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Maintenance schedule optimization based on distribution characteristics of the extreme temperature and relative humidity of Cave 87 in the Mogao Grottoes

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Abstract

Frequent fluctuations in microclimate inevitably cause serious irreversible damage to cultural heritage (such as high risks of cracking, flaking, salt efflorescence, swelling, disaggregation, surface layer detachment, and even microbe diseases). For the caves closed to the visitors, specifying a more rational schedule to minimize human influences on the microclimate is urgent and significant for daily maintenance of the Mogao Grottoes. Interior microclimate fluctuations are caused by air convection between the inside and outside environments, which is highly related to internal and external microclimate differences. Therefore, the occurrence times of the extreme values of temperature (T), relative humidity (RH), T difference (inside T minus outside T), and RH difference (inside RH minus outside RH) between the inside and outside environments of Cave 87 were analysed. The results indicated that the times of the extreme T/RH and T/RH differences showed obvious seasonal characteristics. From April to September, both the daily minimum T and RH differences mainly occurred from 8 am ~ 11 am, and the maximum differences were observed from 16 pm ~ 21 pm. This indicates that door openings for daily investigation and maintenance should be arranged in the morning rather than in the afternoon. The times of the daily extreme T and RH differences occurred from 16 pm ~ 19 pm (minimum) and 8 am ~ 11 am (maximum) from January ~ March and October ~ December, and the door opening time should be accordingly optimized. The analysis results provide more reasonable and specific door opening times for Cave 87 and a scientific reference for preventive conservation of the Mogao Grottoes.

Keywords Mogao Grottoes, Environmental monitoring, Extremum time, Schedule optimization

Introduction

As an important branch of cultural heritage conservation, microclimatic monitoring plays a decisive role in the conservation and management of cultural heritage, especially when serious active diseases persist [1–6]. The internal microclimate of cultural heritage gradually reaches a relatively stable condition after hundreds or thousands of years of no-interference history. However, this balance can be easily and inevitably disturbed by various factors, such as environmental change (rain, storm, dust events) and human activities, including the maintenance activities of conservators [7–10]. The rapid fluctuations in microclimate are mostly detrimental to the preservation of cultural heritage. The accumulation of frequent environmental disturbances consequentially causes changes (in many cases with relevant degenerative and irreversible effects) in cultural heritage over time

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[11–14]. The Mogao Grottoes, a World Heritage Site in Northwest China, is known for its surviving 492 painted Buddhist cave temples hewn into a 1.6 km long cliff face stemming from the fourth to fourteenth centuries [15, 16]. All painted caves have suffered from various deterioration processes throughout the past centuries after commissioning. Surveys have found that more than 50% of the mural paintings in the Mogao Grottoes exhibit extremely serious deterioration problems in the forms of alkali efflorescence, flaking, and detachment [17]. Most of these diseases are highly sensitive to internal microclimate variations, mainly referring to the temperature (T) and relative humidity (RH) [18–20]. The typical structure of wall paintings is composed of coarse earthen plaster, fine earthen plaster, and paint layer in the Mogao Grottoes [15]. Different layers with different physical properties may be altered by the frequent change of T and RH due to thermal/hygroscopic expansions and cold/drying contractions [1, 5, 10]. The long-term accumulation of microstructure deformation will also cause irreversible damage to mural materials. But more importantly, hydrochloride and sulfates are known to be among the most harmful soluble salts in the field of mural conservation since salts may migrate and crystallize inside the pores [6, 14]. The salt dynamics are heavily controlled by a variable indoor microclimate with daily and seasonal cyclicality [12]. In addition, T can greatly affect the evaporation and adsorption rates of moisture [3, 21, 22]. T fluctuation tends to enhance accumulated moisture adsorption at high RH levels or accumulated moisture desorption at low RH levels [23]. Both people and air infiltration can affect the indoor climate, which leads to environmental variations that might jeopardize the artworks contained within [28]. A larger climate difference between the interior and exterior of the cave will inevitably lead to greater fluctuation in the interior microclimate. Therefore, the time of the daily extreme T difference between inside and outside (maximum and minimum) and extreme RH difference between inside and outside (maximum and minimum) values tend to be the critical times of energy and moisture exchange between the inside and outside environments of the cave. It should be noted that daily extreme T/RH values refer to maximum and minimum values of T/RH in a day selected by ANSYS from the monitoring data. The daily extreme T/RH difference values between inside and outside the cave are absolute values.

