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Multi-model ensemble of frost risks across East Asia (1850–2100)

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Abstract

Frost events can cause the deterioration of a wide range of heritage materials, including stone, brick and earth. In a warming world, the frequency and location of frost events is likely to change, affecting the conservation strategies required at heritage sites. We use a multi-model ensemble approach to investigate three types of frost events in East Asia: freeze–thaw cycles; deep frost days and wet frosts. The study uses nine CMIP6 models for the period 1850 to 2100, with future projections run under the SPS585 scenario. Additional analysis is undertaken for five specific 2° X 2° areas located across East Asia. The three frost event parameters are spatially and temporally distinct. A decrease in all three frost parameters is found in Japan, South Korea and East China, with some areas projected to have no frost events by the end of the twenty-first century. However, Northwest China is distinctive as wet frosts are projected to increase over the twenty-first century, while on the Tibetan plateau of Southwest China, freeze–thaw cycles are projected to increase. This suggests that except in some localised regions, heritage managers can focus on risks other than frost weathering in developing plans to address climate change.

Keywords Cultural heritage · Climate change · Multi-model ensemble · Freezing events · Frost damage · CMIP6

Highlights Assessed a changing risk of frost damage on built heritage from 1850–2100.
A multi-model ensemble was useful in assessing interactions between climate and heritage materials.
Multiple frost parameters are required to capture differences in frost damage processes.
In a warming world, frost damage is less of a conservation concern at many East Asia sites.

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1 Introduction

Climate and weather events can drive the deterioration of heritage materials (Deprez et al. 2020; Hatir et al. 2020; Steiger et al. 2011) and the role played by climate change has been of increasing interest (Blavier et al. 2023; Orr et al. 2021; Sesana et al. 2021). Frost events, defined by air temperature dropping below the freezing point of water (Webb and Snyder 2013), are a well-documented driver of the deterioration in regions where temperatures fall below zero degrees. In saturated, constrained systems, the 9% volumetric expansion associated with the phase change of water to ice causes internal pressures within a material. However, most materials are in unconstrained systems. In these systems, damage is predominantly driven by cryosuction processes, where unfrozen films of water supply the growth of ice, propagating cracks within the material (Hallet 2006; Rempel and Rempel 2019).

Frost damage is a general term used in many disciplines including biology (Augspurger 2013) and construction science (Choi et al 2017), though here we adopt the term to describe any frost process that causes deterioration to porous materials. Heritage materials including stone (Bertolin and Cavazzani 2022; Hallet 2006; Sun et al. 2023), earth (Cui et al. 2019), brick (Balksten and Strandberg-de Bruijn 2021), mortar (Ruegenberg et al. 2021) and timber (Bertolin and Cavazzani 2022; Brimblecombe and Richards 2022; Richards and Brimblecombe 2022), are susceptible to frost damage. This deterioration process has been studied using laboratory (Guilbert et al. 2019; Labus & Bochen 2012; Martínez-Martínez et al. 2013; Mohamed Aly Abdelhamid et al. 2020; Ruegenberg et al. 2021), field (Coombes et al. 2018; Thomachot et al. 2006) and modelling methods (Bertolin and Cavazzani 2022; Vyshkvarkova and Sukhonos 2023), with a recent focus on tuning and developing climate parameters to better represent processes that damage heritage (Brimblecombe 2010; Brimblecombe and Richards 2023; Calle and Bossche 2017) . The severity of frost damage is influenced both by climate (e.g. frequency, intensity and rate of freeze events) and material properties (e.g. porosity, pore distribution and moisture content) (Everett 1961; Hall 2004; Kapsomenakis et al. 2022; Richards et al. 2022), and have been reviewed by Deprez et al. (2020).

It is useful to consider frost damage through a range of parameterisations (Calle and Bossche 2017). One of the most commonly used parameters to assess frost is the freeze–thaw cycle, i.e. the number of times the air temperature shifts to less than zero degrees (e.g. Vyshkvarkova and Sukhonos 2023). This parameter aims to capture the number of times ice crystals exert pressure on a material (Camuffo 2019). However, when air temperatures reach 0 °C, this does not necessarily mean that moisture inside the material has frozen, as the material might be warmer than the air temperature and internal pore pressures lower the temperature required for water to freeze (Rempel and Rempel 2019).

