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Impact of opening the entrance on cave temple murals in different climate zones for preventive conservation



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Many precious cave murals around the world face challenges in preventive conservation. Opening these caves to the public alters their microenvironment, posing new challenges for mural conservation. While previous research has focused on specific climate impacts, the effects of public access across different climates remain underexplored. This study evaluates the impact of open caves on mural preservation in humid, semi-humid, semi-arid, and arid regions of China. Using a validated two-dimensional heat and moisture transfer model, this study simulates the hygrothermal behavior of murals and their degradation risks before and after cave openings. The key findings are as follows: (1) Open caves amplify the annual temperature fluctuations of murals, most notably in arid regions; (2) Open caves reduce the annual RH (relative humidity) fluctuations, particularly in semi-arid regions; (3) Open caves increase days with excessive daily hygrothermal variations, especially in semi-arid regions; and (4) Open caves raise salt efflorescence risk in humid, semi-humid, and semi-arid regions while reducing it in the arid region. These results offer valuable guidance for the conservation and management of cave relics across varied climates.

Cave murals are artworks painted on the interior walls of caves or chambers. These murals often depict the religious, historical, cultural, and social life of their time, making them valuable artifacts for the study of history and culture. China is home to the largest and most historically extensive collection of cave murals in the world, renowned for their exquisite painting techniques and diverse artistic themes. Notable cave sites, such as Dunhuang, Yungang, and Longmen, have been inscribed on the UNESCO World Heritage List¹. These caves are distributed across vast regions of China², with significant climatic differences ranging from the arid deserts in the north to the humid subtropical areas in the south³.

Chinese cave murals, such as those in the Mogao Caves at Dunhuang, have withstood the test of time, remaining relatively well-preserved for centuries despite harsh environmental conditions. However, the decision to open these caves to the public (e.g., a million people in Mogao Caves in 2023) and the scientific community have introduced new risks to the murals, particularly due to changes in the microclimatic conditions. As illustrated in Fig. 1, when visitors enter the caves, they release heat and moisture, which increases the indoor temperature and relative humidity (RH)^{4–6}. This, in turn, promotes microbial growth^{6,7} and leads to a rise in pollutant concentrations⁸, both of which are detrimental to the long-term preservation of the murals⁹. Zhang et al. found through monitoring that when 30 visitors entered a cave for 5–6 mins, the temperature inside rose by 3–10 °C,

and the RH increased by 10–20%¹⁰. Li et al. developed a two-dimensional numerical Heat-Air-Moisture (HAM) model of Cave 98 in the Mogao Caves to assess the impact of cave openings on the murals. The findings revealed that the number of days per year with increased risk of mural degradation due to hygrothermal fluctuations rose by over 100 days after the caves were opened to visitors¹¹.

Although the impact of environmental factors on mural preservation has been widely acknowledged, existing studies have primarily focused on specific climatic regions. The effects of opening caves to visitors in other climatic zones across China remain understudied. Previous research has demonstrated that outdoor climate conditions significantly influence the deterioration of heritage sites^{12–14}. Given the diversity of China's climatic regions, it is essential to further explore and adapt these findings to ensure effective preservation strategies for cave murals in different environmental contexts.

The primary objective of this study is to assess how opening caves to visitors impacts the microclimate surrounding murals in China's humid, semi-humid, semi-arid, and arid regions. The study utilized the validated Cave 98 HAM model to simulate the thermal and humid behavior of the mural paintings before and after the opening of the caves under the four climatic conditions and to assess the risk of mural degradation. The findings of this study are intended to provide valuable

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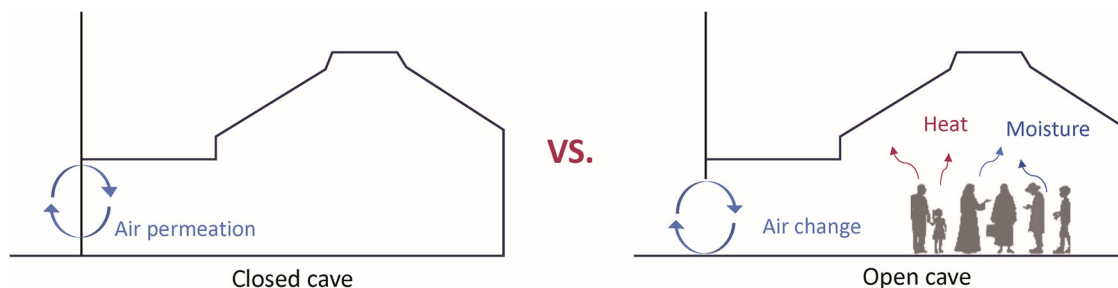


Fig. 1 | Visitor impacts on cave environments.