All the caves in the Mogao Grottoes are open to the atmosphere through the only door in the east wall and are naturally ventilated [24]. Air convection mainly driven by the inside-outside T difference brings moisture exchange [25]. The larger the inside-outside T difference is, the greater the resulting air convection. The larger the RH difference is, the greater the resultant moisture exchange [26], this is more important to the heritages in arid areas, such as the Mogao Grottoes. In addition to natural factors such as precipitation and sudden weather changes, door openings for daily inspection and maintenance is a crucial factor that causes relatively stable microclimate fluctuations in closed caves. Hence, it is necessary to find the maximum and minimum values of the T and RH differences between inside and outside the cave. The time of the extreme T/RH difference is crucial time in terms of indoor microclimate fluctuations. However, the occurrence time of the extreme T/RH difference is not constant either within a day or year, it varies with the seasons. Accordingly, the door opening should be adjusted over the time extreme value occurs. The small-sized Cave 87 has not attracted the attention of conservators before until it was found that the deteriorations in Cave 87 were very serious and still active. Also, disease investigation, sampling, and salt analysis of earthen plaster were conducted. Therefore, researchers conducted constant microclimate monitoring (T and RH) both inside and outside Cave 87 for an entire year as a representative testing site. Then, the variation characteristics of the extreme T and RH differences of Cave 87 were analysed. According to the analysis results, a systematic management schedule for routine maintenance during the different seasons was further refined and optimized.

Research object and methodology

Research object

The Mogao Caves, located in the hinterland of the Gobi Desert in northwest China, is a typical continental arid climate environment affected by the Mongolian high pressure all year round. Cave 87 is a small-scale cave of the Five Dynasties period (907–960 A.D.) in the Mogao Grottoes. It is located 67 m to the north of the prominent Nine-Story Pagoda at ground level (Fig. 1). The murals and coloured clay sculptures in the cave were originally built during the prosperous Tang Dynasty (618–907 A.D.) and were rebuilt and restored during the Five Dynasties (907–960 A.D.). Field investigations revealed that the mural paintings in Cave 87 exhibit severe and still active diseases, which not only affect their artistic quality and integrity but also threaten their safety [17] (Fig. 2).

Methodology

In this research, we monitored the indoor and outdoor climate parameters for a year; after that, selected times of daily extreme T, RH, and differences of internal and external. Then, conduct statistical analysis by accumulating the frequency of occurrence times (taking 1 h as an interval). Finally, based on the analysis and discussion

