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MITIGATION AND ADAPTATION TO CLIMATE CHANGE IN THE CONSERVATION AND PRESERVATION OF THE ARCHITECTURE AND FUNERAL LANDSCAPE IN QUBBET EL HAWA, ASWAN, EGYPT

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SUMMARY
On the western coast of Egypt, high-ranking officials and members of the Elephantine elite chose the east-facing hill of Qubbet el-Hawa as a cemetery. Until a few decades ago, when these tombs remained untouched, the environmental conditions inside remained constant. However, the process of exhumation and excavation of many of these tombs in the necropolis has accelerated their deterioration. Additionally, the impact of climate change, including increases in interior temperature and relative humidity, has further compounded to the problem. This research proposes a method for evaluating the impact of future climate scenarios on the preservation and conservation of tombs. An experimental method was followed, combining analytical formulations and in-situ measurements. The climate change scenarios predicted for 2030, 2050, and 2100 were based on the projected temperature variations. The case studies focused on the Qubbet el-Hawa tombs located in Elephantine.Data obtained from the monitoring campaign carried out in these tombs were used to validate simulation models. Design Builder, Energy Plus, and Dialux Evo software were used to generate models that replicated the tombs in detail, simulating indoor environmental conditions. One of the main conclusion of this study, is that measures to ensure the preservation and conservation of this heritage should be the reduction in fluctuations in relative air humidity and UV radiation in the interior space.

INTRODUCTION
Climate change poses a threat to the preservation of monuments and natural heritage sites worldwide, and it is crucial to protect them from its impact. At present, there is a commitment to integrate the preservation of world heritage into climate actions and strategies to mitigate and adapt to global warming.

The Egyptian funeral architecture and landscape are at risk of disappearing in less than a century due to the effects of climate change. Increasing exposure to the extreme changing climate could leave a footprint that endangers one of the most significant monuments for humanity, as highlighted during the last COP27 in Egypt.

According to the IPCC (Intergovernmental Panel on Climate Change) document, there are four possible scenarios of climate change, known as Representative Concentration Pathways (RCP), which consider climate policies (IPCC, 2014). These pathways represent a theoretical projection of greenhouse gas concentration (not emissions), adopted by the IPCC. At present, four different pathways for future climate change modelling (RCP 2.6, 4.5, 6.0, and 8.5) can be distinguished according to radiative forcing ranging from 2.6 W/m^2 to 8.5 W/m^2. These RCPs are associated with policies which aim to limit 21st-century climate change. In the case of RCP 6.0 and RCP 8.5, this radiative energy reaching the earth does not reach its maximum until 2100. For RCP 2.6, it reaches a maximum and then decreases, while for the intermediate scenario of RCP 4.5 it reaches a maximum in 2040 and then decreases until it stabilizes towards 2100. This last scenario could cause a global temperature increase of 2-3°C and a 35% average increase in sea level (Mugiyo *et al*. 2002).

1. DETERIORATION, CLIMATE AND IMPACT OF CLIMATE CHANGE IN EGYPT

The climate and geography of Egypt play a crucial role in the preservation of Egyptian tombs, as the desert environment in which they were built has influenced their construction and deterioration over time. However, their conservation is now at risk due to the effects of climate change, which in turn also puts them at risk of deterioration. (Moreno Cifuentes 2013).

Floods and torrential rains caused by the changing climate have resulted in the deterioration of some of the tombs. In response, drainage systems and channels have been set up to control water, preventing it from entering the interior chambers (Köpp-Junk 2020). Wind erosion has also been a factor in the deterioration of the tombs, with the impact of sand particles causing surface abrasion on the walls. In recent years, storms and winds far more severe than any observed previously have been recorded in Egypt, and are also considered the result of climate change (Azouz & Salem 2023).