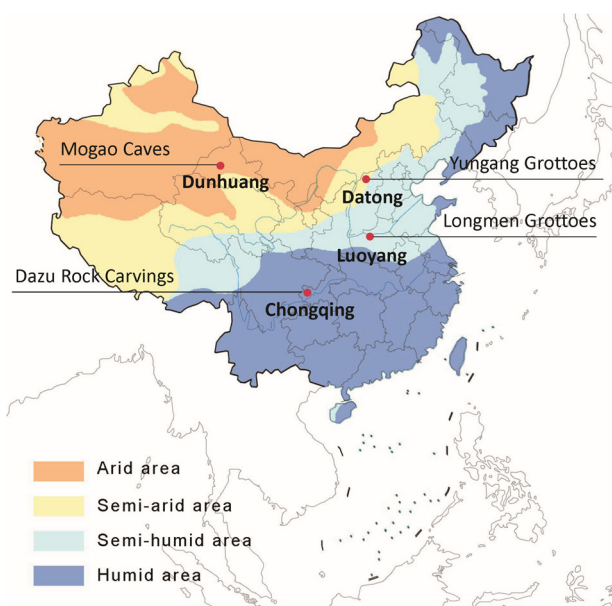


Fig. 2 | Location map of the grottoes and climates in China⁴³.

insights into the preservation and management of cave temple sites across China.

Materials and methods

Selection of caves

Climatic zones can be categorized in multiple ways based on diverse indices. Previously, Wang et al. found that precipitation significantly impacted the deterioration risk of sites in different regions¹². Therefore, this study used humidity as the climatic zoning criterion and selected typical cave temples from four different humidity zones in China. In the humid area, the annual precipitation exceeds 800 mm, the climate is warm, and the vegetation is lush. In the semi-humid area, the annual precipitation ranges from 400 mm to 800 mm, with relatively more rainfall and a moderate climate. In the semi-arid area, the annual precipitation is between 200 and 400 mm, with less rainfall, high evaporation, and sparse vegetation. In the arid area, the annual precipitation is below 200 mm, and the evaporation rate far exceeds the precipitation, resulting in an extremely dry climate.

We inputted local climatic conditions into the model for each of these temples to compare the differences in hygrothermal behavior of murals in closed caves and those open to visitors. These cave temples are UNESCO World Heritage Sites, including Mogao Caves in an arid region, Datong Yungang Grottoes in a semi-arid area, Luoyang Longmen Grottoes in a semi-humid area, and Chongqing Dazu Rock Carvings in a humid area (Fig. 2). These grottoes were built along the mountains, comprising hundreds of caves. Despite differing climatic conditions, they have been relatively intact in their local environments for over a thousand years. After the founding of the People's Republic of China, specialized institutions were

established to protect and manage these grottoes. Since then, the grotto relics have been well-preserved and opened to the public for visitation. Management typically selects caves with better-preserved interior artifacts for regular or rotational public access. Some caves still retain their original doors, while others have lost them over time. For most grottoes, protective agencies have restored and installed new doors to ensure their preservation.

Heat and moisture transfer simulation

This study employs Fortran programming within the Visual Studio platform. The program allows for the flexible input of material parameters and boundary conditions, enabling the calculation of salt crystallization days. The computational process includes establishing the computational domain, mesh division, input of material physical properties, input of external climatic conditions, execution of coupled heat and moisture transfer calculations, and degradation risk assessment. The heat and moisture transfer balance equations are discretized using the finite difference method¹⁵. This method has been widely applied in numerous cultural heritage studies, and its simulation accuracy has been extensively validated^{16–18}.

Fundamental equations. Fundamental equations of numerical simulation used in this study are coupled heat and moisture transfer equations by Matsumoto M^{19,20}, as shown in Equations. (1) and (2) (the notation is explained in the Appendix). The driving potential of heat and moisture transfer are temperature and water chemical potential, respectively.

Conservation equation of heat:

$$c_p \frac{\partial T}{\partial t} = \nabla \cdot \left[\left(\lambda + r\lambda'_{Tg} \right) \cdot \nabla T + r\lambda'_{ug} \cdot \nabla \mu \right] \quad (1)$$

Conservation equation of moisture:

$$\rho_w \frac{\partial \psi}{\partial t} = \nabla \cdot \left[\lambda'_u (\nabla \mu - n_s g) + \lambda'_T \nabla T \right] \quad (2)$$

Water chemical potential is an indicator of the state of the water, determined by temperature and RH:

$$\mu = R_v T \ln(RH) \quad (3)$$

The heat and moisture balance of indoor air is shown in Equations. (4) and (5):

$$(c_p)_{air} V \frac{\partial T_{in}}{\partial t} = \sum_{j=1}^{m1} S_j \alpha_{in} (T_{Sj} - T_{in}) + (c_p)_{air} V N (T_{out} - T_{in}) \quad (4)$$