Deep frost days is a frost parameter that captures periods of intense freezing events (e.g. below -5 °C; (Brimblecombe and Richards 2023). This can be useful for determining frost damage where the freezing process has penetrated deep into the material, and thus known to be particularly damaging to some, such as Doulting stone (Curthoys 2017). It also captures the “frost cracking window”, typically thought to be between -3 and -10 °C, where cracks can be wedged open by ice crystals while still being fed from liquid flowing through films (Rempel and Rempel 2019). Furthermore, frost damage can be particularly severe when a rainfall event increases moisture content of a material, and is then followed by freezing temperatures. These ‘wet frost’ events have previously been studied (e.g. Sabbioni et al. 2010; Vyshkvarkova and Sukhonos 2023), but are not often used, likely because it is not commonly calculated in climate science and requires combining daily data for both temperature and rainfall (Brimblecombe and Richards 2023).

Assessing the threat of frost damage is of particular interest in the context of a warming world (Gutiérrez et al. 2021). The IPCC Working group II report (Pörtner et al. 2022) has acknowledged that climate change is negatively affecting cultural heritage, with for example, rising sea levels causing coastal flooding at coastal sites and extreme weather events causing structural damage to buildings. As average temperatures increase, it would seem likely that frost events will decrease in mild regions where temperatures no longer fall below freezing, but might increase in cold regions, where increases in temperature result in the temperature fluctuating more frequently over the freezing threshold (Grossi et al. 2007a; Vyshkvarkova and Sukhonos 2023). Understanding such changes is important in projecting future damage that could cause a loss of value to heritage, as well as having relevance to frost processes within wider geomorphic contexts and agronomy (Jeong et al. 2018; Masaki 2020; Ru et al. 2023; Xiao et al. 2018).

In temperate areas of Europe, the threat of future frost damage has been projected to decrease (Grossi et al. 2007a; Kapsomenakis et al. 2022), while in Russia the number of freeze–thaw cycles between 1960 — 2020 decreased in southern areas and increased in northern areas (Vyshkvarkova and Sukhonos 2023). However, there is little research on longer timescales that capture past and future climate conditions for East Asia despite recognition of the importance of frost events that are known to drive deterioration (Miura et al. 1988).

Asia is a particularly important region to understand future frost damage processes due to the large heritage stock constructed from friable or porous materials located across the continent that could be subjected to frost damage processes (e.g. WHEAP 2012). It is also an interesting region due to its diversity of climates stretching from the humid subtropical to arid regions (Kottek et al. 2006). This regional scale means the threat of frost damage is relevant to many heritage sites, including those along the ancient Silk Roads in northwest China, (e.g. Jiaohe ancient city, Shao et al. 2013; Zhang et al. 2012; Yungang Grottoes, Zhang et al. 2023, and the Ming Great Wall, Pu et al. 2016), Japan (Ishizaki and Takami 2015) and other forms of heritage such as the dinosaur tracks in Korea's South Gyeongsang province (Park and Park 2017).

Previous research has used climate model output to develop parameters tuned to a heritage context (Leissner et al. 2015; Sabbioni et al. 2010). However, these have typically been derived from a single climate model or reanalysis dataset (Grossi et al. 2007a, b; Richards and Brimblecombe 2022; Vyshkvarkova and Sukhonos 2023). Multiple model ensembles (MMEs) allow agreement between model outputs to be assessed, minimising issues of individual model biases (Parker 2013). This approach has recently been used to assess the heritage climate parameter, for Africa (Richards et al., n.d.; Tola and Brimblecombe 2022-), Europe (Kotova et al. 2023), South East Asia (Tantra and Brimblecombe 2022) and globally (Richards and Brimblecombe 2022).

The current study aims to assess the risk of frost damage to materials across East Asia by modelling three frost parameters over the period 1850 — 2100. We use a multi-model ensemble approach to assess three different metrics representing frost: freeze–thaw cycles, deep frost days and the number of wet frosts. Quantifying changing threats should enable heritage decision makers to develop conservation strategies that: (i) address current and future risks and (ii) focus action on locations where risks may be greatest.

