mathrm{D}-3)/16.7$, with the summation over twelve months with the monthly mean temperature (Tm) and D number of days in the month with ≥ 0.3 mm of rain (D) [Richards and Brimblecombe 2022a]
Humidity range	which is the difference between the maximum and minimum relative humidity (ΔRH) for a given period [Richards and Brimblecombe 2022a]
Time of wetness	which represents the amount of time which the surface is wet and promotes biological growth. It can involve both measures precipitation or relative humidity [Brimblecombe and Richards 2023; Richards and Brimblecombe 2022a]
Wind driven rain	drives water deep into wood and other porous materials. Typically expressed as a function of precipitation (P) and wind velocity (U). A simple formulation takes it as the number of days per year when rain is > 4 mm and mean wind speed is > 2 m s^{-1}[Richards and Brimblecombe 2022a]
Crystallisation cycles	where relative humidity cycles across a relative threshold (Th) for the salt within the wood [Richards and Brimblecombe 2022a]
(c) Buildings	
Flooding	of ground surfaces or rivers driven by large falls of precipitation (P) that may fall at some distance in the case of flooded rivers
Extreme winds	as gusts (U_{mx}) in storms
Wind driven rain	drives water deep into roofs (especially thatching), walls and under eaves of buildings. Typically expressed as a function of precipitation (P) and wind velocity (U). because aspect and orientation of a building may be important, wind direction (WD) can also be a relevant parameter
Sediment-laden wind	drives sand and or other materials against building surfaces causing abrasion and ultimately burying building elements water deep into wood and other porous materials. Typically expressed as a function of precipitation wind velocity (U) and the water content of the surface vegetation cover etc. Aspect and orientation of a building may be important wind direction (WD) can also be a relevant parameter. Water content of the ground can also affect the movement of sediment
(d) Landscape	
Degree-days	calculated as a sum that accumulates only when $T_D > T_{Th}$, T_D being the daily temperature and T_{Th} the threshold temperature for development of an organism. [Brimblecombe and Richards 2023]
Drought	there are many indices to represent drought. For fires the Keetch-Byram Drought Index (KBDI) takes the net effect of evapotranspiration (ET) and precipitation (P) to represent cumulative moisture deficiency in soil layers. The index ranges from zero, such as number of days without rain can affect the frequency of wildfires [Tantra and Brimblecombe 2022]
Rain and rainfall intensity	as large falls of rain in a short time can drive mass movements such as soil loss or landslides
(e) Sport	
Snow cover and depth	is important for skiing, and has considerable commercial relevance with variables such as temperature (T) and precipitation (P_{snow})
Frozen water bodies	are key to achieve the ice depth suitable for skating, so persistent low temperatures are important [Richards 2024]
Wind driven rain	drives water into stadia affecting spectators. Wind driven rain is typically expressed as a function of precipitation (P) and wind velocity (U). As aspect and orientation of a building may be important wind direction (WD) can also be a relevant parameter
Extreme heat	is a problem for spectators and participants in sporting events, with temperature and isolation relevant. Extreme heat policies have been developed for tennis (https://ausopen.com/articles/news/ao-heat-stress-scale-grand-slam-first)
Persistent rain (P)	can affect many sport events by affecting the state of the ground
Poor light	can affect fixtures such as cricket matches and can be a function of cloud cover

decisions. It can be tempting to use pre-existing maps of temperature or precipitation, but these are likely to be of greater relevance if parameters especially tailored to heritage were mapped e.g., the Scheffer index (Fig. 1b), combines temperature and rainfall parameters and can provide assessments of wood-decay risk, both regionally and globally (Richards and Brimblecombe 2022a; Oh et al. 2022).

Heritage researchers also need to consider time scales over which processes operate. The accessibility of data can often mean that only monthly or annual averages are available. However, many heritage processes require data at finer

resolutions (e.g. daily or hourly) if the threat is to be captured (Bienvenido-Huertas et al. 2021; Brimblecombe and Richards 2023a). The use of appropriate time scales is especially important for seasonal processes, as even small shifts of a few days or weeks can have implications for heritage practice and management e.g., in Japan, the Yayoi festival celebrates springtime with floats decorated in cherry blossoms, but the date of the festival is fixed, so artificial flowers have to be used because cherry trees are now blooming earlier (Brimblecombe and Hayashi 2018). Similarly, even small changes in processes can have implications for the timing of maintenance or open seasons at heritage sites that then have to be carefully managed. Heritage climatology requires research to engage more explicitly with such concepts of scale.

4 Heritage management and transfer of knowledge

Heritage climatology, like many branches of applied climatology, seeks to be operational and contribute to management decisions regarding heritage conservation and protection. Tailored climate metrics can aid managers in determining which processes are likely to be important in conservation and thus prioritise resources or conservation strategies e.g., in many temperate regions it is likely that frosts will decline under future climates, so the threat of frost weathering will become less of a concern so other threats may need greater attention. Furthermore, subtle shifts in seasonality captured by a heritage climate approach can be especially important in terms of heritage management given that visitor numbers can be markedly influenced by season (Brimblecombe and Hayashi 2018; Mateusz 2021). Prioritising conservation and maintenance through heritage climatology can focus action on relevant processes in a warming world.