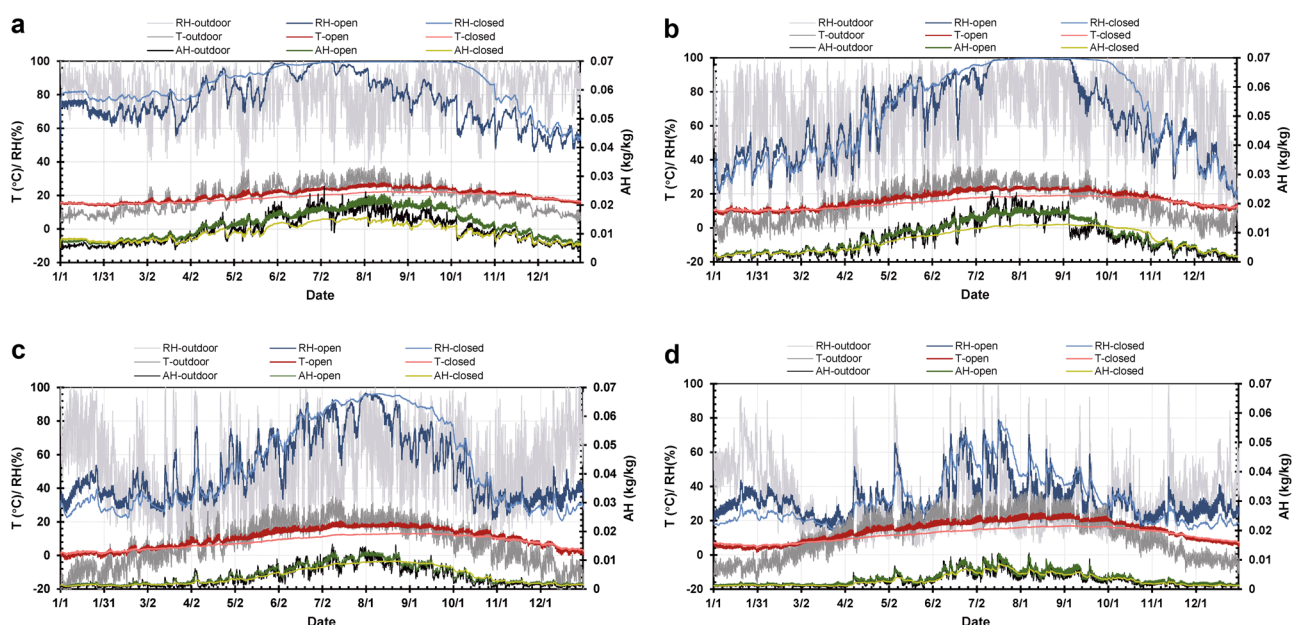
$$c_{air} V \frac{\partial P_{v_{in}}}{\partial t} = \sum_{j=1}^{m1} S_j \alpha'_{in} (P_{v_{Sj}} - P_{v_{in}}) + c_{air} V N (P_{v_{out}} - P_{v_{in}}) \quad (5)$$

Equation of heat transfer between cliff surface and outdoor air:

$$(\alpha'_{out} + r\alpha'_{T_{out}})(T_{out} - T_s) + r\alpha'_{\mu_{out}}(\mu_{out} - \mu_s) + q_{sol} - q_{nec} = \left(\lambda + r\lambda'_{Tg} \right) \nabla T + r\lambda'_{ug} \nabla \mu \quad (6)$$

Table 1 | Parameters setting for closed caves and open caves

Scenario	Number of visitors at each moment [persons]	Per capita heat dissipation [W]	Per capita moisture dissipation [g/h]	ACH [1/h]
Closed cave	0	0	0	0.49 (Jan.), 0.34 (Feb.), 0.1 (Mar.) 0.17 (Apr.), 0.17 (May), 0.2 (Jun.) 0.2 (Jul.), 0.16 (Aug.), 0.15 (Sep.) 0.25 (Oct.), 0.4 (Nov.), 0.48 (Dec.)
Open cave (with visitors)	50	105	60 (Jan. 1st–Mar. 20th & Dec. 21st–Dec. 31st) 162 (Jun. 21st–Sep. 20th) 103 (Mar. 21st–Jun. 20th & Sep. 21st–Dec. 20th)	1.5 (09:00–17:00) same as the closed cave (17:00–09:00 the following morning)

**Fig. 4 | Annual temperature, AH, and RH of the mural in open and closed caves. a** Humid area: Chongqing (CQ); **(b)** semi-humid area: Luoyang (LY); **(c)** semi-arid area: Datong (DT); **(d)** arid area: Dunhuang (DH).

Salt efflorescence risk assessment. The crystallization and dissolution process of soluble salts is a significant cause of weathering and deterioration in porous materials³⁰. Crystals precipitate below the critical RH for salt deliquescence and dissolve above it. The risk of salt weathering in porous materials can be evaluated by comparing their temperature and RH with the threshold for soluble salt crystallization and dissolution. This method has been verified to be effective^{31,32} and has been applied in many studies^{33–35}.

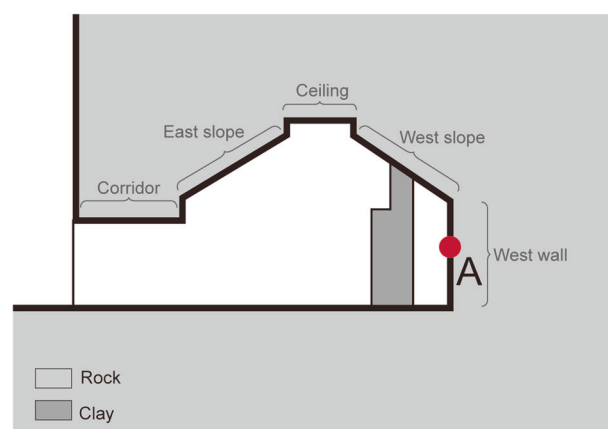
This study assessed salt weathering risk for two common soluble salts in architectural heritage: NaCl and Na₂SO₄^{36,37}. The average hourly temperature and RH of the relics were compared with the deliquescent thresholds of these salts. The risk of salt weathering increases when the temperature and RH at the site fluctuate near the critical values for NaCl and Na₂SO₄. The critical RH value of deliquescence of NaCl is 75.3%³⁸. The critical value of deliquescence of Na₂SO₄ has a linear relationship with temperature³²:

$$RH = 0.8485 \times T + 60 \quad (10)$$

Results

Mural's annual hygrothermal fluctuation

Figure 4 illustrates the annual temperature, absolute humidity (AH), and RH fluctuations at point A in the murals within caves that were either open

**Fig. 5 | The location of point A in Cave 98.**

all year or closed all year, across four different regions. The location of point A is shown in Fig. 5. The differences in temperature and moisture of the murals under varying climatic conditions are obvious. The annual fluctuations ranges, means, and SDs in temperature, RH, and AH are presented in Table 2.

