Review

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Review

Decoding the Microclimate in Subterranean Heritage Structures

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Abstract

This paper addresses the important issue of the proper management and protection of subterranean monuments. It concerns the analysis and decoding of the microclimate that is created in heritage structures, which are structures located beneath the soil or carved into rock. The aim of this study is to understand the hygrothermal processes occurring in the mass of underground structural elements, such as evaporation, condensation, water content and heat fluxes, based on the principles of building physics. The methodology used is the following: A systematic literature review on the topic, an overview of the factors affecting the microclimate, the assessment methodology and the simulation tools used to decode and evaluate microclimate in subterranean heritage structures, a discussion of the current gaps and finally a proposal of future directions for research. A review of the literature reveals that researchers worldwide have employed similar methodologies to approach this complex issue. Recordings and analyses of the microclimate inside underground monuments lead to decision making and the formulation of actions for optimal preservation. Due to the large number of parameters involved in microclimate analysis, computer software for numerical simulation has been used in many cases. Following the review of the relevant literature in the field of study, a critical discussion concludes proposing directions for future research on this important topic. Basic results of this research identify current gaps, problems and limitations. These include technical and practical issues or gaps concerning lack of data for material properties and weather conditions. Another significant limitation arises from the complexity of physical interactions, as well as from the human factor, which involves the proper use of the simulation program and the correct interpretation of the calculation results. This study demonstrates that the microclimate of subterranean heritage structures is the result of complex interactions between climate, geology, architectural design, material properties, and human use. Across different geographical and cultural contexts, subterranean monuments exhibit distinct microclimatic behaviors. The comparative analysis of case studies highlights that while subterranean environments generally benefit from thermal stability, they remain highly vulnerable to moisture dynamics, ventilation changes, and external climatic coupling. Hence, there is a necessity of context-specific approaches rather than generalized conservation solutions. Decoding subterranean microclimates requires a multi-disciplinary framework that combines environmental monitoring, material indicators, architectural analysis and numerical modeling.

Keywords: cultural heritage; built heritage; underground historic structures; monumental tombs; indoor microclimate; heritage microclimate; hygrothermal numerical simulation; sustainability; climate change; building physics

1. Introduction

This paper concerns the analysis and decoding of the microclimate inside subterranean heritage structures that are under an embankment or carved into rock. It is not a typical review paper, since it examines iconic subterranean monuments of world cultural heritage, whether or not they are listed on UNESCO World Heritage List. Furthermore, we synthesize and review published work of others and of ourselves. Regarding our own work we clarify and emphasize in a better manner results and conclusions of our own research. A review paper on this subject is challenging indeed since all aspects involve interdisciplinary scientific work as well as field research.

In particular, this paper studies the proper management of underground heritage structures to achieve preservation, sustainability and resilience to climate change. A review of the work which has been carried out on monuments with similarities all over the world is presented, aiming to critically analyze current gaps or problems and provide recommendations for future research.

Monumental subterranean structures were created all over the world, in different historic periods, for different uses. Royal tombs in northern Greece for example, named Macedonian tombs, were constructed to become the burials of important people, kings and emperors. They are unique and valuable examples of the architecture of their era. Some of these tombs have been carved into a soft rock (rock-cut cavities) and others have been built with large blocks of stone with vaulted roofs, having as a special characteristic the artificial covering by earth, named “tumulus”. All of them are decorated with exceptional wall paintings of great archaeological importance in the interior and on their façade. They are buildings constructed to remain underground, covered with soil, because of their special use as afterlife homes for the dead. Most of them have been preserved over the centuries in excellent condition being in a stable microclimate, which was disturbed after the excavation works. After the excavation they were converted into visiting places or museums, because of their historical significance.

Proper protection of these heritage structures could be achieved by adjusting the microclimatic conditions. There is a need to intervene in their micro-environment in order to control -as far as possible- the microclimate. The main objective is to stop any potential deterioration processes and to take precautionary measures for sustainable management and future preservation of cultural heritage. Sustainable management of archaeological sites and built heritage is a topic of the UNESCO Sustainable Development Goals, the SDG11: “Make cities and human settlements inclusive, safe, resilient and sustainable”, target 11.4: “Strengthen efforts to protect and safeguard the world’s cultural and natural heritage” [1,2].

Attempting to define the challenge of deterioration in subterranean monuments due to their hygrothermal status, scholars all over the world have been involved in recording and analyzing their particular characteristics. Systematic monitoring and evaluation of the indoor climatic conditions has shown that the deterioration processes are mainly caused by cyclical changes of temperature and relative humidity when the monuments are exposed to the environment and the presence of visitors. Protection against future deterioration can only be assured through proper interventions to stabilize the indoor microclimate. Specific protection measures are needed on the site during and after the excavation procedure. Mainly, the protection measures include a proper shelter that will operate as a regulator for the microclimate. Case studies worldwide show that the main issue to be addressed by constructing shelters on the site is the stabilization of the temperature and humidity, thus reducing and minimizing the fluctuations of the exterior climate [3].

To decode the microclimate in subterranean heritage structures, we should define research questions, which are:

What are the physical and environmental laws governing microclimatic behavior?
Which are the foundational Building Physics principles?
What shapes a specific monument’s microclimate, in different geographical locations? Which are the determining factors in each location?
How microclimate is observed and quantified?
How data are interpreted and integrated in assessment methods?

Those questions will be answered in the following sections.

This paper is organized as follows:

In Section 2 the problem of the deterioration processes in underground monuments is studied and their hygrothermal behavior is analyzed based on the building physics science. More specifically, subsection 2.4.1 investigates the “ideal conditions” for preserving ancient materials.

In Section 3 a review of case studies is presented. By examining case studies applied on important subterranean monuments worldwide valuable conclusions are drawn regarding their protection. At the end of this section, we constructed a comparative table presenting environmental and accessibility control aspects.

In Section 4 there is a discussion regarding the concept of sustainability and how it could be balanced with the monuments’ preservation. Climate change adaptation and resilience of the archaeological sites are also very important issues.

In Section 5 a critical analysis of the literature and a discussion are presented, including the working methodology, the use of hygrothermal simulation computer programs, and an example application using the WUFI®Pro software.

Section 6 identifies current gaps, problems and limitations and examines in detail all aspects covered in our paper.

Finally, Section 7 provides future directions for further research.

2. Issues Related to the Deterioration Processes in Underground Monuments

The issue of underground monuments’ protection needs to be resolved immediately to prevent the ancient materials’ degradation. Incorrect actions during the excavation and immediately after the discovery of the tombs can lead to irreparable damage or even loss of some valuable items, i.e., the building itself (building materials, wall paintings) and the movable findings contained therein. The disturbance of the equilibrium occurs at different stages. Its size and intensity are related to interventions derived from the human factor, not only during the excavation process, but also before that.

To address the issue of the deterioration caused by the microclimatic conditions in underground monuments, scientists worldwide are based on the principles of building physics.

2.1. Hygrothermal Behavior and Threats from the Environment

A subterranean structure is subjected to annual periods and daily ones. The coupled thermal and moisture behavior within the subterranean structure depends on the following aspects:

a. The thermal energy is transmitted from the soil through the building’s elements to the interior air. This transfer occurs via conduction through the materials and then via convection from the surfaces to the air [4].

b. Water exchanges take place at all states between soil and indoor air, and they are in close connection with the exchanges of thermal energy [5].

The building materials of a subterranean monument are subjected to the annual cycle of wetting-drying procedures. The same cycle is created on a daily basis to the parts of the tomb that remain exposed to changes in climatic conditions.

2.2. Key Questions

The following key questions have been formulated and will be discussed subsequently:

- Which are the factors that damage the materials?
- Where does moisture come from in the materials and how does it work?
- How is moisture transfer explained by natural processes?
- How is the moisture transfer phenomenon simulated and what this simulation can contribute to the protection of materials?
- What is the meaning of protecting materials from damage and to what extent is it feasible?

2.3. Moisture and Heat Transfer

The most important source of energy that supplies heat to the earth is the sun. The underground microclimate is characterized by a slow deviation due to the thermal inertia of the surrounding materials and the rapid attenuation they cause in the daytime temperature oscillations relative to the slower seasonal ones. These dynamics can result in water exchanges between the walls and the interior due to condensation, evaporation and absorption processes that determine the system's hygrometric data. Therefore, the relative humidity of the interior of the tomb is influenced by the thermal energy flow through the water vapor injections from the masonry.