Factors such as high temperatures, high relative humidity, direct sunlight, and sudden changes in environmental parameters inside the tombs can cause disintegration and decohesion of the elements which make up these tombs, particularly in the lower areas of these buildings (Wing *et al*. 2018). In areas near rivers, high subsurface humidity and high temperatures can lead to water vapour condensation, which can form deposits on the materials of the tombs, leaving crystalline deposits causing the surfaces to disintegrate. Thermal fluctuations can also cause the dispersion or loss of material inside the tombs (Iamarino, Neira Cordero, Lovecky, & Ojeda 2021).

Overall, climate change poses a serious risk to the conservation and preservation of Egyptian tombs. Therefore, conservation efforts must take into account the effects of climate change in order to ensure their long-term preservation.

The phenomenon of water vapour condensation near rivers in Egypt can negatively impact the materials of these tombs (Duivenvoorden *et al*. 2022). The combination of high subsurface humidity and high temperatures causes water vapour to condense and accumulate on the surfaces of the tombs, typically during early morning and dusk, when the air is relatively cooler and more humid. During the day, when the air is dry and hot, the humidity evaporates, leaving behind any salts that were carried by the water vapour. These salts deposited on the surfaces of the tombs or penetrating them through capillarity form crystalline deposits capable of causing surface disintegration. Additionally, thermal fluctuations can cause material inside the tombs to disperse or be lost (Sakr, Mahmoud, Ghaly, Edwards, & Elbashar 2021).

Another factor to consider is that of direct sunlight on surfaces with Egyptian paintings, where continuous exposure causes discoloration of the pigments due to ultraviolet rays and an increase in surface temperature due to infrared rays (Iamarino, Neira Cordero, Lovecky, & Ojeda 2021). Egypt is very vulnerable to the effects of climate change. Furthermore, the Nile Delta is considered the most threatened delta in the world and one of the three most extremely vulnerable areas on the planet, affected by climate change. This fragility is due to the increase in high temperatures, the annual sinking of its coast, the rise in the Mediterranean sea level, and a lack of foresight and means of adaptation.

2. METHODOLOGY

This research project aims to analyse the current microclimate of the tombs and the consequences of future climate change. An analysis will be carried out on the environmental parameters for the preservation and conservation of funerary architecture in Qubbet el-Hawa, Aswan.

This section presents the methodology employed in this research, which is based on an in-situ experimental method combining in-situ measurements and analytical formulations simulated by software to predict the interior environment of the tombs. The in-situ measurements are subsequently used to generate simulation models for real buildings which are then validated.

2.1 CASE STUDY

This research focuses on the study of the double tomb belonging to the high officials Mekhu and his son Sabni (catalogued today as QH25 and QH26, respectively), members of the social elite of the community of Elephantine (Jiménez-Serrano 2023). This project is perhaps one of the most prominent in the necropolis, located at the southernmost end of the hill, creating a striking visual image looking over the island. The two monumental ascending ramps with a shared common space halfway up the slope, limited by a carved stone facade, are easily recognizable from a distance. Although originally intended as a burial site for Mekhu, it was later transformed into an expanded double tomb, a space excavated for father and son. The two thresholds connecting to the shared chapel appear as two large cutouts in shadow on the stone, flanked by numerous subsidiary tombs arranged on the common reception courtyard. The large worship chapel is perceived as a single space, although its design and composition clearly show that it is the result of two merged projects. Even so, it is possible to perfectly identify the worship axes of both spaces, connecting the threshold with the false door located in the niche, a sacred space par excellence which is protected both physically and visually by adobe walls.

Among the sea of circular and square section columns that invade the worship space, a series of panels are distributed as supports for images of the owners and their families, as well as false doors and funerary chambers. The position of these images, showing likenesses of father and son, and everyday activities such as hunting and fishing, guarantees that they receive sunlight through the two cutouts in the facade (Joyanes Díaz, Muñoz González, Martínez de Dios, & Ruiz Jaramillo 2022).