Compared to closed caves, the annual mean temperature and SD of the mural in open caves across the four climate zones increased by approximately 2 °C. The most significant temperature impact was observed in the arid region, where the annual mean temperature and SD both increased by 2.3 °C, followed by the semi-arid region (Mean + 2.3 °C, SD + 2.1 °C),

Table 2 | Comparative results of annual T, RH, and AH between open and closed caves for the four regions

Climate	Scenario	T (°C)	RH (%)	AH (kg/kg)
		Min-Max Mean ± SD	Min-Max Mean ± SD	Min-Max Mean ± SD
Humid	Closed	14.4–22.4	51.8–100	0.0053–0.0116
		18.6 ± 2.5	86.6 ± 12.9	0.0104 ± 0.0029
	Open	13.2–27.8	45.8–100	0.0061–0.0238
		20.2 ± 3.7	75.4 ± 11.7	0.0134 ± 0.0049
Semi-humid	Closed	9.3–19.2	19.6–100	0.0015–0.0129
		14.8 ± 3.2	67.5 ± 26.7	0.0076 ± 0.0039
	Open	7.5–25.0	16.9–100	0.0013–0.0188
		16.8 ± 4.9	64.3 ± 23.7	0.0088 ± 0.0053
Semi-arid	Closed	0.4–13.1	20.6–96.2	0.0009–0.0098
		8.0 ± 3.9	53.7 ± 26.2	0.0044 ± 0.0031
	Open	−2.6 to 20.5	21.2–96.6	0.0009–0.0131
		10.3 ± 6.0	52.1 ± 20.4	0.0048 ± 0.0034
Arid	Closed	4.4–17.1	14.6–77.7	0.0010–0.0085
		11.8 ± 3.8	32.6 ± 15.3	0.0031 ± 0.0020
	Open	1.5–24.7	14.3–78.9	0.0009–0.0120
		14.1 ± 6.1	32.4 ± 12.0	0.0036 ± 0.0023

semi-humid region (Mean + 2.0 °C, SD + 1.7 °C), and humid region (Mean + 1.6 °C, SD + 1.2 °C).

After the caves were opened, both the mean and fluctuations of AH in murals across the four climate zones increased, with the most significant impact observed in the humid region (Mean + 0.0030 kg/kg, SD + 0.0020 kg/kg), followed by semi-humid (Mean + 0.0012 kg/kg, SD + 0.0014 kg/kg), arid (Mean + 0.0005 kg/kg, SD + 0.0003 kg/kg), and semi-arid (Mean + 0.0004 kg/kg, SD + 0.0003 kg/kg) regions. The results indicate that the more humid the climate, the greater the impact of cave openness on AH fluctuations.

In contrast to the changes in temperature and AH, the annual mean and fluctuations of RH in open caves across the four climate zones decreased compared to closed caves. The most significant decrease in annual mean RH was observed in humid regions, with a reduction of 11.2%, while the decrease in other regions was within 5%. The greatest reduction in RH fluctuation was observed in semi-arid regions, with an SD decrease of 5.8%, followed by the arid region (SD-3.3%), semi-humid region (SD-3.0%), and lastly the humid region (SD-1.2%).

Overall, in different climatic zones, opening the caves increased the annual fluctuation of mural temperature and AH, with the magnitude of the increase being related to the outdoor temperature and AH conditions. Interestingly, in all climatic zones, opening the caves reduced the fluctuation of mural RH, which is related to the combined effects of temperature and AH fluctuations.

Mural's diurnal hygrothermal fluctuation

Figure 6 displays the diurnal fluctuations in temperature and RH at point A in both open and closed caves across the four regions. When the caves were closed, the number of days where daily temperature and RH fluctuations exceeded ASHRAE standards was minimal across all four regions. However, upon opening the caves, there was a significant increase in the number of days with temperature and RH fluctuations exceeding the standard in all