In particular, materials after buried underground follow a process of adaptation to their new environment, which is followed by changes that affect their color, size, weight, etc. These changes begin to slow down or stop when materials reach a point of equilibrium with their environment. Sensitive organic materials can surprisingly be maintained in three opposite situations: extreme dryness, such as desert sand, wet anaerobic conditions, such as in swamps, and in situations in which temperatures never rise above 0°C. In all these cases the reasons for the preservation are the stability of humidity and temperature conditions, the lack of oxygen and therefore the lack of biological deterioration. Many researchers agree with this view and point out that mainly the change in humidity and the movement of water in the mass of the materials are the cause of the large changes in them.

This balance is interrupted at the time of excavation. New environmental conditions invade, and the deterioration process resumes so fast that many times it results in the complete disappearance of some materials within a few hours of their discovery. It has been observed that large changes occurring rapidly in excavation are neither by the oxygen of the air, nor by light, but by the change of humidity.

The deterioration process is a complex process. Organic materials degrade, pigments fade, minerals corrode and stones disintegrate. The processes of damage to materials are distinguished in physical, chemical and biological.

Moisture in the walls may come from the following sources:

a. Water filtration from roof holes, leakage of gutters or pipes, or direct exposure to rain.

b. Rising moisture in the walls which are in contact with wet soil.

Factors involved in these processes that accelerate or make their results worse are:

- The presence of water (in all its forms) and the changes in its concentration.
- Temperature fluctuations.
- The radiation (solar or artificial).
- Pollution of the atmosphere.
- Dust and other molecules that air carries.
- The action of frost and wind.
- The actions of fire and vibration (seismic or mechanical).
- The effect of internal pressures, due to salt concentration or oxidation.
- Human intervention (incorrect maintenance, heating).
- Human presence.

Causes of deterioration may be the presence of soluble salts, and the humidification and drying processes. In the environment of the underground monument and in the mass of its building materials, there is a constant movement of water (in liquid or gaseous form) [6]. In practice, there are two processes operating in opposite directions: wetting and drying. Most changes in materials occur not during water absorption but during evaporation (drying). Even though the materials are usually dry, short wet periods can cause problems that are not balanced by long dry periods.

The chemical or biological action accompanying wetting and drying processes are not reversible.

Almost every material is more or less porous. This means that water can penetrate the pores and may also evaporate. The structure of the pores, as well as the physical rules that determine the transfer of moisture (in the liquid and gaseous phase) into the pores, are not exactly known.

Nevertheless, there is a number on the pore-size distribution curve (PSD) that represents the material's structure and it is essential for understanding the fundamental features of their thermo-hygro-mechanical behavior. This number is correlated with the practical behavior of many materials, i.e., under hygro-mechanical processes (e.g., compaction, saturation–swelling processes) and it is important for the materials' applications in various engineering fields [7].

The simulation program WUFI, which will be presented in Section 5.2., uses the porosity of materials as an input to compute results on the hygrothermal behavior of building elements [3,37,38].

2.4. Ideal Conditions

Bearing in mind that the changes in humidity and temperature are the main causes of the deterioration processes in subterranean monuments, we could say that preventing deterioration can be achieved by controlling the microclimate inside and out of the tombs. The most important factor for protection is to achieve the "ideal conditions". But the term raises the following questions:

- What are the "ideal conditions" for preserving ancient materials?
- What are the "ideal conditions" for the visitor's comfort?
- How will they contribute to minimizing the cost to regulate the microclimate by using mechanical systems?
- Finally, how could all the above be balanced on the basis of sustainability?

Stefan Michalski, having a wide experience on museum collections, noted: "Temperature control in a museum raises issues of human comfort, energy cost, environmental impact and sustainability" and also "RH (relative humidity) control is best approached from the perspective of risk management that is, being aware of the most damaging values of incorrect RH and focusing on their regulation. A correct RH is, at best, a compromise between conflicting issues" [8,9].

At first, the term "ideal conditions" means the optimum range - the maximum and minimum permissible levels - of temperature and relative humidity values, to avoid deterioration and preserve the ancient materials. The following subsections deal with this issue. In particular, subsection 2.4.1 is a review on "ideal conditions" as they are proposed for museums, while subsection 2.4.2 focuses on monuments on the site, such as subterranean monuments are.

Additionally, other parameters are addressed: visitor impact, energy consumption, environmental considerations and sustainability.

2.4.1. A Review on Ideal Conditions

This part investigates the "ideal conditions" for preserving ancient materials, as they are proposed for museum environments in the literature and in the international standards and guidelines.

The microenvironment inside a closed shelter/museum is determined by a number of factors such as temperature, humidity, radiation, vibrations, dust particles, carbon dioxide. Appropriate values and limits must be set for each.

Particulate matter and vibrations are recognized as primary degradation agents; international standards (e.g., EN 15759-1) recommend their mitigation to the lowest achievable baseline.

Thus, their values should be reduced to the minimum possible, although this is not easy to achieve in practice. Temperature and humidity are different from other environmental factors and their effects on objects are more varied and complex than other factors' effects. A temperature or humidity value accepted for an object can be disastrous for another. Temperature and humidity cannot be eliminated, but satisfactory values must be established for each. Materials are also affected by the range of the changes, which makes it inadequate to simply set an average value. The relative humidity depends directly on the temperature range.

The indoor climate conditions of museums should serve two purposes:

- provide adequate conditions to preserve the artifacts and
- provide thermal comfort to visitors and staff [10].

Since the early 1990s, a consensus has grown among scientists and conservators with wide experience of collections that objects have a range within which they tolerate fluctuations without damage.

Earlier climate specifications often lacked empirical backing regarding material longevity, focusing instead on anthropocentric comfort levels [10,16].

The human comfort temperatures were conveniently assumed to be suitable for collections too. Over time, this assumption evolved into the belief that these were the correct conditions for preservation. In reality, this was never true for most collections—and outright false for many, including libraries and archives.

Also, permissible fluctuations were assumed to be very small.

The historical emphasis on tight climate control has been challenged by recent conservation science, which advocates for broader tolerance ranges based on the specific materials history of acclimatization. Stefan Michalski is the primary scientist on this specific concept, i.e., that an object adapts to its long-term environment. [76]

Lucchi [11], concludes that the idea of "museum buildings" has changed substantially over the last 40 years, opening new and urgent problems related to conservation and enhancement of cultural heritage, environmental quality, human comfort, energy efficiency and safety for users, buildings and collections.

Over time, the definition of the museum as a "static place", intended to preserve, protect, conserve, and display the heritage has been replaced by a "dynamic vision" of transmission and dissemination of knowledge, according to the ICCROM Teamwork for Preventive Conservation, as well as researchers, as Eco and Davies [12–14].

Conservation science is moving away from rigid climate control toward broader, material-specific tolerance ranges. It was a historic shift when the world's two largest conservation bodies, ICOM-CC and IIC [77], officially agreed that rigid set-points are no longer the absolute requirement.

2.4.2. Optimal Conditions for Monuments in Situ

There are complex phenomena taking place in a subterranean monument which is exposed to the surrounding environment. The optimal conditions inside and outside the historic construction must be determined. Investigation of the enclosure is therefore not sufficient, but the microclimate of the surrounding area must also be taken into account. The relationship between them is crucial for the monument, to be in a balance of moisture and temperature exchanges between the interior and the environment. If we consider the built shelter over an underground monument as a "museum showcase" for a collection of ancient materials, then we should define the "set point" for this specific group of materials [1,3].

In the above Figure 1, Davies [14] ~~shows~~ included the recommended relative humidity values for different materials. It is clear that there is no "ideal" RH for the protection of subterranean monuments' structural components.

More specifically, there is not one "ideal" value, but a range of values, which:

- may be more or less accurate or reliable,
- can only be applied to specific types of materials or objects,
- different types of decay can be stopped, started, increased or decreased.

Additionally, from Figure 1 it is easy to understand how relative humidity values around 50% have become so widely accepted.

A comparison between the above ideal conditions and the onsite recorded conditions will determine in which period the existing values of temperature and relative humidity exceed the tolerable values and to what extent.

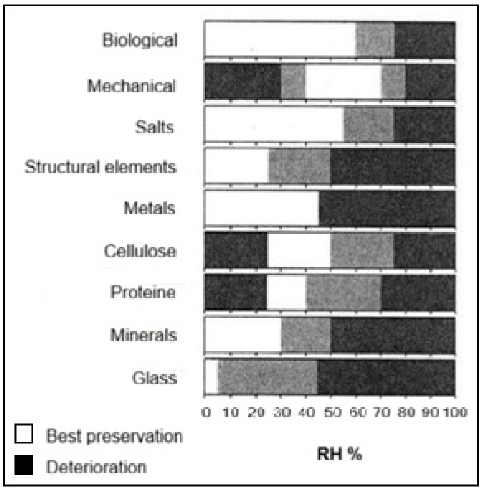

Figure 1. Overall humidity, relative humidity and deterioration zones (from [14]).