Figure 1: Tombs Q25-Q26.
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Tombs Q25 and Q26 (Fig. 1) were excavated in the necropolis in sandstone and lutites rocks, which is prone to self-destruction given its characteristic sedimentary nature. These rocky surfaces, as can be seen in the images, are not suited to carving or painting, so that in some cases, they have been covered with mortars and plaster to support a layer of decoration.
An initial inspection showed that the tombs had also been subject to natural deterioration together with the human actions, as intentional fire, provoked by ancient looters.

2.2 OUTDOOR CLIMATE

Currently, in Aswan, summers are very hot and winters are mild, but there are daily abrupt changes in temperature and relative humidity between day and night, reaching differences of up to 10-15ºC and 20-35%, respectively. The thermal jump is less pronounced in winter than in summer, although the difference in relative humidity is greater in the winter season than in the summer (see Fig. 2). In the early morning and at sunset, temperatures are lower and relative humidity is higher, while at noon temperatures rise due to the effect of solar radiation. These fluctuations in temperature and relative humidity can cause the mineral stone to expand, generating internal tensions.

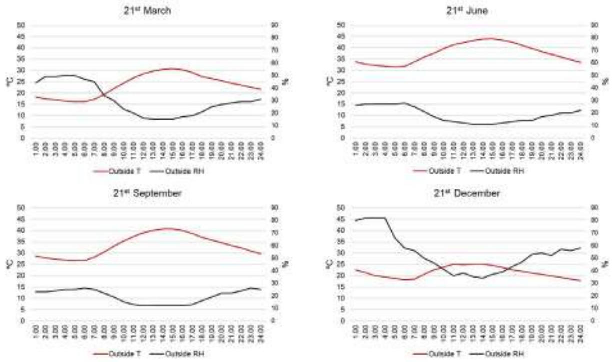

Figure 2: Hourly data of temperature and relative humidity in Aswan. 21st day.
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The local wind, which is dusty, dry, and warm, lasts for about 5 months, and usually occurs between May and September, dragging large amounts of sand and dust from the desert and causing temperature rises. The predominant direction during this time is southwest, while for the rest of the year it is north and east (see Fig. 3). This environmental parameter is one of the most aggressive for conservation because it produces abrasion and excessive dry humidity affecting the stone. This causes changes and losses in morphology, producing rounded shapes. Additionally, this sand-laden wind penetrates into excavated tombs with no protection at the entrances, directly affecting the chambers and walls, wearing down the reliefs and polychromy.

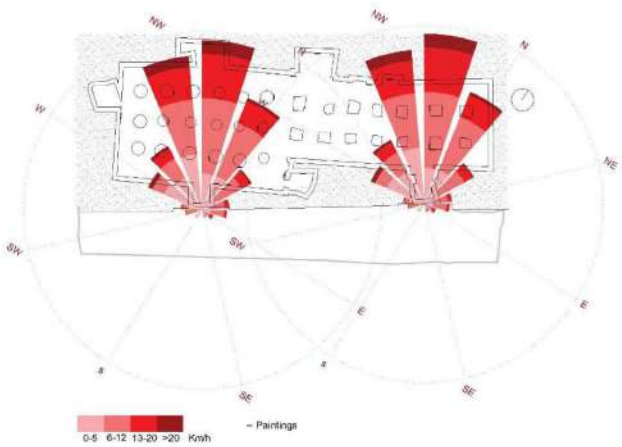

Figure 3: Prevailling wind direction.
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2.3 MEASUREMENTS AND COMPUTATIONAL MODELLING

Simultaneous measurements of temperature and relative humidity, as well as point measurements of lighting levels inside the tombs, were taken during several campaign periods from 2019 to 2021 (Jiménez Serrano 2019), (Joyanes Díaz 2021). The recording range was from -35 to 80ºC and 0-100%, with an accuracy of ±3ºC and a resolution of 0.03ºC, and ±2%

and a resolution of 0.05% in the case of relative humidity. Measurements for external temperature, relative humidity, wind, global radiation, cloud cover, and pressure were obtained from a nearby meteorological station.