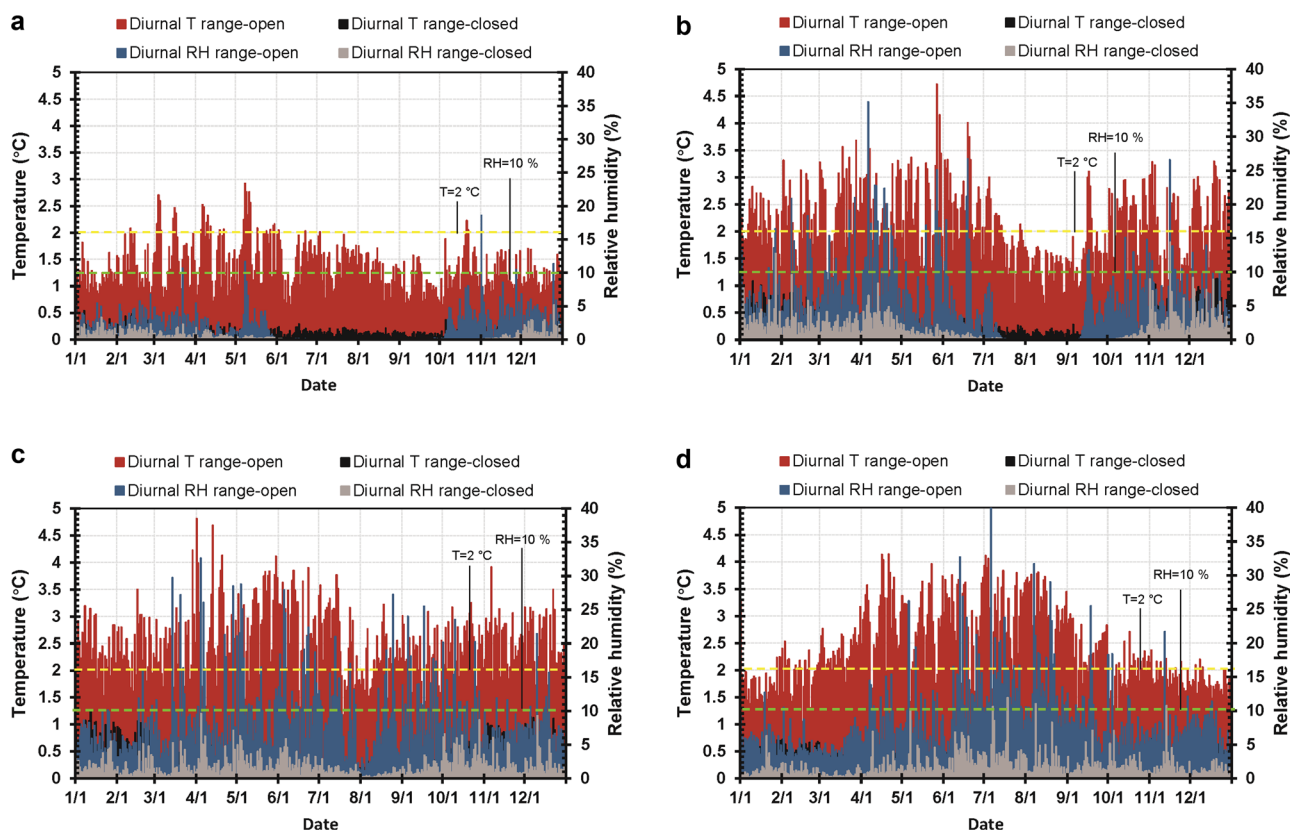


Fig. 6 | Diurnal fluctuations in temperature and RH of the mural between open and closed caves. a Humid area: Chongqing (CQ); **(b)** semi-humid area: Luoyang (LY); **(c)** semi-arid area: Datong (DT); **(d)** arid area: Dunhuang (DH).