2 Material and methods

2.1 Study site

We assessed frost parameters for the region bounded by 30 — 45°N and 74.5 — 145.5°E (Fig. 1). This region of Asia was chosen as it includes a range of climate zones from humid subtropical to desert environments (Kottek et al. 2006), and is home to a rich and diverse range of cultural heritage built from materials including stone (Ishizaki and Takami 2015), brick (Coaldrake 1994; Han et al. 2022; Lee et al., 2023), timber (Brimblecombe and Hayashi 2022; Long et al. 2023) and earth [WHEAP 2012]. Within this region, frost parameters were compared at five 2 × 2° areas located in China, Japan and South Korea, These sites were chosen to cover a range of environmental conditions, from maritime to dryland regions, so incorporate different heritage typologies (Fig. 1, Table 1). The site locations are aligned with the model grid coordinates and are referred to in this paper by codes (Fig. 1, Table 1).

2.2 Frost damage parameters

We used three parameters to assess frost damage: (i) freeze–thaw cycles (ii) deep frost days and (iii) wet frosts. We chose these as they capture a range of frost damage mechanisms including shallow and deep freezes, and the interaction between rainfall and freezing events. Each parameter was calculated on an annual basis, using daily data.

(i) Freeze-thaw cycles were counted on a daily basis when T_{max} >0 °C and T_{min} <0 °C within any given day, where T_{max} is the maximum daily temperature and T_{min} is the minimum. This offers slightly higher resolution than the approach of Grossi et al. (2007a, b) as they used daily means not maxima and minima.

(ii) Deep frost days were counted as the number of days when T_{min} < -5 °C. Following Brimblecombe and Richards (2023),

(iii) Wet frosts were assumed to occur when it rained (T_{min} > 0 °C; precipitation >0.2 mm- chosen as our study incudes dryland climates) on a given day and then the minimum temperature fell below 0 °C the following day.

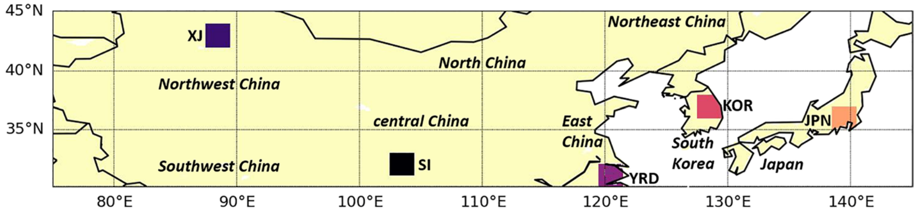

Fig. 1 Map of the study region showing five 2° × 2° areas used in further analysis. Details of the five areas are provided in Table 1. Note: The codes are either three-letter country codes (JPN, Japan; KOR, South Korea), or conventional codes in China (YRD, Yangtze River Delta; SI, Sichuan; XJ, Xinjiang). The regions marked in italics loosely follow the Chinese Greater Administrative Regions, although we have adopted the notion of "central China" as marked on the map

Table 1 Location and description of five 2° × 2° areas used in this study

Code	Country	Co-ordinates	Description	Primary Köppen classification	Examples of built heritage
JPN	Japan	35 — 37°N 138.5 — 140.5°E	Kanto region- coast and mountains with cities e.g. Tokyo	Cfa (Humid subtropical)	Temples of Nikkō Tsuruoka Hachimangu shrine, Kamakura
KOR	South Korea	36 — 38°N 127.5 — 129.5°E	Gangwon and North Gyeongsang—coast and mountains	Dwa (humid continental)	Hahoe Historic Village The Sansa Buddhist mountain monasteries
YRD	China	30 — 32°N 119.5 — 121.5°E	Yangtze River Delta coastal area with cities e.g.. Shanghai	Cfa (Humid subtropical)	Classical gardens of Suzhou Hangzhou cultural landscape
SI	China	31 — 33°N 102.5 — 104.5°E	Sichuan Province- mountainous area near Chengdu	ET/Cwa (Tundra/Humid subtropical)	Taoping Qiang village Songzhou Ancient City
XJ	China	42 — 44°N 87.5 — 89.5°E	Xinjiang Region- dryland area with city of Ürümqi	BWk (Cold desert)	Jiaohe Ruins

2.3 Multi-model ensemble approach

A multi-model ensemble approach was used to assess the three frost damage parameters between 1850 and 2100, broadly following the approach taken by Richards et al. (2023). Temperature and precipitation outputs from CMIP6 models (Eyring et al. 2016) were obtained from the Centre for Environmental Data Analysis (CEDA) archive in February 2023 [https://catalogue.ceda.ac.uk/uuid/b96ce180077f4810abc4eef0e48901d9]. We used the historical period (CMIP experiment) output for the years 1850 — 2014 and future projections scenario SSP585 (ScenarioMIP experiment) for the years 2015 — 2100. We chose the SSP585 pathway for future projections to illustrate a high-change scenario and only used model runs of the variant r1i1p1f*.

