# Applying Attribution Science to Cultural Heritage Impact Assessment

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## Abstract

Climate change is widely recognised as a major threat to cultural heritage, yet heritage risk assessment often describes changing hazards without testing how much of these changes is caused by human-induced climate change. This limits the causal strength of evidence used in heritage policy and management. Here we apply attribution science to cultural heritage risk assessment by comparing factual climate simulations with counterfactual simulations without human influence. We show that human activities have already increased extreme hot days at World Heritage Sites globally, with stronger attributable risks in low-income countries. We also show that attribution can be applied to heritage-related deterioration processes, including fungal decay risk and frost damage. These results suggest that attribution science can support clearer heritage risk assessment by separating human-caused climate signals from natural variability, while still requiring local evidence on material condition, vulnerability, management, and heritage values.

## 1. Heritage risk assessment needs causal evidence

Climate change is now widely recognised as one of the largest threats to cultural heritage (Day et al. 2020; Megarry 2023; Bonazza and Sardella 2023). Reports by heritage organisations and international bodies often state that many World Heritage properties are already affected, or will be affected, by climate change (Sesana et al. 2020; Falk and Hagsten 2023). These statements are important because they make climate change visible in heritage policy and management. However, they can also create an incomplete assessment narrative. The statement that “climate change threatens heritage” is useful, but it is not enough for risk assessment. Cultural heritage risk assessment needs to ask more specific questions: what hazard is changing, which sites or materials are affected, whether impacts are always negative, and how much of the observed impact is due to human-induced climate change rather than natural variability.

This paper argues that attribution science can help answer these questions. It adds a causal evidence layer to cultural heritage risk assessment. Instead of only asking whether a site is exposed to climate change, attribution study asks how much human-induced climate change has altered the hazard or damage pressure affecting the site (Otto 2017; Stott et al. 2016). This helps move heritage assessment from general risk description toward causal climate assessment (Simpson et al. 2022; Zhao et al. 2026). Heritage risk is shaped by the interactions between hazard, exposure, vulnerability, and response (Intergovernmental Panel On Climate Change, 2023). Climate change may alter the hazard, but the final impact also depends on where heritage assets are located, what materials they contain, how they are managed, and what resources are available for response. Attribution science clarifies one key part: the human-caused climate signal behind the hazard or damage pressure.

Attribution science compares two worlds. The first is the factual world, with human influence, including greenhouse gas emissions, aerosols, land-use change, and other human forcings. The second is the counterfactual world, without human-induced climate change, where only natural forcings such as volcanic activity and solar variability are included. The difference between these two worlds estimates the anthropogenic climate change signal. This comparison can be applied to climate hazards and heritage-related damage pressures (Zhao et al. 2026). If a heat-related hazard is higher in the factual world than in the counterfactual world, the difference can be treated as the human-induced increase. If a frost-related indicator is lower in the factual world, the result may show that human-induced warming has reduced frost damage. This matters because climate change does not amplify all heritage risks.

Attribution science also strengthens how existing heritage risks are interpreted. Previous heritage studies have already translated climate variables into material- and site-relevant indicators, such as fungal decay risk, salt weathering, and humidity fluctuations (Richards and Brimblecombe 2022; Grau-Bové et al. 2025). However, these indicators usually describe changing risk patterns, but they do not demonstrate how much of that change is caused by human influence on the climate system. Here, attribution science addresses this gap by comparing factual and counterfactual climate simulations, turning established indicators from descriptive risk measures into causal evidence for heritage risk assessment.

## 2. Methods and data

The method begins with climate model simulations under factual and counterfactual conditions. In the work discussed here, large climate model ensembles from the Max Planck Institute under the CMIP6 protocol are used (Olonscheck et al. 2023). Daily temperature and rainfall data are used to calculate climate or heritage-relevant indicators. The calculated results under all forcings are then compared with simulations under natural forcings only.

For extreme hazards, standard climate indices can be used. For example, extreme heat days can be defined as days when daily maximum temperature is greater than the 90th percentile of a baseline period. This allows the assessment to compare changes in extreme heat under different climate worlds (Intergovernmental Panel On Climate Change, 2023a). The climate data can then be linked with the World Heritage List, including site locations, heritage types, inscription year, and stated values. This makes it possible to move from climate simulations to heritage risk assessment at different scales.

For heritage deterioration processes, climate variables are translated into damage-related indicators. For example, the Scheffer Index can estimate climate suitability for fungal decay in timber heritage (Scheffer 1971). Frost Intensity can estimate the severity of freezing conditions relevant to porous masonry (Grossi et al. 2007). These indicators do not fully describe heritage impact, but they provide risk proxies that are closer to deterioration processes than climate variables alone.

Two forms of attribution can then be calculated. The first is intensity attribution. It asks how much an indicator has changed due to anthropogenic climate change:

**Anthropogenic change = factual intensity − counterfactual intensity**

Positive values mean that anthropogenic climate change has increased the indicator, and negative values mean that anthropogenic climate change has reduced the indicator.