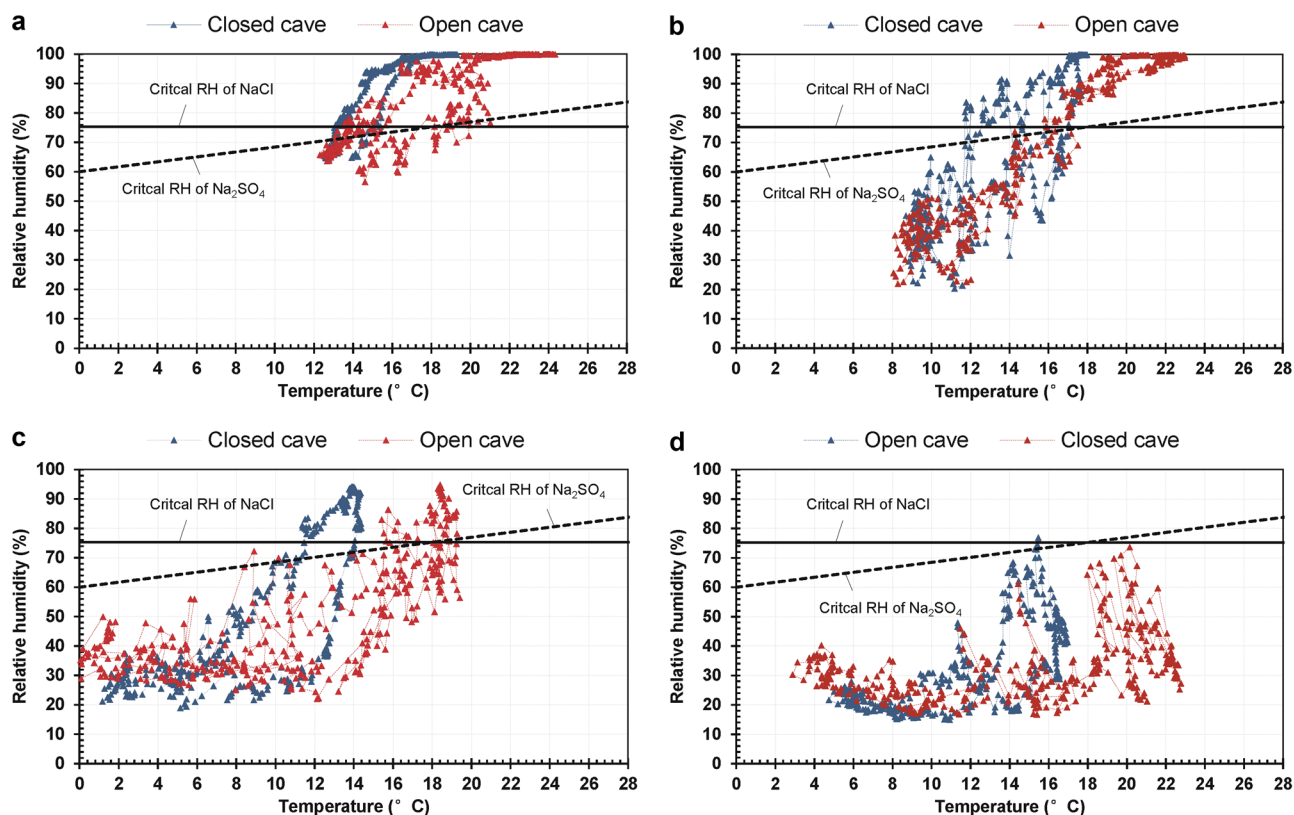


Fig. 7 | Salt efflorescence risk of murals between open and closed caves and open caves. a Humid area: Chongqing (CQ); **(b)** semi-humid area: Luoyang (LY); **(c)** semi-arid area: Datong (DT); **(d)** arid area: Dunhuang (DH).

climatic zones, with the semi-arid region being the most affected. Specifically, the number of days with temperature fluctuations exceeding the standard increased by 293 days in the semi-arid region, followed by 249 days in the arid region, 192 days in the semi-humid region, and only 32 days in the humid region. Similarly, the number of days with RH fluctuations exceeding 10% also increased after opening the caves: by 106 days in the semi-arid region, 98 days in the arid region, 59 days in the semi-humid region, and 5 days in the humid region.

Salt efflorescence risk

Figure 7 shows a comparison of temperature, RH, and salinization thresholds for murals in open and closed caves in the four climatic zones, and Fig. 8 counts the number of days in the year when caves are open and closed that the salt efflorescence risk occurs. In different climate zones, the periods of high salt weathering activity on murals exhibit distinct seasonal characteristics influenced by the climate. In humid regions, salt weathering was most prevalent during the spring and winter months; in semi-humid regions, this phenomenon typically occurred in the spring; whereas in semi-arid and arid regions, salt weathering tended to be more frequent during the summer (Figs. 7 and 8). The results also show that the effect of open caves on efflorescence is closely related to the local climate. The opening of caves increased the salinization risk in humid, semi-humid, and semi-arid regions. In particular, the risk in humid regions increased by 30 days, with a notable rise in the number of days affected in March and November. Additionally, the number of risk days in semi-arid regions increased by 25 days, with these risks primarily occurring during the summer. The number of risk days in semi-humid regions increased by 15 days. However, in arid regions, the number of risk days decreased by 5 days following the opening of caves.

Table 3 presents a comparison of the number of risk days (both daily hygrothermal fluctuation and salt risk) for murals in both open and closed caves across these regions. Opening the caves increased risk days for diurnal temperature and RH fluctuations, posing an additional threat to mural

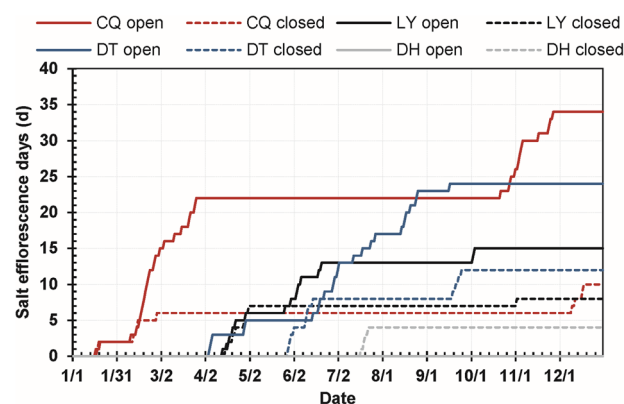


Fig. 8 | Annual comparison of salt efflorescence risk days between open and closed caves across four areas. CQ: Chongqing, humid area; **LY:** Luoyang, semi-humid area; **DT:** Datong, semi-arid area; **DH:** Dunhuang, arid area.

preservation. However, the variation in salt weathering risk exhibits a clear climate dependency. Also, Table 3 details potential periods of risk in different climates, and these findings can help in the development of open management strategies for caves under different climatic conditions.

Discussion

Mural's hygrothermal fluctuation

The impact of open cave visitation on murals primarily comes from increased air exchange and visitors. Previously, Li et al. analyzed the effects of these two factors in Cave 98 of Mogao Caves, located in an arid region. Their findings revealed that increased ventilation led to higher mural temperatures and AH, along with greater fluctuations. In contrast, visitor activities raised the annual average values of temperature and AH but had a

Table 3 | Comparative results of risk days between open and closed caves for the four regions

Climate	Scenario	Days with diurnal T range over 2 °C (d)	Days with diurnal RH range over 10% (d)	Days with salt weathering risk (d)	Periods with salt weathering risk
Humid	Closed	0	0	10	Jan., Feb., Dec.
	Open	32	5	34	Jan., Feb., Mar., Oct., Nov.
Semi-humid	Closed	0	3	12	May, Jun., Sep.
	Open	192	62	24	Apr., Jun., Jul., Aug., Sep.
Semi-arid	Closed	0	0	8	May, May, Nov.
	Open	293	106	15	Apr., May, Jun., Oct.
Arid	Closed	0	4	4	Jul.
	Open	249	102	0	None

relatively smaller impact on their fluctuations¹¹. Since the conditions for visitors are the same across the open cave models in the four regions studied in this research, the differences in hygrothermal variations of the murals across different climate zones are mainly due to the variations in outdoor climate.