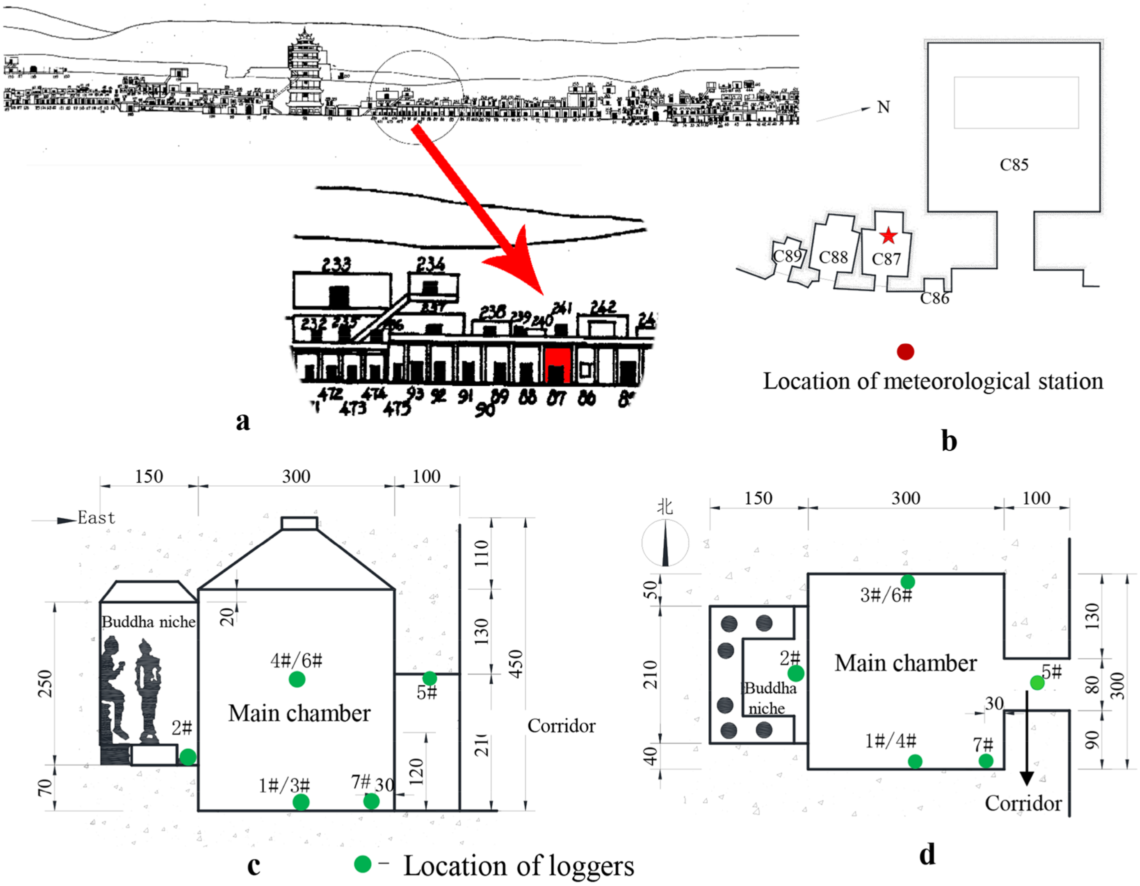

Fig. 1 Location of Cave 87 and Location of loggers. **a** is the location of Cave 87. **b** is the plan of Cave 87 and location of meteorological station. **c** is the elevation of loggers' location. **d** is the plan of loggers' location

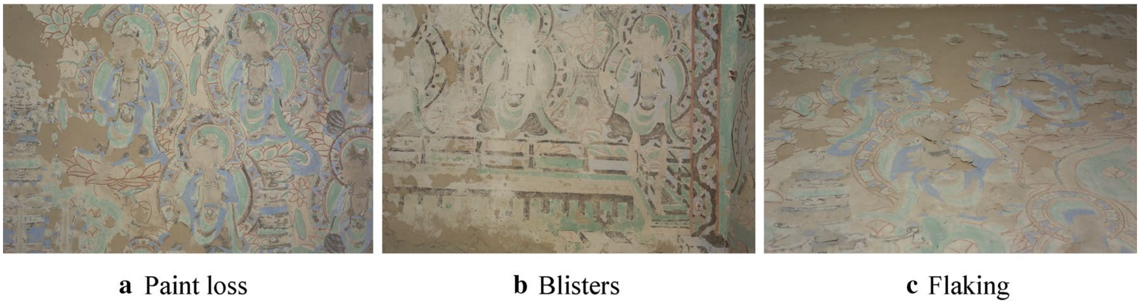
a Paint loss **b** Blisters **c** Flaking

Fig.2 Typical mural deteriorations in Cave 87

results, provide a more reasonable schedule for the management and conservation of the Cave 87.

Seven Hobo U23 data loggers (No. 1-No. 7) (range: − 40 ~ 100 ℃/0 ~ 100%; resolution: 0.02 ℃/0.03%; accuracy: ± 0.21 ℃/ ± 2.5%) were installed at different locations in Cave 87, as shown in Fig. 1. All data loggers continuously saved the T and RH data at 15 min intervals. The outdoor microclimate T and RH were simultaneously recorded in front of Cave 87 by a small meteorological station. One logger (No 5) was placed in the corridor (close to the only door) since all murals in the corridor have been totally damaged and disappeared. There are six Buddha statues inside the narrow and uneven Buddhist niche, which is far from the openings or low influenced by the incoming air flow from outside, one logger was placed inside the Buddhist niche (No 2). Loggers No 3 and No 6 are located at the same location but at different heights near the North wall. Loggers No 1 and No 4 are placed in the same way but near the South wall. No7 logger was placed near the South wall at about 30 cm from the corridor.