2.5. Built Shelters as Microclimate Regulators

Artificially created environment for monuments includes built shelters that aim to protect them from the influence of the weather conditions.

These constructions contribute to the formation of the microclimatic conditions both inside the monument and around it, using mechanical systems. Therefore, in order to evaluate the shelters' contribution to the creation of a stable microclimatic environment and minimization of heat and moisture exchanges, we need to define sustainable criteria and specifications for their construction, including the use of renewable energy systems to reduce energy consumption [15,16].

Proper protection of heritage structures could be achieved by adjusting the microclimatic conditions. The very nature of these constructions contributes to the formation of the microclimatic conditions both inside the monument and around it. The main objective is to stop any potential damage-inducing process and to take precautionary measures for sustainable management. "Smart" buildings and integrated systems are central to successfully addressing challenges posed by climate change and natural disasters. The improvement of energy efficiency is becoming increasingly important for monuments' preservation. Solutions more suitable for heritage buildings should be found in a wider range. Improving heat and light technology, and involv**ing** urban possibilities influence users' behavior and are starting points when it comes to developing innovative solutions that do not harm the monuments.

Importantly, shelter effectiveness cannot be generalized solely by form. Performance depends on soil properties, construction materials, entrance geometry, and regional climate, underscoring the need for site-specific evaluation rather than typological replication.

Shelter design emerges as a critical differentiating factor. Macedonian tombs exhibit a wide range of shelter configurations, from fully earth-covered tumuli to partially exposed structures with modern protective enclosures [1,3].

Analyses show that:

- Traditional tumulus cover provides the most stable hygrothermal conditions by buffering both temperature and moisture fluxes
- Lightweight or poorly ventilated modern shelters, although intended to protect from rainfall, often disrupt vapor diffusion and airflow, leading to condensation and localized deterioration [1,3]).

In order to evaluate the shelters' contribution to the creation of a stable microclimatic environment and the sustainable management of monuments, criteria and specifications should be defined regarding the construction of the housing shelter, the control of the indoor climate conditions, the properties of the construction materials and the promotion of the monuments [1,17].

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In the next section specific examples are presented regarding criteria and specifications for shelters.

3. Research Background–Applied Case Studies

Underground burial monuments have been the subject of research since the middle of the 20th century. Many scholars have been involved in recording and analyzing the characteristics of subterranean monuments all over the world.

Studies and management plans have been formulated and, in many cases, implemented to safeguard underground monuments.

All of these monuments have been constructed under the ground level, either as rock-cut cavities, or built with stone and covered with a tumulus. They have different features in building technology and decoration techniques, according to their historic period. Nevertheless, all of them have similar characteristics concerning the indoor microclimatic conditions, due to their contact with the soil or rock.

By examining different case studies, valuable conclusions can be drawn regarding subterranean monuments protection.

Additionally, more recent studies dealing with subterranean monuments are authored by the following researchers:

Becherini *et al.* (2010) [17], Scatigno et al. (2016) [18], Kim and Lee (2019) [19], Kyriakou and Panoskaltsis (2019) [20], Frasca, et al. (2020) [21], Zicarelli, et al. (2023) [22], Xia, *et al*. (2025) [23], Hu, et al. (2025) [24], Choi, and Lee (2025) [25].

3.1. Case Studies

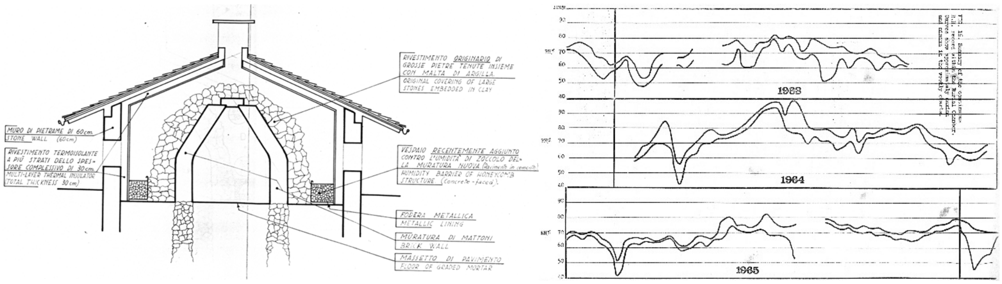
Below, we will review case studies which concern important subterranean monuments, in different regions:

Eastern Europe. Thracian Tombs (Bulgaria)
Southern Europe. Etruscan Tumuli (Italy) and Macedonian Tombs (Greece)
Egypt Rock-Cut Tombs
East Asia Japanese Tumuli (Kofun)
Chinese Rock-Cut Grottoes

3.1.1. The Thracian Tomb in Kazanluk, Bulgaria

Worldwide, since the middle of the 20th century, local cultural services and world organizations have begun to raise awareness on the issue of subterranean tombs. The pioneer in this field proved to be the UNESCO team. In 1966 they undertook the study on the protection of a Thracian tomb in Kazanluk, in Bulgaria.

Discovered in 1944, the tomb dates from late 4th to early 3rd century B.C. and it was inscribed on the UNESCO World Heritage List in 1979. It is one of the most significant monuments of Thracian funerary architecture and mural paintings of Hellenistic-style frescoes. The first systematic stabilization of the wall paintings and structural reinforcement have been done by Bulgarian conservation specialists. In 1964 the tomb was secured under a permanent protective shelter with air conditioning to ensure a stable temperature. The negative impact of the visitors was minimized by constructing in 1973–1974 a nearby museum that contains a full-scale replica of the tomb and its decoration for public display [26,27].



(a) (b)

Figure 2. The Thracian tomb of Kazanluk. (a) The tomb chamber and the protective shelter. (b) Fluctuations of the relative humidity, before the construction of the shelter in 1964 and after the construction, in two different periods, 1965 and 1988 (from [26,27]).

As is seen in the figure, there is a wide range of fluctuations during 1964, when the shelter's construction took place. After that, measurements during 1965 show that the range of relative humidity has been minimized, but still remained high due to the impact of the visitors. Measurements during 1988, after the construction of the replica, show a significant relative humidity stabilization.

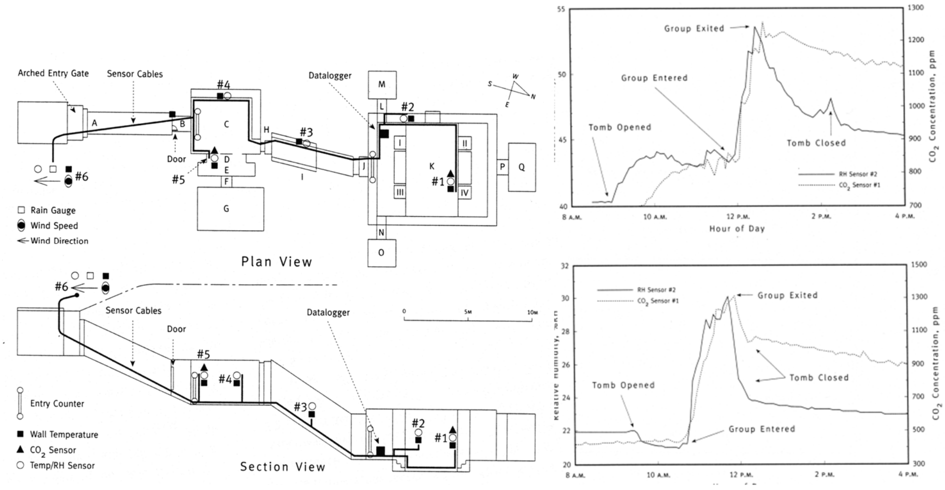
3.1.2. The Nefertari's Tomb and Tomb of Amon, in Egypt

In 1985, UNESCO in collaboration with the Getty Institute undertook a study on the protection of Nefertari's tomb in Egypt (1255 B.C.). Nefertari was the wife of Rameses II (1279-1213, B.C.).

Complete recordings of conservation status, analyses, evaluation of up-to-date interventions, microclimate recordings and guest control program proposals were studied by the Getty Institute. The UNESCO team has done great pilot studies and has shown that the right approach to the problem should be based on two main parameters:

- the composition of a team of scientists from different disciplines on one hand,
- and the systematic and long-term documentation before any intervention on the other.