The murals in open caves within arid and semi-arid regions exhibited the highest temperature increases. This could be attributed to the larger diurnal temperature variations in these regions compared to more humid climates³⁹. When the caves are open during the day, the greater temperature difference between the interior and exterior allows more heat to enter the caves, thereby enhancing the warming effect in arid regions. The impact of open caves on the AH of murals is positively correlated with the degree of climate humidity; the more humid the climate, the more moisture enters the cave when the doors are open. Previous studies have also confirmed a strong correlation between indoor and outdoor AH^{40,41}. Open caves can mitigate RH fluctuations because the RH of the murals is influenced by both temperature and AH. An increase in temperature allows the air around the murals to hold more water vapor, thereby raising the saturation vapor pressure. If the actual amount of water vapor does not increase as rapidly as the saturation vapor pressure, the RH will decrease. This is because RH is calculated based on the ratio of actual water vapor to the saturation vapor content, so when the saturation level increases faster, the RH declines. The effect of open caves in mitigating RH fluctuations is more pronounced in arid regions, as the temperature fluctuations of the murals are greater under dry conditions.

Nevertheless, in all four climate zones, the number of days when the daily hygrothermal fluctuations in the mural exceeded the risk threshold significantly increased under the open cave condition. Notably, in arid and semi-arid regions, the daily RH fluctuation increased significantly after the cave was opened, while the change in RH fluctuation was minimal in humid and semi-humid regions. This may be attributed to the varying impact of visitors under different climate conditions. Under conditions of high RH (RH > 80%), the moisture emitted by visitors has a relatively small effect on short-term fluctuations in environmental RH¹².

Salt efflorescence risk

In different climate zones, the periods of high salt weathering risk for murals vary due to the differences in when temperature and RH conditions reach the critical values for salt crystallization, which are influenced by regional climate variations. Figure 7 illustrates that the temperature and RH conditions under which salt efflorescence occurs on murals typically range between 12 and 22 °C and 65–75%. The timing at which murals reach these conditions varies seasonally across different climate zones. In humid regions, the RH of murals remains high throughout the year, ranging from 60% to 100%. The winter season has the lowest RH levels of the year, generally fluctuating around 70%, making salt efflorescence more likely during this period. In contrast, murals in arid regions can only reach an RH of 70% or higher during the summer when the RH is relatively high, making summer the high-risk period for salt efflorescence in these areas. Similarly, in semi-humid and semi-arid regions, the humidity levels are moderate, and both transitional seasons and summer are peak periods for salt efflorescence.

Similarly, the impact of an open cave on the number of days with salt weathering risk is also influenced by climate conditions. In humid, semi-humid, and semi-arid regions, opening the cave increased the salt weathering risk for murals, as it led to more frequent fluctuations in temperature and RH around the critical thresholds. In contrast, in arid regions, opening the cave reduced the risk of salt weathering on murals during the summer. This is because the temperature of the murals increased after opening compared to the closed cave, and at higher temperatures, higher RH is required for salt dissolution. However, in the arid region, RH in the open cave decreased during the summer, thereby reducing the number of days with salt weathering (Fig. 7d).

Conservation and management recommendations for caves

In humid regions, compared to when closed, opening the cave significantly increases both the values and fluctuations of temperature and AH in summer and autumn. However, it reduces the average RH and shortens the duration when mural RH is continuously close to 100% by about a month during these seasons, thereby lowering the risk of condensation and mold growth on the mural surfaces. Yet, regardless of whether the cave is open or closed, murals in humid regions face the risk of excessive RH, particularly in summer. Therefore, the use of dehumidifying equipment is recommended in humid regions.

In semi-humid regions, opening the cave causes daily temperature and RH fluctuations to exceed ASHRAE standards, especially in spring, autumn, and winter. Additionally, as in humid regions, opening the cave reduces the risk of excessively high RH for murals in summer and autumn. Therefore, it is recommended to close the cave in semi-humid regions, except in summer, and to increase the use of indoor dehumidifying equipment.

In semi-arid regions, opening the cave results in daily temperature and RH fluctuations of the murals exceeding standard ranges in all seasons, and posing a risk of freeze-thaw cycles for the murals in winter. Therefore, it is not advisable to open the cave for visitors in semi-arid regions without air conditioning facilities.

In arid regions, opening the cave increases the peak values and fluctuations of temperature and AH of the murals in summer. However, its impact on mural temperature and AH in winter is minimal. When the cave is open, the daily fluctuation of winter mural temperature and RH remains within the recommended range. Hence, opening the cave for visitors in arid regions during winter is feasible.

In the routine conservation of caves, it is advisable to introduce hygroscopic materials to mitigate fluctuations in mural moisture due to external ambient changes. Furthermore, when the interior AH exceeds the external levels, appropriate ventilation methods should be implemented. This helps to reduce the RH of indoor air and walls. However, during overcast or rainy days when outdoor AH exceeds indoor levels, cave openings can cause a rapid increase in RH, leading to potential risks of salt weathering. In such cases, caves should be closed, and dehumidification equipment activated as necessary. Additionally, daily ventilation should be carried out after visitor tours to dissipate heat and moisture generated by visitors within the caves.