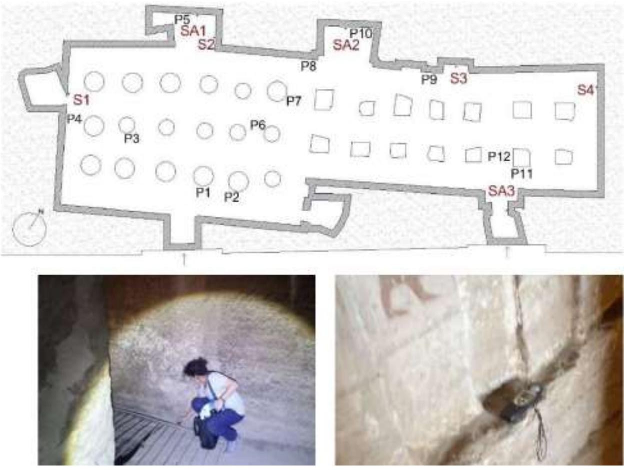

Figure 4: Layout of the tomb and location of the measurement points (S), painting location (P).
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A simulation model was generated to reproduce the interior and exterior, construction conditions, and materials of the tombs. DesignBuilder software, version 7.0.2.006 (Design Builder 2023), was used to simulate hygrothermal conditions indoors and lighting, and DiaLux evo version 10 (Dialux 2023) was used (see Fig. 5). These programs use Energyplus, Radiance, and Daysim calculation engines. The model was validated using monitoring data. The deviation between the in-situ results and the values obtained through simulations was evaluated using two statistical measurement indicators, following ASHRAE 14-2014 (Ashrae 2014): Hourly Mean Bias Error (MBE) and Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) (Muñoz Gonzalez, Leon Rodriguez, & Navarro Casas, 2016).

The same validated tomb model was used to evaluate the impact of climate change in different future scenarios. This required the original climate data file to be modified, taking into account climate change for the years 2030, 2050, and 2100. Future climate files for the climatic zone were generated through Meteonorm 8.0 software and then incorporated into the simulation tool. This software provides access to more than 8,000 meteorological stations and presents three IPCC climate change projections, RCP 2.6 (low), 4.5 (medium), and 8.5 (high), based on the Coupled Model Intercomparison Project CMIP5. The characteristics of these scenarios show the possible variability throughout the 21st century. The RCP 2.6 scenario is the closest to the goal established by the Paris Agreement, while the RCP 8.5 scenario is the most unfavourable, with a high increase in temperature and serious effects on the planet. RCP 4.5 was used for the purpose of this study.

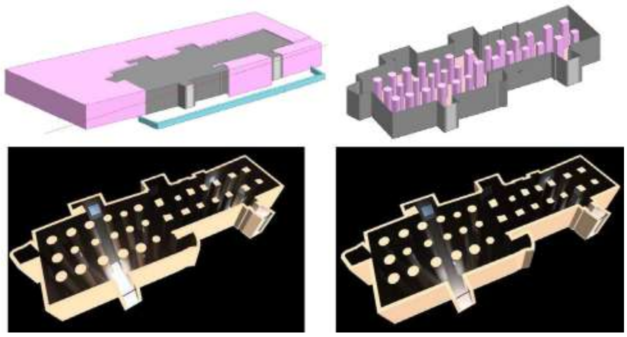

Figure 5: Software used in this study, DesignBuilder and Dialux Evo.
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3. RESULT

In Figure 6, several box plots based on quartiles are represented in order to visualize the set of hourly values of the temperature of the tombs. These graphs provide information on the minimum and maximum values (determined by the lines), quartiles Q1 (25% of data), median (50% of data), and Q3 (75% of data). They provide a general view of the symmetry of the distribution of temperature and relative humidity data and their dispersion in different seasons of the year. The summer and winter months present a symmetrical distribution and minimal dispersion with respect to the median (a concentration of data is found). In the case of the autumn and spring months, the symmetry continues, but the dispersion of values increases in different climatic scenarios. The range between the maximum and minimum temperature in the summer months is 3ºC, in winter and spring 5ºC, and in autumn it doubles, reaching a difference of 10ºC. In the case of relative humidity, the greatest dispersion occurs in autumn, with up to 35% difference, while for the rest of the year, the dispersion is 10-15%. Although it is observed that the dispersion in autumn is greater at present, in future scenarios it will decrease, due to the increasing temperatures.