Past mistakes have shown that temporary interventions can lead to major disasters. Interdisciplinary cooperation between many scientific fields is a necessity. Archaeologists, architects, civil engineers, geotechnical engineers, mechanical engineers, environmental engineers, conservationists, chemists, biologists and geologists need to work together [28–30].



(a) (b)

Figure 3. The tomb of Queen Nefertari. (a) Longitudinal sections of the preservation facilities constructed on the site, showing the points of the sensors; (b) Fluctuations of the relative humidity and CO_2 (from [29,30]).

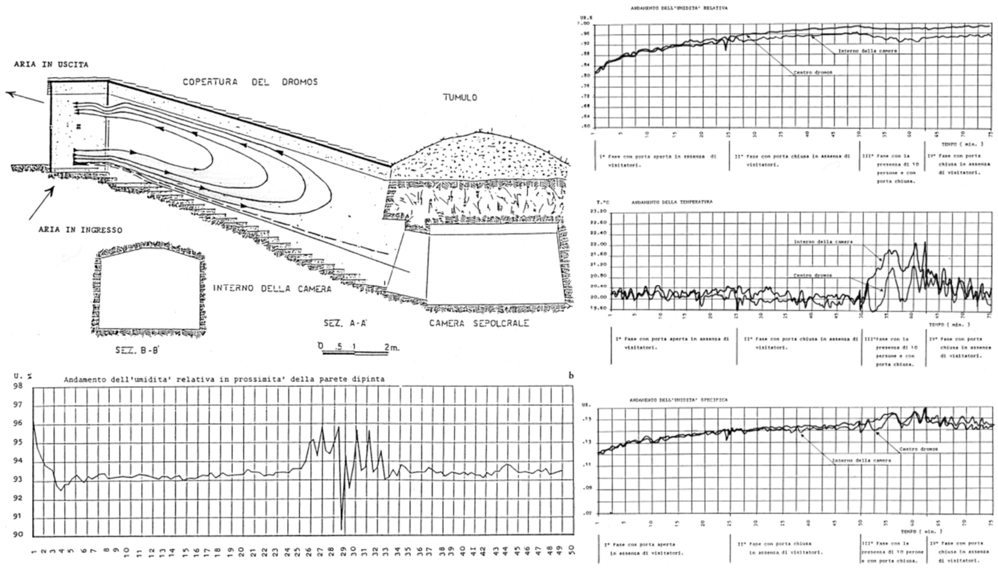
The relative humidity is stable before the opening of the tomb for visitors. After that, it rises to very high levels and drops again after the exit of the visitors.

3.1.3. The Etruscan Tombs in Italy

Since the 1980s, the Etruscan tombs, dated between the 7th and 2nd centuries B.C., were explored in Italy. All of them are carved out of bedrock, with exceptional wall paintings. Problems of humidity were addressed inside the tombs. After the frescoes have been repaired, transparent barriers, low-heat lighting and climatic monitoring systems were installed.

On-site research with monitoring has been carried out in the necropolis of Tarquinia and Cerveteri. Its purpose was to assess the possible relationship between the state of deterioration of the painted surfaces of the tombs and the microclimate conditions in the interior resulting from heat and moisture exchanges [32].

The authors used a mathematical model, by which the quantities of water vapor in the space were calculated and their changes were interpreted as exchanges of water absorbed or released by the materials. The conclusion was that hygrometric dynamics is determined by the movement of water through the walls, which is due to the circular flow of thermal energy. It became apparent that the microclimate is affected by thermal energy flows and water flows, which occur mainly between materials and the interior [31–33].



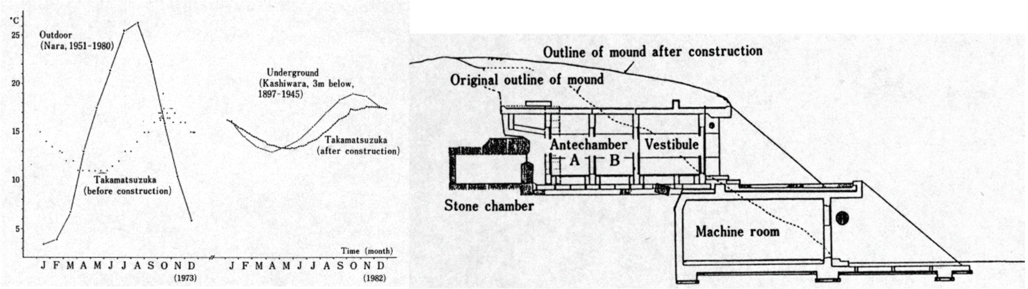
(a) (b)

Figure 4. Tombs in Tarquinia. (a) Cross section of the tomb of the Giocolieri and the shelter; (b) Monitoring of the relative humidity, during experiments (from [32]).

The experiments were conducted with the door of the shelter open or closed, and in the presence of ten visitors. The values of humidity are very high and the fluctuations are very intense, meaning that the stable microclimate is interrupted.

3.1.4. The Tombs of the Emperors in Japan

In Japan, similar research was carried out in 1983, at the Tombs of the Emperors dated in the 7th century A.D. These are monuments built with stone and covered by soil embankment. Scientific investigation of the conditions in the Emperors' Tombs began in 1983 and protective shelters with adjustable climatic conditions were constructed. The goal in all operations was to ensure stable temperature and humidity conditions, with different technical solutions and to restore at some degree the lost hygrothermal equilibrium [34–37].



(a) (b)

Figure 5. The Takamatsuzuka tomb. (a) Annual changes in temperature inside and outside of the stone chamber of the Takamatsuzuka tomb. (b) Longitudinal sections of the preservation facilities, shelter and mechanical equipment (from [34–37]).

Before constructing the preservation facilities in 1973, the range of temperature values were very high in the interior of the tomb. After the construction of the shelter in 1982, there is a stabilization of the temperature.

3.1.5. The Macedonian Tombs in Greece

Macedonian tombs in Greece have been excavated since the 1950s [38,39]. During this period protective shelters were constructed over the tombs in Imathia, the ancient Mieza (see Figure 6). After 2000, shelters were constructed over the tombs in Agios Athanasios and Foinikas [40], in Derveni [41] (see Figure 7c), in Aigai-Vergina [42–44] (see Figure 8) and in Pella [45] (see Figure 9).

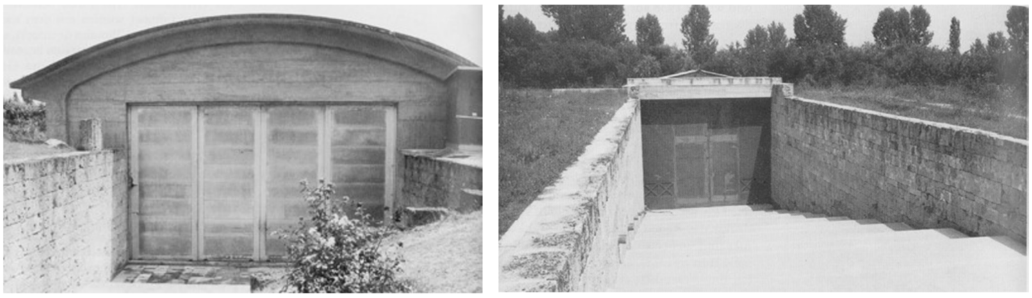
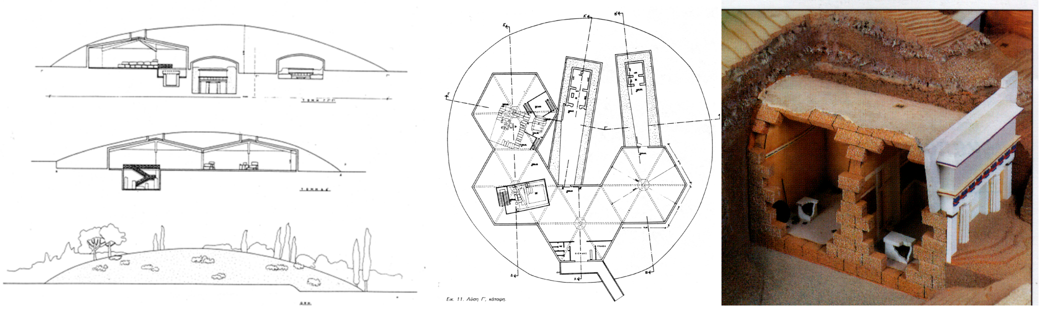


Figure 6. Shelters for Macedonian tombs in ancient Mieza – Imathia, (Photos by V. Kyriakou).