The second is probability attribution. It asks how much human-induced climate change has altered the probability of exceeding a defined threshold. A common measure is the Fraction Attributable Risk (FAR):

$$FAR = 1 - P(counterfactual) / P(factual)$$

P(factual) is the probability of exceeding the threshold in the factual climate with human influence, while P(counterfactual) is the probability of exceeding the same threshold in the counterfactual climate without human influence. FAR estimates the share of risk that can be attributed to human-induced climate change. This is useful because risk assessment often depends not only on how severe a hazard is, but also on how likely it is to pass a damaging threshold.

## 3. Applying attribution science to World Heritage Sites

World Heritage Sites provide a useful global test case for applying attribution to heritage risk assessment. The World Heritage List has recognised heritage values, recorded locations, and international monitoring systems. By linking climate model outputs with the list, it is possible to assess how anthropogenic climate change has altered hazards and damage processes at these sites.

Attribution evidence shows that human-induced climate change has already changed extreme heat hazards at many World Heritage Sites. In one example, attribution analysis shows that human activities have increased extreme hot days by 46 days per year at WHSs globally. This result translates broad climate change dynamics into a clearer risk assessment statement: WHSs are not only exposed to heat; their heat exposure has already been changed by human-induced climate change.

Attribution evidence also shows that these human-induced risks are distributed unevenly. Low-income countries face greater attributable risks, with many World Heritage Sites showing moderate-to-high increases in extreme heat days. This is important because risk is not only a question of hazard. It also depends on exposure, vulnerability, and response capacity. In this context, exposure can be represented by the number of World Heritage Sites within each reference region. Vulnerability can be represented, in a broad way, by the World Bank income classification of the State Party. This is not a full measure of vulnerability, but it shows that anthropogenically intensified hazards are not distributed evenly. Some countries face stronger increases in extreme heat while also having fewer economic and institutional resources for response.

Attribution evidence can also be applied to heritage-related deterioration processes. The Scheffer Index measures climate suitability for fungal decay in timber, based on temperature and wetness conditions. Fungal-related decay is often linked to warm and humid conditions, which makes it sensitive to climate change. Here we show extreme fungal decay conditions increased from around 5% under the counterfactual climate to around 14% under the factual climate. This gives a FAR of about 60%, meaning that a large share of extreme fungal decay risk is attributable to human-induced climate change. The strongest signals appear in parts of Eurasia and eastern North America.

Attribution evidence also shows that climate change does not increase every heritage risk. Frost Intensity measures the severity of freezing conditions that can affect masonry materials. In this case, climate change reduces frost-related risk in many regions, especially across Northern Europe and North America. The exceedance probability declined from about 3.0% under the counterfactual climate to about 0.3% under anthropogenic climate change. This result shows that climate change may reduce some cold-related risks while increasing heat, humidity, biological, or salt-related risks.

Attribution evidence can also help reinterpret existing heritage monitoring systems. The UNESCO State of Conservation system records both climate change threats, such as flooding and temperature change, and local conditions affecting physical fabric, such as water, rainfall, water table change, and temperature (Bertolin and Perry 2020). These categories are useful for management, but they can separate “climate change” from “local condition” too strongly. For example, attribution results for the Chavín Archaeological Site in Peru show an increase of 150 extreme hot days and a 1.5°C increase in daily maximum temperature due to climate change. This does not mean that climate change is the only cause of risk at the site, as material condition, drainage, conservation history, and management practice still matter. However, it shows how attribution science can reveal when a local conservation problem also contains a human-caused climate signal.

## 4. Discussion and conclusion

Attribution science strengthens cultural heritage risk assessment by adding causal climate evidence to screening, scoping, significance judgement, communication, and adaptation planning. It can identify which hazards and damage pressures already have a strong human-caused signal, and which risk pathways require closer assessment. This is especially useful when heritage risks are linked to thresholds, such as extreme heat days, high humidity periods, fungal growth conditions, or frost damage. Attribution evidence can also make climate risk statements clearer by showing how many additional extreme heat days are due to human influence, or what share of an extreme damage threshold is attributable to human-induced climate change.

Attribution science is not a full cultural heritage risk assessment by itself. It clarifies the climate component of risk, but it does not replace local evidence on site condition, material type, conservation history, management capacity, exposure, vulnerability, heritage values, and community context. A strong anthropogenic climate signal does not mean that all observed heritage damage is caused by climate change, as damage often results from combined factors. The examples from World Heritage Sites show that attribution can quantify anthropogenic changes in extreme hazards and connect human-induced climate change to heritage-related deterioration processes. Cultural heritage risk assessment needs this causal climate evidence, but it must still be combined with local conservation assessment, material knowledge, vulnerability analysis, and heritage values.

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