The inclusion of a model in the ensemble was dependent on the model having daily precipitation and mean, minimum and maximum daily temperature for the years 1850 — 2100. Where more than one model was available from the same modelling group, we retained only one model to reduce the risk of structural biases introduced by model interdependencies (Knutti et al. 2013; Kuma et al. 2023). The model retained was typically the model with the highest spatial resolution. Table 2 details the nine models that were included in our analysis. As the models had different spatial resolution, all models were interpolated onto a common 1° X 1° grid to aid model comparison (Creese and Washington 2018; Richards et al. 2023).

2.4 Statistical analysis and data visualisation

Thirty-year averages are commonly used in climate science to assess long term changes in climate. Where possible, we similarly used 30-year time periods. However, the durations of the CMIP and ScenarioMIP experiments meant this was not possible in all cases. Hence, the time periods presented in the results are for the periods: 1850 — 1879, 1880 — 1909, 1910 — 1939, 1940 — 1969,1970 — 1999, 2000 — 2014, 2015 — 2044, 2045 — 2074; 2075 — 2100. While not all durations are equal, the trends remain clear. We use the median to calculate central tendency for the study region, as the frost damage metrics were not normally distributed in 80%, 49% and 60% of model grid cells for freeze–thaw cycles, deep frost days and wet frosts, respectively.

The change in each frost damage parameter was calculated by comparing the multi-model ensemble median from a given period to the 1850 — 1879 baseline. We present our regional results using animated GIFs as they enable spatial and temporal changes to be visualised. The individual frames from each animated GIF are available in the supplementary information (See Supplementary information Figures S1-S27).

For each of the five 2° X 2° areas, the annual value for each frost parameter was calculated using the mean. The mean was chosen because the interval nature of the parameter output (i.e. the number of cycles per day are integer values) meant that subtle changes in the output (i.e. changes < 1) were not captured by the median. Of course, an increase of, say, 0.5 wet frosts per year is not possible in reality, but it reflects a probability that provides a useful indication for heritage management about the direction and rate of change experienced by sites. Additional analysis of the 2° X 2° Area XJ explored the seasonality of frost events. This site was chosen as it showed increased frequency of some frost damage parameters during the 21st Century. Again, the mean is used to present the monthly values from the model ensemble.

Table 2 The CMIP6 models used for determining frost event parameters

Model	Institute	Spatial model resolution / km
ACCESS-ESM1-5	Commonwealth Scientific and Industrial Research Organisation and Bureau of Meteorology Australia (CSIRO–BoM)	140
CanESM5	Canadian Centre for Climate Modelling and Analysis (CCCma)	250
FGOALS-g3	State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG) and Institute of Atmospheric Physics (IAP)	190
HadGEM3-GC31-MM	Met Office Hadley Centre (MOHC)	60
MIROC6	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (MIROC)	250
MPI-ESM1-2-HR	Max Planck Institut für Meteorologie (MPI-M)	80
MRI-ESM2-0	Meteorological Research Institute (MRI)	100
NESM3	Nanjing University of Information Science and Technology (NUIST)	170
NorESM2-MM	Norwegian Climate Centre (NCC)	100

3 Results

3.1 Regional frost events

3.1.1 Freeze–thaw cycles

The number of freeze–thaw cycles vary across the region from 0 to > 200 cycles per year (Video 1). In 1850—1879, the majority of models show that the fewest cycles occurred in southern Japan, with the largest number occurring in Southwest China. However, there is notable difference between the models with for example, (i) the CanESM5 and FGOALS-g3 models (Video 1b,c) indicating low numbers of cycles in Southwest China due to low temperatures resulting in areas remaining below freezing for much of the year and (ii) the NESM3 indicating many fewer cycles than the other models (Video 1h). The spatial distribution of freeze–thaw cycles remains similar throughout the twentieth century, although it is worth noting that the areas with low numbers of freeze–thaw cycles in Southwest China in the CanESM5 and FGOALS-g3 models contract in the late twentieth century as temperatures increase.

Projections for the twenty-first century show notable decreases of > 50 freeze–thaw cycles per year across Japan, South Korea, East China and Northwest China (Video 1). Some areas of Japan, East China and South Korea are projected to experience almost no freezing by the period 2075 — 2100 (Video 1). There is a small increase in the annual number of freeze–thaw cycles in Northeast China and Southwest China (i.e. Tibet and Sichuan), where warming means that cold regions experience temperatures that cross the 0 °C threshold more frequently.