Prioritising conservation and maintenance actions entails managing risk from both extreme and gradual processes. However, their threat profiles are very different. Typically, the risk associated with extreme events is driven by high impact, while gradual processes are driven by occurrence over a longer period of time. Consequently, the management of risk from extreme weather events can be similar to approaches used in managing natural hazards (Bosher 2023), where measures need to be pre-emptive. In contrast, for processes causing gradual change, their on-going nature means that processes can be modified even when damage has begun. Reducing risks to heritage can involve a lowering of the probability that a given event will happen (e.g. forest management to reduce the threat of wildfires) or reducing the extent of damage (e.g. sprinkler systems). Heritage climates further illustrate that the risk from cyclic processes can be reduced by lowering the amplitude of cycles or shifting the baseline (e.g. insulating walls from frost or warming them), while for cumulative exposures it involves reducing the dose (e.g. shading material from sunlight exposure or at least reducing the length of exposure).

Conservation approaches may be easily applied in cases where changing environmental conditions increase a threat that is already apparent albeit at a low level, so knowledge of a response is already part of management protocols. However, protection is more challenging if new processes or new combinations of processes result in: (i) the emergence of new threats; or (ii) the amplification of existing processes beyond levels previously experienced. Heritage climatology provides insight on the risk from processes that are new to a given area (e.g. freeze thaw cycles in once permanently frozen regions), so heritage managers may be able to learn from management strategies employed in other places that have already faced similar threats. For processes that are new for the entire globe (e.g. temperatures at record highs), managers are likely to have to develop novel approaches to manage this change, based on thoughtfully constructed heritage climates.

Nevertheless, heritage managers have reason to be cautious about the output and application of results from climate models and damage functions; they have valuable sites and objects to protect, so they are concerned less about potential threats than their manifestation. There is a tension between academic research and the active decision-making required to protect heritage (Richards and Brimblecombe 2022b) e.g., practitioners are concerned about how errors in the assessment of climate change or dose–response functions may lead to poor conservation decisions. This is a reasonable concern, because although there is a correlation between climate-based parameters and responses in materials, the relationship becomes much weaker when trying to represent the effects of a changing climate. As Vandemeulebroucke et al (2023) argue a climate-based analysis is unable to represent the spread impacts over a range of parameter variations under climate change. It may be that understanding the direction of change, rather than the absolute magnitude of change, could provide a useful starting point for managers to establish plans suitable for addressing a given threat e.g., along the Mediterranean coast of Europe, the Scheffer index for wood decay is likely to decrease (Brimblecombe and Richards 2023b), so heritage managers can reasonably consider this a decreasing problem.

Much heritage management is undertaken over relatively short periods with planning horizons being typically three to perhaps as much as ten years. Therefore, it can be difficult to deal with processes that operate over longer time scales (decades to centuries). Gradual change can mean that (i) heritage threats can be overlooked or

(ii) if conservation policies are implemented, they can be subsequently discontinued as strategic priorities change. However, recent shifts towards sustainable conservation practices within heritage organisations such as English Heritage (EH 2023) show there is momentum within parts of the heritage sector to take a longer-term view. This benefits from the strategic vision offered by heritage climatology.

Successful heritage policy will require a balance of adaptation and mitigation procedures coupled with effective transfer of knowledge between academic disciplines and practice. Climate scientists have been able to disseminate information beyond core academic research groups. Heritage researchers and managers could learn from climate scientists on how to work more closely with policy makers.

5 Conclusion

There is now wide recognition of the important relationship between heritage and climate. However, while much is known about this interaction, a systematised approach is not as widely adopted as necessary. We present heritage climatology as an applied, interdisciplinary field of science that examines aspects of climate that affect heritage and provides data, statistics, well-tuned climate parameters and projections that can aid interpreting past changes and future management of heritage. The development of heritage climatology is not only desirable, but likely to be useful and timely in a changing climate. It can refine our understanding of the processes that affect heritage and provide a framework for future research on heritage and climate, that engages more fully with climate metrics that threaten heritage. This will also contribute to other disciplines, such as agricultural climatology.

Adopting a heritage climate approach highlights a role for data and models at spatial and temporal scales that meet the needs of heritage concerns. This would enable a greater understanding of climate drivers of damage to heritage, thus helping heritage managers and policy makers develop appropriate conservation strategies.

There is still an urgent need to better understand issues surrounding the development of appropriate heritage climate metrics, along with improved estimates of climate impacts on heritage, e.g. dose–response functions. There also needs to be an assessment of the way modelling errors might propagate into management decisions. Future research will require cooperation and collaboration between those working in heritage and climate fields.

Author contributions P.B. and J.R. developed the ideas and wrote the main manuscript text. P.B. created the figure. All authors reviewed the manuscript.

Declarations

Competing interests The authors declare no competing interests.

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