In order to establish suitable environmental parameters for the preservation of the tombs, various factors, including annual mean data, seasonal cycles, and short-term fluctuations, must be considered. The following graph shows the recorded data for temperature and relative humidity, as well as indicating the annual mean of these parameters, which in the current case are 25ºC and 27%, respectively. Similarly, the seasonal changes inside the tomb throughout the year are shown. To determine if the current environmental conditions can cause mechanical damage to the walls, short-term daily fluctuations of both temperature and relative humidity inside the tomb were calculated. Figure 7 summarizes the daily fluctuations and presents the limits established according to ASHRAE, oscillations of ±2ºC. The percentage of temperature fluctuation values outside the band is minimal, 2%, increasing to 3-4% in scenarios 2050 and 2100. According to these results, interior temperature fluctuations do not pose a serious risk to the preservation of hieroglyphs and paintings.

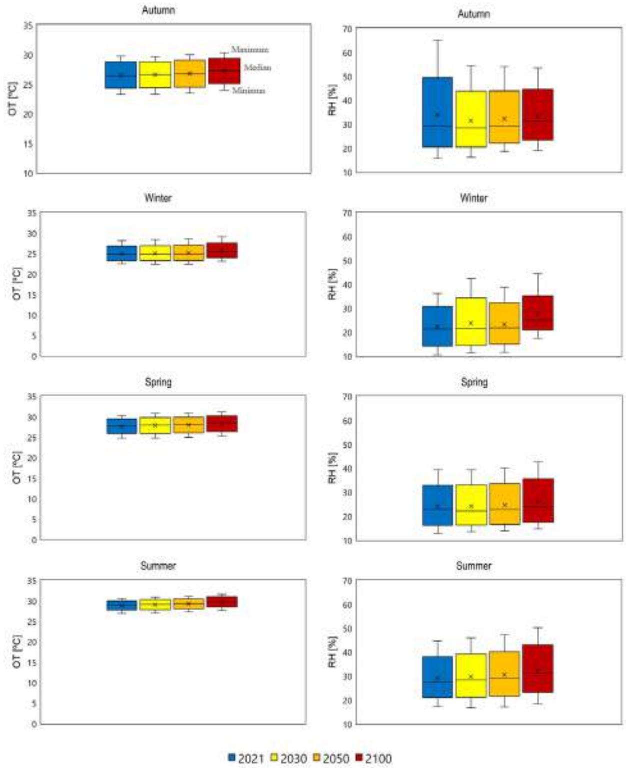

Figure 6: Statistics, the quartile, median, maximum and minimum T and RH.
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According to the normative requirements of UNE-EN 15757, the lower and upper limits of the reference interval for RH fluctuations are the 7th and 93rd percentiles of the simulation fluctuations, respectively. In both instances in this case study, this is 7%. According to the results obtained in the current situation, there is a risk due to the deviation of this parameter for 20% of the time, worsening during the autumn months and during nighttime hours. The impact of climate change worsens the current situation, so that this percentage increases to 22% for 2050 and 25% for the year 2100. This parameter should be considered given the low mechanical resistance of the limestone composition of the tomb, which can easily break into slabs. It also has high porosity and moisture absorption capacity.

The Egyptian terrain is characterized by having organic compounds that, with the contribution of underground moisture and high temperatures, make it highly fertile for plants and vegetation, as well as generating biodeterioration stains caused by microorganisms present in the soil. These organisms easily develop at a temperature between 20-30ºC and with a relative humidity above 65%. According to the analysis of the data obtained, currently biodeterioration does not pose a risk to preservation in this tomb, as these environmental thresholds are exceeded during only 1% of the time in autumn. Similarly, in future scenarios, due to the increase in temperature, a decrease in relative humidity is expected, so that it will not exceed 65%.