(a) (b)

Figure 7. (a, b) The Macedonian tomb in Agios Athanasios and plan of its shelter [40].

Over the Royal Tombs at Aigai (modern day Vergina) a museum has been constructed during 1993-1997 [42–44]. It is a built shelter in the shape of a tumulus with a soil embankment. This construction regulates the temperature and relative humidity conditions using mechanical equipment.



(a) (b) (c)

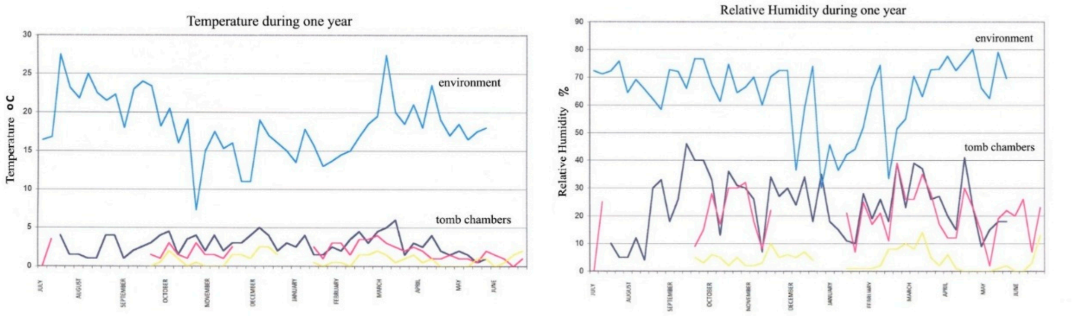
Figure 8. The shelter over the tombs at Vergina. (a, b) Drawings of the tumulus-shaped shelter (by Dimakopoulos and Zaglaniki, [43,44]). (b) 3D model of the Macedonian tomb (from [43,44]).

In Pella, there are excavations newer than Vergina's, where open shelters were constructed (Figure 9). The names –from the Greek alphabet- Γ and Δ are given by the excavators.

Recordings of the microclimate inside three tombs, i.e., the tombs Γ and Δ in Pella and one tomb in Agios Athanasios, gave comparative diagrams for temperature and relative humidity (Figure 10). All these results were obtained by using the simulation environment WUFI, which will be presented in detail in the next Section 5.2. [45,46].

(a) (b)

Figure 9. Open shelters in Pella. (a) Macedonian tumulus Δ. (b) Macedonian tumulus Γ. (Photos by V. Kyriakou.).



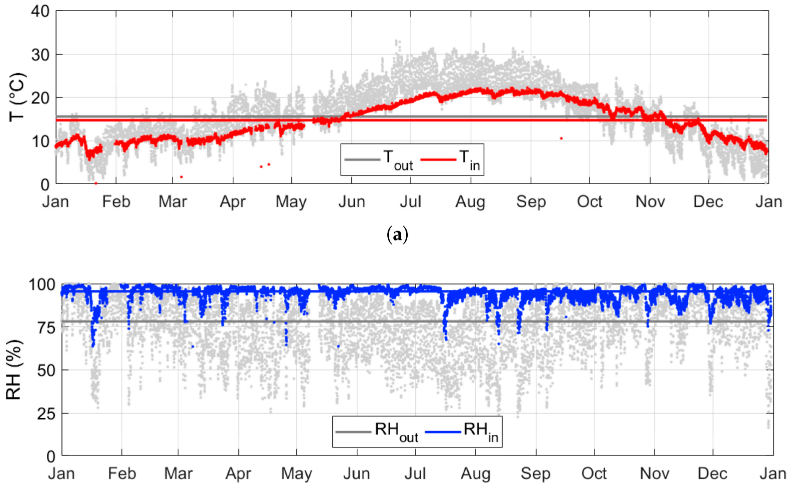
(a) (b)

Figure 10. Comparison between three tombs and the environment. Diagrams of temperature and relative humidity during one year (starting in July) showing the annual fluctuations inside the three tombs and the environment (blue line). (a) Temperature. (b) Relative humidity (from [45,46]).

Comparing the three tombs to the surrounding environment, there is a significant difference in temperature and relative humidity between the interior and exterior spaces. The temperature is quite stable, but the relative humidity has many fluctuations. The diagrams represent the conditions recorded while the tombs were covered by temporary, not closed shelters.

3.1.6. Hypogeal Sites: The Mithraeum of the Baths of Caracalla (Rome) [21]

Frasca et al. studied the deterioration processes inside the subterranean Mithraeum of the Baths of Caracalla (Rome). In their paper they presented the environmental monitoring campaign that was conducted during a period spanning 10 years. The study proposed a methodology to assess the frequently occurring hazards in such sites and evaluate the deterioration before and after maintenance interventions.



(**a**)

(**b**)

Figure 11. Hygrothermal conditions inside the monument. (a) temperature. (b) relative humidity (from [21]).

3.1.7. The Ancient Tombs of Baekje Dynasty in Republic of Korea [19]

Goguryeo tombs are found throughout North Korea and in the Jian region, China. Sixty-three of these tombs have been designated as UNESCO World Heritage Sites since 2004. Ten tombs of this type are in Republic of Korea, constructed from the 5th to 15th centuries. They have been managed as historical sites for their cultural importance. Currently, access to these tombs is restricted because of damage caused by exposure to the external environment and influx.

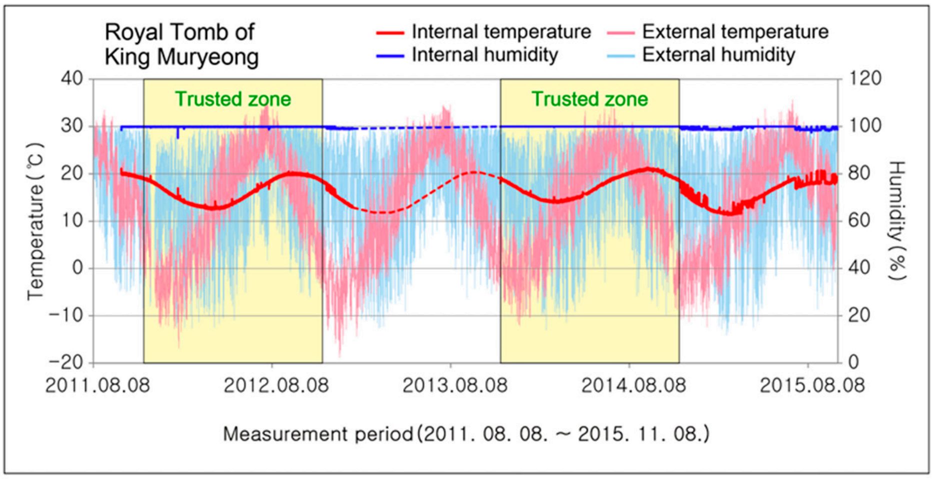


Figure 12. Microclimatic characteristics inside the tomb (from [19]). The indoor temperature differs from the outdoor temperature, as the heat transfer was minimized due to the tumulus.

3.2. Comparative Analysis Across Regions

Comparative overview of subterranean monuments from different regions, Southern Europe, Eastern Europe, East Asia, and Egypt, demonstrate that subterranean microclimates are governed by regional climate acting through local geological and architectural characteristics.

All share defining characteristics: construction below ground level, massive masonry or rock-cut envelopes, tumulus earth cover and decorated interiors. Comparatively, while absolute temperature and moisture levels vary regionally, the governing processes remain consistent: slow heat transfer through soil, moisture buffering by porous materials and limited air exchange.

3.2.1. Southern Europe. Macedonian Tombs (Greece) and Etruscan Tumuli (Italy)

Mediterranean climate: Hot, dry summers. Mild, wet winters. Strong seasonal contrasts in surface temperature.

Macedonian tombs, such as those at Vergina and Lefkadia, exhibit microclimatic behavior comparable to Etruscan tumulus tombs: high relative humidity (often >90%), minimal diurnal temperature variation, and strong dependence on soil cover thickness which reduces diurnal and seasonal fluctuation.

Implications: Good long-term preservation. Wall paintings are vulnerable to salt crystallization and moisture infiltration from winter rains. Ventilation affects condensation cycles.

3.2.2. Eastern Europe. Thracian Tombs (Bulgaria)

Continental climate: Hot summer, cold winters, sometimes severe, greater seasonal temperature amplitude than Mediterranean regions.

Microclimate: Subterranean tombs buffer extremes effectively. Strong seasonal moisture gradients in surrounding soils. Freeze–thaw cycles affect overlying mounds and entrances.