3.1.2 Deep frost days

The spatial distribution of deep frost days shows good agreement between models (Video 2) and its distribution is similar to freeze–thaw cycles, with the fewest deep frost days occurring in Japan and East China. The greatest number of deep frost days are located in high mountainous areas of Southwest China. Unlike future projections for freeze–thaw cycles, a decrease in the number of deep frost days is projected to over the twenty-first century for almost all areas, with areas of Japan, South Korea and East and central China being projected to have no deep frost days by the end of the twenty-first century (Video 2).

3.1.3 Wet frost days

The spatial distribution of wet frost days is distinct from freeze–thaw cycles and deep frost days. Historically, the greatest number of wet frosts occurred in Japan and central China, with few wet frosts occurring in the dryland areas of Northwestern China (Video 3). This spatial pattern is broadly apparent in all models, although the CanESM5 model has a greater area of low wet frost days in Southwest China (Video 3b) and the NorESM2 model has a region of high wet frost events in central China (Video 3i).

There is minimal change in the ensemble-median wet frost days over the nineteenth and twentieth centuries (Video 3k). In contrast, through the twenty-first century there is a notable decrease in wet frost days over Japan, South Korea and central and Southwest China, which arise from warming temperatures. In contrast, there is an increase in wet frost days in Northwest China due to enhanced precipitation.

3.2 Frost events at 2 × 2° study areas

Results for the three frost parameters from the five 2 × 2° study areas, again shows that the frequency of frost events varies substantially across East Asia (Fig. 2). Between 1850 and 2000, Area XJ had the second greatest number of freeze–thaw cycles (~70 — 80 cycles per year) and greatest number of deep frost days (~6 — 7 days per year), but had the lowest number of wet frost days (~2 — 4 days per year). In contrast, Area JPN had the lowest number of deep frost days; approximately half the number of freeze thaw cycles as Area XJ, making it joint lowest; but had over double the number of wet frost days, making it second highest (Fig. 2).

As shown in Fig. 2, the magnitude of the three frost parameters remained stable for the 19th and majority of the twentieth century. However, from the late twentieth century, notable changes are projected. In Areas JPN, KOR and YRD, the number of freeze–thaw cycles, deep frost days and wet frost days are projected to decrease throughout the twenty-first century. Area XJ is the only one of our study areas where a frost parameter is projected to increase (Fig. 2). Here, the number of freeze–thaw cycles remain constant, while the number of wet frost days are projected to increase throughout the twenty-first century.

3.2.1 Seasonality of Area XJ

In Area XJ, the seasonality of frost events is projected to change over the 21st Century (Fig. 3). In the nineteenth and twentieth centuries the number of freeze–thaw cycles was typically greatest in November and March with few in mid-winter (Fig. 3a). However, by the end of the twenty-first century, freeze–thaw cycles are projected to increase in the winter months, with freeze–thaw cycles remaining high from November through to March. Deep frost days historically peaked between November and March. However, by the end of the 21st Century, this peak period shrinks to the period December to February (Fig. 3b).

Historically, wet frost days in Area XJ have most commonly occurred in October and April (Fig. 3c). However, future projections show that by the end of the 21st Century, these events will most commonly occur in November and March and at a greater frequency. Also, in December, January and February, wet frosts events are projected to occur when historically they were typically absent.

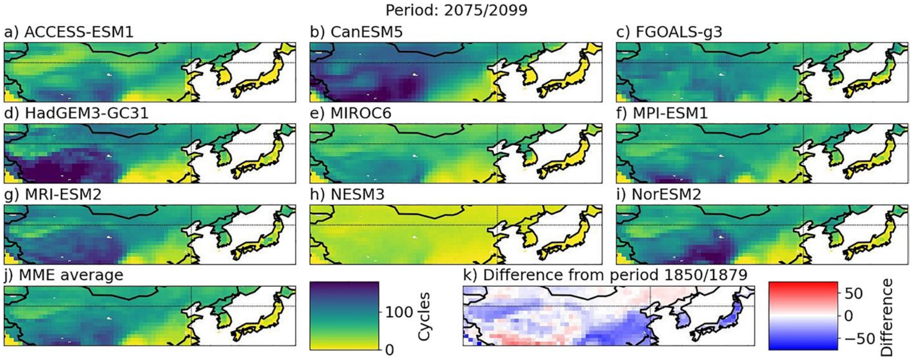

Fig. 2 The number of (**a**) freeze–thaw cycles, (**b**) deep frost days and (**c**) wet frost days per year for each of the five study areas, 1850 to 2100