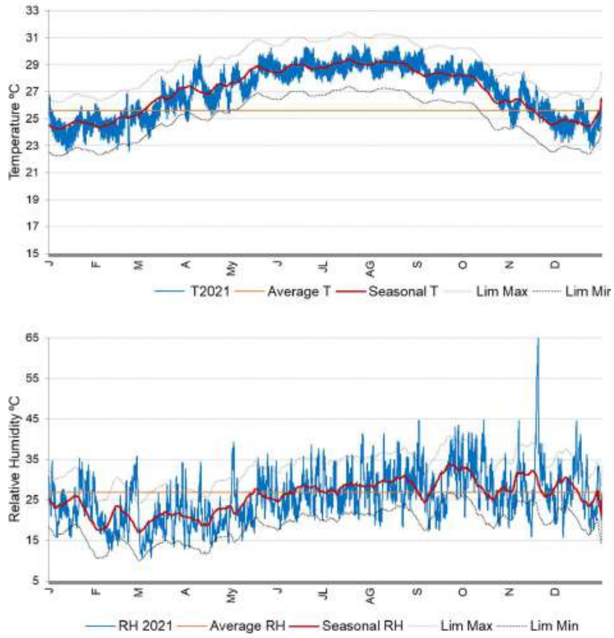

Figure 7: Monitored average T and RH and seasonal average limited.
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Another environmental parameter to consider is solar radiation, which combined with high temperatures causes a sudden decrease in humidity or continued UV radiation, causing colour loss over time. In this tomb, the colours in the polychromatic hieroglyphic inscriptions are altered or lost in some cases due to natural lighting or mechanical risks.

Figure 8: Deterioration of painting inside QH25 and QH26.
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In an initial visual analysis, it was observed that hieroglyphics with reddish colours are better preserved than those with bluish colours. This is explained by the fact that the colour red is made with a natural oxide that is very abundant in the area, providing resistance and stability. However, the colour blue is artificial and is generally created with a mixture of silica, calcite, and copper minerals, which are less stable under unsuitable environmental conditions, becoming more brittle and even taking on greenish tones. In this tomb in particular blue is used in the hieroglyphics located in the niches of the pharaohs, which are less exposed to natural lighting and have more stable climatic conditions.

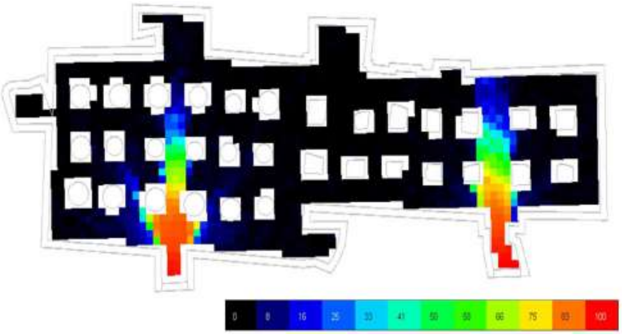

Figure 9: Annual hours of natural lighting (nighttime hours are excluded).
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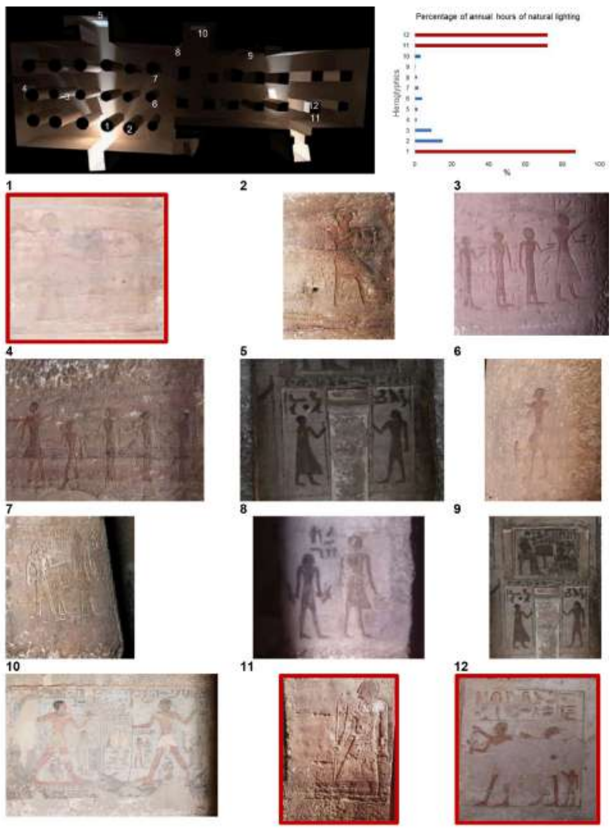