Implications: Interior temperatures relatively stable once sealed**.** Structural and decorative damage often results from: Water infiltration**,** pressure and cracking from seasonal expansion/contraction**, p**ainted reliefs vulnerable to humidity fluctuation rather than heat.

3.2.3. East Asia Japanese Tumuli (Kofun)

Humid temperate to subtropical: High rainfall. Strong monsoonal influence. Frequent typhoons and seasonal saturation of soils.

Microclimate: Earthen tumuli with stone chambers exhibit: high and persistent humidity**,** less thermal stability than deep rock-cut caves**.** Water infiltration is a dominant factor.

Implications: Organic materials degrade rapidly**.** Stone chambers subject to: condensation**,** biological growth (moss, algae)**,** long-term preservation depends on drainage and mound integrity.

3.2.4. Chinese Rock-Cut Grottoes

Highly variable by region: Northern China: arid to semi-arid, large temperature ranges. Central China: continental monsoon climate, seasonal extremes common.

Microclimate: Rock-cut grottoes are often semi-subterranean. Microclimates less stable than deep caves: Temperature and humidity fluctuate seasonally, exposure to wind and dust.

Implications: Major risks include: salt efflorescence**,** wind erosion**,** thermal stress on stone and pigments**.** Preservation is more challenging than in sealed subterranean tombs.

Asian tumuli and grottoes similarly demonstrate delayed but measurable coupling to external climate conditions, particularly through moisture ingress driven by seasonal rainfall and groundwater dynamics.

3.2.5. Egypt Rock-Cut Tombs

Hyper-arid desert climate**.** Extremely low rainfall, high surface temperature extremes**,** minimal biological activity.

Microclimate**:** Subterranean tombs exhibit very low relative humidity**,** high thermal stability despite extreme external heat**,** rock-cut chambers often cool relative to surface.

Implications: Excellent preservation of pigments and reliefs over millennia**.** Threats: increased humidity from tourism**,** condensation from human respiration**,** preservation historically favored by dryness rather than isolation.

3.3. Lessons Learned and Transferability

1. Microclimatic stability is more critical than achieving predefined “optimal” range.

2. Numerical modeling, based on long-term monitoring, is a powerful tool for testing intervention scenarios without risking irreversible damage.
3. Management strategies must prioritize access control and passive measures before considering technical systems.
4. Evidence remains fragmented and site-specific, indicating a research gap in comparative climate-change assessment. A greater availability of measured data for documentation of these issues, would offer further guidance for the sustainable management of subterranean monuments.
5. Transferability lies primarily in the methodological framework - observation, interpretation, modeling and careful intervention.

The following table (Table 1), presents all the monuments included in this comparative study, organized by the specific criteria they fulfill, regarding accessibility and environmental control.

Table 1. Comparative table: accessibility and environmental control in subterranean monuments (by the authors).

Monument / Site	**Use of Shelter as Microclimate Regulator**	**Controlled Environment Strategy**	**Monitoring & Measurement Strategy**	**Public Accessibility & Visitor Flow Control**	**Evidence of Measured Climate Change Impact**	**Microclimatic Stability Level**
Macedonian tombs Royal Tombs of Aigai (Vergina)	Yes (protective museum shelter covered by earth)	Yes (museum enclosure with environmental control – mechanical systems)	Yes (continuous monitoring inside the museum structure)	Yes (controlled indoor access)	Limited published long-term data	**High** (artificially stabilized, use of mechanical systems)
Macedonian Tombs of Pella	Yes (protective structures)	Partial (subterranean chambers under tumuli; mostly passive control)	Yes (periodic monitoring reported)	Limited public access; controlled visitation	Limited published long-term data	**Moderate–High** (passive buffering)
Etruscan tumuli Banditaccia Necropolis	Yes (tumuli as thermal buffer)	Limited (mostly passive control)	Partial (site-specific monitoring)	Yes (open-air site; limited interior control)	No systematic long-term studies	**Moderate** (affected by seasonal variation)
Thracian Tomb of Kazanluk	Yes (artificial shelter was constructed)	Yes (protective shelter; passive control)	Yes / (periodic monitoring)	Limited and regulated access	Limited published quantified data	**Moderate–High** (shelter, visitors restricted)

Japanese tumuli Mozu-Furuichi Kofun Group	Yes (massive earthen mounds)	No active internal control (sealed chambers)	Very limited (due to restricted access)	Generally inaccessible; perimeter viewing only	Limited published available	**Moderate** (humidity-dominated)
Yungang Grottoes North Korea and China	Partial (cliff excavation; limited depth buffering)	Yes (structural shelters; wind/dust mitigation)	Yes (environmental and structural monitoring)	Yes (open to public; managed pathways)	Limited (concerns regarding environmental stress)	**Moderate–Low** (exposed to seasonal variations)
Valley of the Kings, Egypt	Yes (deep rock-cut chambers)	Yes (ventilation systems in selected tombs)	Yes (CO_2, RH, temperature monitoring in biger tombs)	Yes (regulated tomb entrance and visitor limits)	Increasing humidity linked to tourism and climate variability	**High** (dry conditions; visitor-sensitive)

4. The Concept of Sustainability and Climate Change Adaptation

Sustainability in cultural heritage can be stated as "preserving heritage assets as well as possible, at the same time as providing access as well as possible, given limited resources". The UNESCO SDGs (Sustainable Development Goals) included the preservation of built heritage in Goal 11 [47]. The question is how to balance preservation with sustainability, the lack of resources, over-tourism and climate change. Climate Change Response Strategy sets out four primary pillars for management of protected areas: science, adaptation, mitigation and communication [48,49].

First, the science pillar collects all the work that has been done to gather climatic data (measurements, modeling and related issues). There is science to identify and track impacts of climate change on cultural heritage, and there is science that learns from or works with cultural heritage for an improved and broader understanding of climate change.

Adaptation aims to determine what is needed to do about climate change, policy, planning and decision making. There is adaptation of management approaches to address the impacts of climate change on cultural heritage, and there is learning from cultural heritage in order to assist in adapting resource management and society to climate change. For example, the impacts side of the science pillar focuses on methods and data that characterize interactions of climate change phenomena with components of cultural heritage. Materials science compiled in the Atlas of Climate Change Impact on European Cultural Heritage is one example of such work [50]. Mitigation includes efforts to reduce greenhouse gas emissions. Finally, communication means sharing information among resource managers and with the public [54].

The impacts aspect of the adaptation pillar addresses questions of what to do about the impacts of climate change on cultural heritage identified by work in the science pillar. Key parts of this process include scenario planning [51] and development of cultural heritage management options that address climate change impacts and maintain historical integrity [52]. As the outputs from global climate models project that climatic changes will grow larger over the current century with the magnitude of the projected change dependent on the selected path of greenhouse gas (GHG) emissions and the model selected, strategies need to be developed to reduce the negative consequences of climate change on sites of historical value in addition to mitigate climate change by curtailing GHG emissions.

Our tangible cultural heritage is threatened by gradually shifting weather patterns and extreme events. An increase in temperature together with changes in precipitation, relative humidity, and wind, for instance, can negatively impact on the materials comprising cultural heritage assets. This is because a change in average climatic conditions as well as changes in the frequency and intensity of severe weather events can affect the biological, chemical, and physical mechanisms leading to degradation of the assets [53].

Sabbioni et al. [50] developed guidelines for adapting the European cultural heritage to climate change impacts, which were later adopted by the Italian Strategic Agenda. These included strategies for both physical adaptation and for adjusting management practices. Examples of the latter include improving the monitoring, maintenance, and preparedness to floods and landslides at cultural heritage sites. Cassar [54] investigated the impacts of climate change on archaeological sites and suggested adopting solutions that are sensibly designed to the specific conditions of the site after a long-term program of monitoring and maintenance. Additionally, Cassar [55] summarized the adaptation measures suggested by the UN Educational, Scientific and Cultural Organization (UNESCO) and by the International Council On MOnuments and Sites (ICOMOS), who recommend increasing research, knowledge, education, engagement, the upgrading of management plans, including risk assessments, and monitoring procedures to increase the resilience of the sites. However, natural processes have often been ignored in previous assessments of vulnerability.

Climate change adaptation is thus a relatively new challenge and this is particularly the case in the field of cultural heritage. The impacts of climate change on cultural heritage were first mentioned in the chapter on Europe of the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) in 2014. Following the adoption of the Paris Agreement, the World Heritage Committee of UNESCO, at their annual session in 2017 in Krakow, Poland, noted the pressing issue of climate change impacts on World Heritage properties and requested that the UNESCO World Heritage Centre support State Parties in managing climate change impacts and in strengthening collaboration with the UNFCCC and the IPCC [56].