Conclusion and prospect

This study employed a validated 2-dimensional coupled heat and moisture transfer model to simulate the effects of cave openings on mural hygrothermal fluctuations and salt efflorescence risks under four different humid conditions in China. The findings provide recommendations for the protection and management of murals under various climatic conditions. The main conclusions are as follows:

- (1) Opening the cave increases the murals' annual temperature fluctuation across different climatic conditions, with the most pronounced effect in arid regions and the least impact in humid regions.
- (2) Opening the cave mitigates the murals' annual RH fluctuation, especially in the semi-arid region, followed by arid, semi-humid, and humid regions.
- (3) Opening the cave significantly increases the daily temperature and RH fluctuations of murals, enhancing the deterioration risk, with the order of impact being: semi-arid regions, arid regions, semi-humid regions, and humid regions.
- (4) The impact of cave openings on the risk of salt efflorescence on murals is related to the climate of the cave's location. Opening caves increases the risk of salt efflorescence in humid, semi-humid, and semi-arid regions while mitigating the risk in arid regions.

This study has certain limitations. Firstly, the model does not account for the differences between murals and caves in various regions. In reality, murals in different caves may be made from different materials, each with distinct thermal and moisture properties, which could affect the accuracy of the simulation results. Future research will consider these regional material differences to provide more accurate outcomes. Secondly, the current study only assesses the common thresholds of hygrothermal fluctuations and salt efflorescence risk. However, different climate zones present varying types of risks; for example, mold is common in humid regions, while freeze-thaw degradation is more frequent in cold regions. Future research will conduct more detailed assessments of the risks specific to each climate zone.

Appendix material hygrothermal properties

c	heat capacity of the material (J/kg·K)
ρ	density of the material (kg/m ³)
T	temperature (K)
t	time (s)
μ	water chemical potential (J/kg)
λ	thermal conductivity (W/(m·K))
λ'_{Tg}	water vapor conductivity under the gradient of temperature (kg/(m·s·K))
λ'_{ug}	water vapor conductivity under the gradient of water chemical potential (kg/(m·s (J/kg)))
r	phase change heat of the vaporization of water (J/kg)
ρ_w	density of the water (kg/m ³)
ψ	volumetric water content (m ³ /m ³)
λ'_u	water conductivity under the gradient of water chemical potential (kg/(m·s (J/kg)))
λ'_T	water conductivity under the gradient of temperature (kg/(m·s·K))
g	gravity acceleration (9.8 (m/s ²))
n_x	direction vector of gravity (vertical direction is 1, the horizontal direction is 0)
R_v	gas constant of water vapor (J/kg·K)
$(c\rho)_{air}$	heat capacity of the indoor air (J/m ³ ·K)
V	volume of room (m ³)
N	air changes per hour (times/3600 s)
T_s	surface temperature (K)
T_{out}	outdoor temperature (K)
T_{in}	indoor temperature (K)
P_v	partial vapor pressure (Pa)
c_{air}	moisture capacity of the indoor air (kg/(m ³ ·Pa))
P_{v_s}	surface partial vapor pressure (Pa)

$P_{v_{out}}$	outdoor partial vapor pressure (Pa)
$P_{v_{in}}$	indoor partial vapor pressure (Pa)
α_{in}	heat transfer coefficient between wall surface and indoor air (W/(m ² ·K))
α'	moisture transfer coefficient between wall surface and indoor air (kg/m ² ·s·(J/kg))
S	wall surface in contact with indoor air (-)
j	wall number (-)
$m1$	total number of wall surfaces (-)
α_{out}	heat transfer coefficient between cliff surface and outdoor air (W/(m ² ·K))
$\alpha'_{T_{out}}$	moisture transfer coefficient under the gradient of temperature between cliff surface and outdoor air (kg/(m ² ·s·K))
$\alpha'_{\mu_{out}}$	moisture transfer coefficient under the gradient of water chemical potential between cliff surface and outdoor air (kg/m ² ·s·(J/kg))
$\alpha'_{T_{in}}$	moisture transfer coefficient under the gradient of temperature between wall surface and indoor air (kg/(m ² ·s·K))
$\alpha'_{\mu_{in}}$	moisture transfer coefficient under the gradient of water chemical potential between wall surface and indoor air (kg/m ² ·s·(J/kg))
μ_s	surface water chemical potential (J/kg)
μ_{out}	outdoor water chemical potential (J/kg)
μ_{in}	indoor water chemical potential (J/kg)
q_{sol}	solar radiation (W/m ²)
q_{noc}	nocturnal radiation (W/m ²)
J_s	amount of precipitation (kg/(m ² ·s))

Data availability

No datasets were generated or analyzed during the current study.

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X. H.: Conceptualization, Formal analysis, Investigation, Methodology, Software, Visualization, Writing – original draft. R. W.: Validation, Methodology, Writing – review & editing. Y. L.: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. H. X.: Conceptualization, Validation, Methodology. Z. Z.: Data curation, Funding acquisition. S. H.: Writing – review & editing, Supervision, Conceptualization, Funding acquisition. B. S.: Data curation, Project administration, Resources. All authors reviewed the manuscript.

Competing interests

The authors declare no competing interests.

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