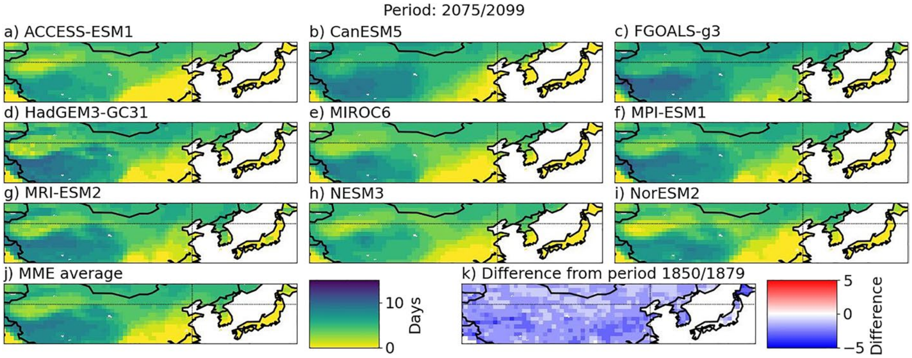

Fig. 3 The average number of monthly (**a**) freeze–thaw cycles, (**b**) deep frost days and (**c**) wet frost days per year for Area XJ for July—June in the periods 1850 — 1879, 1970 — 1999, 2015 — 2044 and 2070 — 2099

4 Discussion

4.1 Multi-model ensemble approach

A multi-model ensemble approach enables a range of model projections to be assessed, minimising the effect of individual model biases on the overall results (Parker 2013). For simple frost event parameters based only on temperature (e.g. deep frost days), model output is aligned over time and space, as temperature is well-determined within climate models. This alignment between model output was also found for the temperature component of the Scheffer index (Scheffer 1971) over Africa (Richards et al. 2023). However, greater variability between model output was found where frost event parameters:

(i) were based on a cycle over a set temperature threshold (e.g. freeze–thaw), as even small temperature biases in the model can cause notable changes in the number of times the temperature crosses a threshold.

(ii) required precipitation in addition to temperature parameters (e.g. wet frosts). The parameterisation of precipitation processes within climate models can result in uncertainty in rainfall projection (Kendon et al. 2018). Developments in convection-permitting climate models will likely improve the ability of future models to capture precipitation (Gao et al. 2020; Kendon et al. 2017), but it is not currently feasible to run these models over the temporal and spatial scales applied to a regional heritage context.

4.2 Change in frost events over time and space

Our results show that frost events have decreased since the mid-twentieth century for many areas of Asia between 30 — 35°N and 74.5 — 145.5°E, with warmer temperatures reducing the occurrence of frost, in agreement with trends projected for Russia (Vyshkvarkova and Sukhonos 2023) and Europe (Brimblecombe and Richards 2023; Grossi et al. 2007a; Kapsomenakis et al. 2022). This suggests that for most heritage sites in East Asia, the rate of frost damage is likely to become less severe in future. For example, in Japan, projections suggest almost no wet frosts and deep frost days by the end of the 21st Century (Videos 2 and 3). Thus, future conservation strategies for heritage sites in this region might not need to address the action of frost. Instead, other damage processes such as salt weathering

(Grossi et al. 2011; Hu et al. 2023; Matsukura et al. 2004) and insect attack (Brimblecombe and Hayashi 2022) may increase in importance, so conservation and management plans could benefit from a shift in focus. In urban areas, the reduction in frost events might be further enhanced due to urban heat island effects (Guilbert et al. 2019), but heritage in these areas can face threats from an array of other mechanisms including pollution, resulting in pollution crusts (La Russa et al. 2018) and yellow tones via its oxidation (Comite et al. 2018; Grossi et al. 2007b); urbanisation (Li et al. 2020) and changing hydrology (Brimblecombe et al. 2020; Wang 2015).