The World Heritage Committee is responsible for the World Heritage Convention and consists of representatives from twenty one of the State Parties, which are elected by the General Assembly. This led to the IPCC consulting with UNESCO to identify topics to be incorporated as part of AR6 to be published in 2021. Climate change impacts were only briefly mentioned in AR5 and the impacts presented in the report were mainly the results of initiatives funded by the European Commission (EC) over the last 15 years such as the Noah’s Ark (2003–2007) and Climate for Culture (2009–2015) projects. These projects focused on the threats of climate change on cultural heritage with limited attention given to adaptation of cultural heritage to climate [51].

The change of global climate affects underground microclimates, primarily through indirect and delayed mechanisms. Rising mean surface temperatures, and increased frequency of extreme weather events progressively modify the boundary conditions governing heat and moisture exchange between soil, rock, and enclosed underground spaces.

Subterranean monuments should no longer be treated as climatically isolated systems. Instead, they must be understood as coupled surface–subsurface environments, where climatic conditions interact with local geology, hydrology, and human use. Conservation strategies should therefore prioritize continuous monitoring, early detection of threats baseline shifts, and flexible management approaches aligned with preventive conservation principles and long-term risk assessment methods [57–60].

5. Critical Analysis of Literature–Discussion

Researchers worldwide have been using similar methodology to approach the complicated issue of analyzing the microclimate inside underground monuments in order to support the decision making and propose actions for optimal preservation.

Due to the large number of parameters to be considered in analyzing the microclimate, the use of computer software is essential to achieve this objective. The computer can perform repeated test cycles using different data and enables experimentation with alternative approaches e.g., use of different materials and building techniques (see Table 2).

Table 2. Hygrothermal Simulation Tools (from [63] and addition of websites by authors).

1D-HAM	1D heat-air-moisture	http://www.buildingphysics.com
BSim	1D heat-moisture	http://www.sbi.dk/
Delphin 5	1-2Dheat-air-moisture-salt-pollutant	http://bauklimatik-dresden.de
HAM	1D heat-air-moisture	http://archbps1.campus.tue.nl/bpswiki/index.php/Hamlab
HAMLab	1-2-3D heat-air-moisture	http://www.byggnadsteknologi.se/ibpt.html
HygIRC-1D	1D heat-air-moisture	http://www.nrc-cnrc.gc.ca/eng/projects/irc/hygirc.html
HygIRC-2D	2D heat-air-moisture	http://www.nrc-cnrc.gc.ca/eng/projects/irc/hygirc.html
LATENITE	1D heat-moisture	Previous version of the HygIRC
MATCH	1D heat-air-moisture	http://www.match-box.dk/uk/whatisdatasheet.htm
MOISTURE-EXPERT	1D heat-air-moisture	http://www.ornl.gov/
WUFI-2D	2D heat-moisture	https://wufi.de/
WUFI ORNL	1D heat-moisture	https://www.ornl.gov/content/wufi-software
WUFI-Plus	1D heat-moisture	https://wufi.de/
WUFI-Pro	1D heat-moisture	https://wufi.de/

5.1. The Working Methodology

Decision making should be done having full understanding of the monuments' behavior and the contribution of each individual factor to the deterioration processes. Strategic management and control of the microclimate in the tombs will be based on the result of the evaluation which can assess strategies using a simulation program.

Through data collection, analysis, simulation and interpretation of the results, research provides an assessment methodology of microclimate control strategies aiming to protect subterranean tombs.

The following methodology can be applied in all the subterranean monuments:

- The first step consists of the investigation of the microclimatic conditions in the subterranean monuments, i.e., temperature and relative humidity (RH) recordings. A specific recording methodology must be followed for at least one year. By specific methodology we mean the positions of the instruments in the monument and the time step of data recording. Digital recorders, which have the appropriate sensors in order to record both temperature and relative humidity are commonly used.
- The second step pertains the input of data, i.e., of the recordings, to the computer program that will be used. The simulation provides results regarding fluxes of heat and humidity inside the structural elements of the monuments.
- The third step is the analysis and interpretation of the output; with these we are able to assess the hygrothermal performance of the monuments' structural elements.

- Then, in case a shelter has been built over the monument, the program is executed again, using the new boundary conditions.
- The last step consists of the interpretation of the results and leads to conclusions about the effect of the applied microclimate on the hygrothermal performance of the monument, because of the built shelter.

5.2. Hygrothermal Computer Programs

Many software programs have been developed for hygrothermal simulation. Until 2010 more than 57 hygrothermal software programs existed, see Table 2 [63].

Delgado et al. [64,65] used the DELPHIN program to verify the WUFI program and concluded that DELPHIN [66] gives more realistic results for moisture. Hejazi et al. [62] compared results from WUFI and DELPHIN programs for three different materials and concluded that the results obtained are very close, except for total water content during the wetting period.

Mundt-Petersen and Harderup [61] compared results from WUFI and DELPHIN for the risk of mold growth.

WUFI® is a family of software products that allows realistic calculation of the transient coupled one and two - dimensional heat and moisture transport in walls and other multi-layer building components exposed to natural weather. WUFI® is an acronym for Wärme Und Feuchte Instationär - which, translated, means heat and moisture transiency.

WUFI® has four products: WUFI® Pro is used for one-dimensional analysis of building components under pre-defined indoor climates, WUFI® 2D for two-dimensional analyses, WUFI® Plus for analyzing energy usage and interior comfort, WUFI® Passive has the same energy usage capabilities as WUFI® Plus, but it also enables optimization of 'passive house' design by providing monthly energy balances [67].

5.2.1. Example of an Application of the Simulation Software WUFI® Pro

The software WUFI® Pro, is a one-dimensional program, which determines the content of the moisture in the building elements as well as its transfer. It also determines the simultaneous transfer of heat through the building components. This program solves numerically a set of partial differential equations -Equations (1) and (2) - and has been validated repeatedly [68–71].

Equation 1. Heat transport

$$\frac{\partial H}{\partial \vartheta}\frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial x}\left(\lambda \frac{\partial \vartheta}{\partial x}\right) + h_v \frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial p}{\partial x}\right) \quad (1)$$

Equation 2. Moisture transport

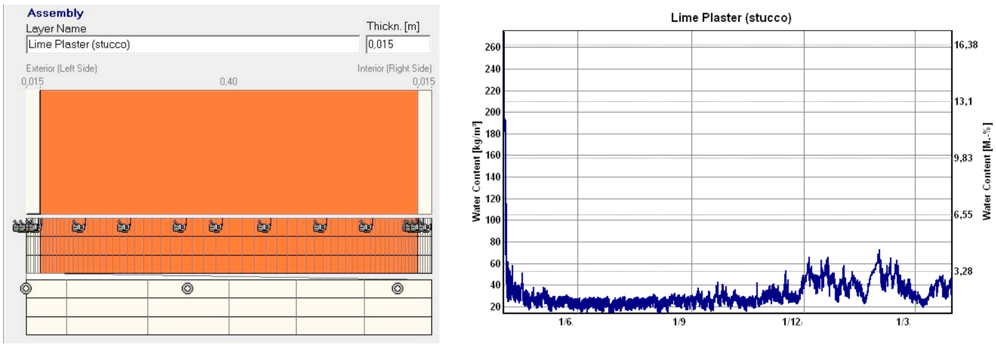
$$\rho_w \frac{\partial u}{\partial \varphi}\frac{\partial \varphi}{\partial t} = \frac{\partial}{\partial x}\left(\rho_w D_w \frac{\partial u}{\partial \varphi}\frac{\partial \varphi}{\partial x}\right) + \frac{\partial}{\partial x}\left(\frac{\delta}{\mu}\frac{\partial p}{\partial x}\right) \quad (2)$$

where,

D_w [m^2/s] is the liquid transport coefficient
H [J/m^3] the enthalpy of moist building material
H_v [J/kg] the evaporation enthalpy of water
p [Pa] the water vapor partial pressure
u [kg/m^3] the water content
δ [kg/msPa] the water vapor diffusion coefficient in air ($kg \cdot s^{-1} \cdot m^{-1} \cdot Pa^{-1}$)
θ [°C] the temperature
λ [W/mK] the heat conductivity of moist material
μ [-] the vapor diffusion resistance factor of dry material
ρ_w [kg/m^3] the water density
φ [-] the relative humidity.

The software WUFI® generates geometric representations of the component under study.

The section of the building component unit introduced in the simulation tool is presented in the following figure. Then the output of the program consists of diagrams showing the variation of temperature, the humidity percentage, the water content, as well as evolution of fluxes during one year [72].