Figure 10: Percentage of annual hours of natural lighting on hieroglyphics.
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As expected, according to the results obtained from computer simulations (Fig. 9), it has been observed that hieroglyphics more exposed to natural lighting present greater deterioration (Fig. 10). The hieroglyphics marked in red, present a greater number of hours of exposure with high light intensities. Considering that Aswan has around 3988 hours of sunlight throughout the year, it is observed that the areas closest to the entrance and central areas have a higher percentage of lighting time, around 80-87%. Similarly, these hieroglyphics present a greater colour loss and more deterioration pathologies due to fragmentation or erosion.

The incidence of UV radiation is expected to increase in future climate scenarios, which will be affected by changes in the stratospheric ozone. The decrease in stratospheric ozone allows more UVB (the most harmful type of UV) to reach the Earth's surface, so that hieroglyphics could deteriorate further, accelerating their disappearance, unless preventive strategies are designed.

Finally, Figure 11 shows colour change due to exposure for four hours a day at an intensity of 200 lux and 400 lux, in three different scenarios (2030, 2050 and 2100). The results determine that the colour intensity, and even all the colour, could disappear in under 50 years due to exposure. By 2030, the colour intensity would be lost, but the colour could start to disappear for the remaining scenarios.

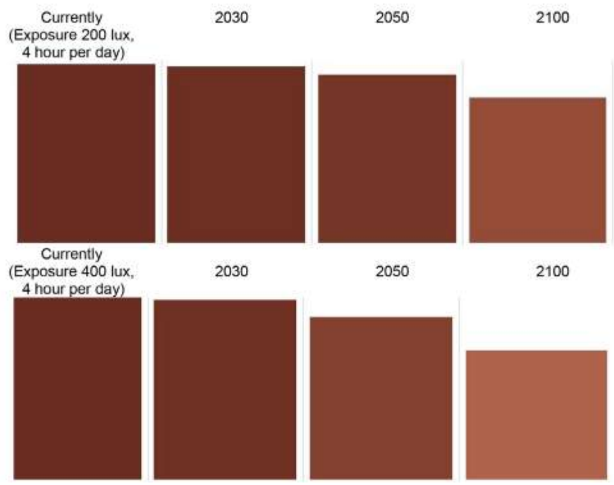

Figure 11: Fading of a single colour in three different scenarios.
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CONCLUSIONS

This research addresses the conservation and preservation of funerary architecture in Aswan, Egypt, in the face of climate change. The study uses an experimental method combining in-situ measurements and analytical formulations to evaluate the impact of future scenarios on the tombs. According to the analysis of the results, current environmental conditions are not suitable for the preservation of hieroglyphics, mainly due to variations in humidity, natural lighting, and wind incidence. The localized damage to the hieroglyphics is primarily due to erosion caused by sand impact and mechanical damage generated by indoor environmental conditions. It is necessary to reduce fluctuations in relative humidity and the incidence of solar radiation and wind impact in order to improve the current microclimate and future scenarios.

This preliminary study is necessary to assess risks and plan adaptation strategies for the tombs. Thanks to the application of these technologies the current and future situations, and the environmental impact of future project strategies aimed at improving these, can be assessed. The conclusions of this study will be used in future research for environmental conditioning and tourism projects for the tombs.

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