Nevertheless, some regions are projected to experience an increase in frost events, e.g. wet frost days in Northwest China (Video 3) and freeze–thaw cycles in Southwest China (Video 1). In the dryland region of Northwest China increased wet frosts could accelerate damage to earthen heritage sites, such as at Jiaohe Ancient City (Shao et al. 2013). Such processes could drive flaking and granular disintegration, as well as enhancing the mobilisation of salts within the material causing loss at the base of the structures (Jia et al. 2021; Richards et al. 2022). Snow melt can be particularly deteriorative (Cui et al. 2019; Jia et al. 2021), so given that frost is projected to remain an important driver of damage in this area, future metrics for Northwest China should also assess the role of snowfall. Furthermore, the change in seasonality of frost events in Area XJ (Fig. 3) shows that frost damage may increasingly occur in winter months (rather than spring and autumn) and so the timing of management strategies might need to change to remain effective. Similarly, the increase in the number of freeze–thaw cycles on the Tibetan Plateau in Southwest China suggest that heritage sites in historically cold regions should increasingly consider enhanced rates of frost damage in conservation strategies.

The distinct spatial patterns of each of the three frost event parameters (Videos 1–3) further demonstrate the need for multiple frost parameters to assess damage to heritage (Calle and Van Den Bossche, 2017; Vyshkvarkova and Sukhonos 2023). If just a single frost parameter was used, it would unlikely capture the full extent of threat. Having multiple frost parameters means that more than one temperature thresholds can be included. In this paper both 0 °C and -5 °C were used, acknowledging that not all moisture in a material will freeze at 0 °C (Rempel and Rempel 2019). Therefore, when multiple frost event parameters decrease concurrently, it suggests heritage will be at a reduced risk of frost damage—while if some parameters increase, while others decrease, it suggests a change in the balance of frost damage processes.

4.3 Transferability of research and management implications

Data from climate models provide scientists and practitioners with a rich resource that can be tuned to investigate heritage deterioration processes, enabling us to design conservation strategies that better incorporate risk (Richards et al. 2023). This use of climate data could similarly quantify the threat of frost damage in other places, contexts (e.g. agriculture) or adapted for other climate threats (e.g. wind-driven rain). Furthermore, uncertainties in climate outputs over central Asia could be reduced with increased observational data (Wang et al. 2020). Here, observational data routinely collected by weather stations at heritage sites could be used to improve the climate observation network across the region, and help reduce climate model uncertainty.

The results in this study are presented at a regional scale, so do not capture site scale microclimatic conditions (Pioppi et al. 2020). Therefore, while the frequency of frost events experienced at individual heritage sites may differ from the model output, such output provides a good indication of the direction and magnitude of change. The resolution of global climate models will unlikely be fine enough to capture climate processes that drive damage to individual elements of heritage. When working at these small scales, we should see global climate models as an input for models that operate at the scale of sites or building elements (Pineda and Iranzo 2017).

We used a SSP585 to illustrate a high-change scenario. This pathway is likely to result in a reduced risk of frost damage for many sites in East Asia, but other climate threats could increase, such as wind and rain (Du et al. 2017; Richards et al. 2020; Richards and Brimblecombe 2022; Shao et al. 2013). With the future risk of deterioration being so strongly dependent on human actions, future climate projections are contingent on the scenario chosen. Therefore, long term conservation strategies need to consider the likelihood of various outcomes and be flexible to ensure they can adapt to a range of future climate scenarios.

5 Conclusions

This study uses a multi-model ensemble approach to assess the risk of frost damage to heritage sites exposed to ambient conditions in East Asia over the period 1850 – 2100. While in the past a single metric (typically freeze thaw cycles) has been used to represent frost damage here we used three: freeze–thaw cycles, deep frost days and wet frost days, all of which required daily resolution data. The results showed that areas where frost damage posed a concern decreased from the late 20th Century. In many areas, decreases in all three parameters were observed. This shows that the trend of future change is relatively insensitive to the frost parameter chosen and thus suggests there is minimal added benefit in fine tuning of frost parameters in areas where frost risk is rapidly decreasing. In contrast, increases in frost risk were found in some arid and mountainous regions of China including areas of the Tibetan Plateau. Here, frost parameters should be further tuned to the specific materials and heritage to inform strategies, including visitor seasons and the timing of conservation measures.

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Author contributions Jenny Richards: Conceptualization; Data curation; Formal analysis; Methodology; Visualization; Roles/Writing—original draft; Writing—review & editing. Peter Brimblecombe: Conceptualization; Formal analysis; Methodology; Roles/Writing—original draft; Writing—review & editing.

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Declarations

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