Assembly
Layer Name: Lime Plaster (stucco)
Thickn. [m]: 0,015

(a) (b)

Figure 13. (a) Profile of the building element created in the simulation software; (b) output showing the variation of water content inside the building element, created in the simulation environment WUFI©Pro (from [45]). The diagram shows that the water content increases during the condensation period.

It should be stressed that the diagrams for Macedonian tombs, presented earlier in Figure 10, were obtained by us with the use of the methodology described here.

The export data of the simulation program are numerical data and diagrams, presenting:

1. The variation of temperature and relative humidity–in the interior of the exposed building elements.
2. The water content evolution in the mass.
3. The condensation period.
4. The heat fluxes in the mass.
5. The moisture fluxes in the mass.
6. The air pressure evolution.

The range of fluctuations inside the monuments depends on [45]:

1. The dimensions of the interior (volume).
2. The size of the tumulus.
3. The degree of excavation and exposure of the structural body to the external environment.
4. The type of protection shelters constructed.

Further research must be done to identify deterioration processes taking place. Energy dissipation in structural materials under the action of general stress and strain histories has been dealt with in detail in Panoskaltsis, 2025 [73].

5.3. Decision Making in the Case Studies

In order to protect and preserve the subterranean monuments we should establish stable hygrothermal conditions by implementing the following actions.

These were applied in case studies presented in section 3.

5.3.1. Procedures Throughout the Excavation Process

Provisional protective actions are required at the entrance to the monument throughout the excavation phase.

These measures are intended to prevent air circulation in front of the monument’s entrance, as well as to stabilize temperature and relative humidity inside.

This can be accomplished by a second room before the monument's gateway to reduce air exchange. Adding thermal insulation could further reduce the impact of the external climatic conditions [3,45].

5.3.2. Actions to Control the Microclimate

The following are recommended. See for more details [3,45].

- A shelter must ensure the control of microclimate conditions and their correct setting to provide protection from humidity, temperature and other effects.
- The choice of shelter design influences to a great degree the internal climatic conditions as well as the cost of supplementary control systems.
- Thermal insulation of the shelter is needed in order to protect the enclosure from overheating in the summer and frost in the winter.
- Double entrance of the shelter is needed - so that one door will be closed when the other opens - in order to minimize the air exchanges.
- In the case of mechanical systems operating - in order to regulate the variations of temperature and relative humidity - energy consumption should be taken into account. Additionally, constant maintenance and good functioning should be ensured.
- Energy consumption may be also influenced by modifications in the adjacent environment.

In order to alter microclimatic conditions outside the shelter, proper plantation and artificial barriers may be used for shading and also for changing the direction and speed of the winds.

Shelter design, climate control, and access policies must therefore be: site-specific, reversible and informed by long-term empirical data.

Across regions and monument types, the literature converges on a central principle:

Successful conservation of subterranean heritage depends on respecting existing microclimatic equilibria while minimizing anthropogenic disturbance.

6. Identifying Current Gaps, Problems and Limitations

Research on the themes presented above involves interdisciplinary scientific subjects and additionally field research. Therefore, there exist limitations to its course. These may be either on technical and practical issues or gaps of knowledge concerning lack of data for material properties as well as weather conditions.

Other limitations are:

- the complexity of physical interactions,
- the human factor, i.e., the right use of the software and the correct interpretation of the calculation results.

All these are analyzed in more detail in the following subsections.

6.1. Technical Limitations

The electronic equipments may give wrong measurements in case they have not been calibrated. The recorders may not have adequate data input channels, so simultaneous recordings may be restricted. Additionally, there may be data gaps due to limited memory of the recorders. Also, the recording must be temporarily paused in order to check the instruments' calibration.

The simulation program also has limitations concerning the criteria for choosing the specific simulation tool. It should be user-friendly and also commercially available. It must have been validated by comparison with experimental results [61]. The results should be checked for plausibility. Some possible problems are: input errors, e.g., insufficient knowledge of the required data, program errors (convergence failures; convergence during all calculations must be checked to be zero [64]). Additional problems are: insufficient knowledge of the required data, limitations of the underlying mathematical model and numerical problems [64]. Clearly, a correct model of the building element must be created in the program. It is essential that reliable outdoor climate boundary conditions be used. Calculations must be made using real climate conditions because there are significant outdoor climate variations between different years that affect the results. Differences in temperature can have a great effect on relative humidity.

Materials' properties used as input to the program is a difficult task since there is a significant lack of data related to the hygrothermal properties of ancient materials. In addition, materials' properties change over time and under different conditions, especially when they have been buried under the soil for centuries. Material data may be taken from laboratory testing. In case of material unavailability from the monument or of laboratory limitations, data may be taken from the program's database [64,66,67].

As discussed by Camuffo [57], laboratory-scale investigations remain essential but must be adapted to heritage constraints, favoring small-sample sorption tests, pore-structure characterization, and moisture-dependent thermal measurements. However, laboratory-derived values should be interpreted as effective rather than intrinsic properties, owing to the heterogeneity, ageing, and alteration of historic materials.

6.2. Interpretation of the Calculation Results

The correct interpretation of the exported data is very important. A very good knowledge of the software and also an excellent understanding of the mathematical equations are needed to avoid wrong conclusions.

6.3. Unpredictable Constraints

Extreme weather conditions and lack of appropriate arrangements at the archaeological sites could be the reasons to interrupt the recordings and lose important data.

Additionally, the uncontrolled entry of workers and visitors in the monuments may alter the recordings' readings.

6.4. Gaps of Knowledge and Conclusions

The above limitations and gaps are not equally problematic. Some of them, such as weather data, could be available from national meteorological stations. Others, such as the properties of ancient materials, require extensive research and laboratory testing. The interactions of moisture with other agents and its impact on human health are issues so complex that high levels of uncertainty still remain in this scientific area.

An updated framework for the assessment of the monument's hygrothermal behavior should therefore be incorporated into the design, construction and use procedures. Regulations and standards should be improved as knowledge increases rapidly in the scientific area of building physics. Corresponding standards are: EN 16893-2018, ISO 15757-2010, ASHRAE Guideline 34.

7. Conclusions and Future Directions

In the paper, the following important points were made:

- Decoding concerns the analysis of the hygrothermal behavior of the monuments and this should be the basis of decision making in order to protect and safeguard the built heritage from climate change.
- Numerical simulation is a necessary and effective tool to decode the microclimate inside subterranean monuments.
- An evaluation methodology based on computer simulation is needed. The steps of the methodology are: data collection, computer simulation, analysis and interpretation of the results. This way, the decision-makers will decide having a full understanding of the monument's hygrothermal behavior and of its deterioration factors contribution.

- There should be a systematic investigation of the deterioration of the subterranean monuments, as a result of human carelessness, abandonment and environmental conditions.
- Evidence remains fragmented and site-specific, indicating a research gap in comparative climate-change assessment.
- Further scientific research should be done on the topic of the built heritage adaptation to climate change. The UNESCO SDGs (Sustainable Development Goals) included the preservation of built heritage in Goal 11.
- The adaptation to climate change identifies four main categories of adaptation measures: technological, behavioral, managerial and policy. Each one should be further investigated with scientific tools.
- In order to increase the resilience of heritage sites there is a need to upgrade management plans, including risk assessments and monitoring procedures. Resilience has to do with the risk of loss. But risk in the case of built heritage does not only measure tangible phenomena, e.g., natural disasters, collapse during an earthquake, the gradual erosion of a wall, which are only half of the risk. The consequences depend on intangible phenomena too, such as loss of value, integrity and authenticity. Identifying and assessing the risks is a crucial step towards resilience of cultural heritage sites.
- There is a need for practical solutions and tools for the incorporation of climate change adaptation in the preservation and management of cultural heritage. Case studies of best practice are needed, both in managerial and decisional aspects.
- It is essential that interdisciplinary research involving different scientific specialties be done.
- Energy efficiency, minimized consumption, zero energy shelters, on site renewable energy production, and distance energy supply, are main issues that should be addressed as quickly as possible. Legislation and policies should be updated in order to support these new challenges in the field of built heritage preservation.
- The impact of shelters is complex; therefore, continues studies and monitoring are crucial for a long-term assessment.
- A great challenge to be addressed nowadays is the use of information and communications technology (ICT), i.e., long distance monitoring, wireless sensor network, smart management systems and virtual reality.
- Finally, monumental and depicted subterranean heritage constructions should be included in the list of UNESCO World Heritage Sites, because of their unique and outstanding universal value.

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