The impact of visitors has been considered two main effects, that is the increasing temperature and humidity due to people's presence and variation of airflow due to the opening of the doors [27–29]. Research conducted by Huerto-Cardenas et al. indicates that, in a huge volume and massive building, people have a greater influence on the indoor climate through the increased air exchange with the outside caused by the interaction with opening doors, rather than their heat and vapour emissions on the environment [27]. There are a total of 492 caves in Mogao Grottoes, of which only 69 are open to tourists. Although the 87 in the Mogao Grottoes cannot be subsumed into a massive building, this study focuses on caves that are not open to tourists. These closed caves only can be opened by conservators for preservation investigation and maintenance conducted by several people. Consequently, this study only considered that visitors only have an influence on fluctuations of indoor T and RH by opening doors.

Results

Annual distribution characteristics of the microclimate

The annual variations in T and RH inside and outside Cave 87 were obtained, as shown in Figs. 3, 4. The climate of the Mogao Grottoes is characterized by a typical arid climate, wide diurnal T range, and obvious seasonality [30]. The annual variations in both the indoor and outdoor T conform to half-wave sine patterns. The monthly average T values outside and inside the cave range from -5.1℃ ~ 26.9 ℃ and 3.0 ℃ ~ 20.3 ℃, respectively. The outdoor T reaches its maximum in July and its minimum in December, while the indoor T reaches its maximum and minimum in August and January, respectively, one month later than outside the cave.

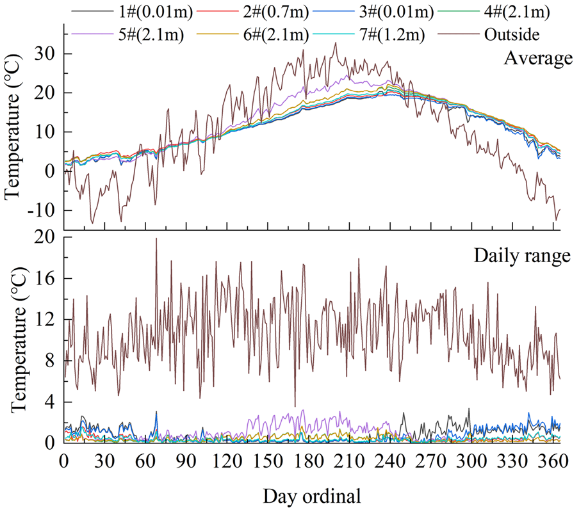

Fig. 3 Annual variation in the temperature

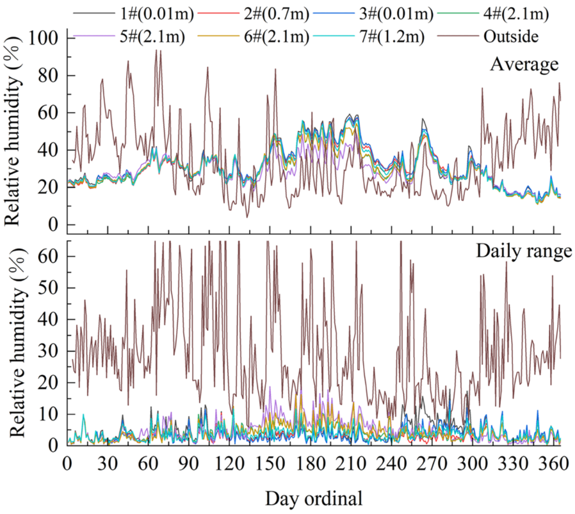

Fig.4 Annual variation in the relative humidity

The annual variation in the indoor RH also approximately conforms to a half-wave sine pattern. The monthly average indoor and outdoor RH values range from 22.7% ~ 53.5% and 16.3 ~ 47.4%, respectively. The diurnal fluctuations in both T and RH outside the cave are much greater than those inside the cave. This could be attributed to the dampening of the high thermal capacity of the envelope on cyclical fluctuations of indoor T and RH [27, 28].

Extreme value distributions

The distributions of the extreme T and extreme RH values can be classified into six types (I ~ VI) according to daily fluctuation modes of T and RH, as shown in Fig. 5. The daily extreme values of T and RH and their occurrence times were extracted for further analysis. According to data analysis, there are environmental differences between the upper and lower measuring points but almost no differences at the same height in Cave 87. Therefore, No. 1 (lower measuring point #1) and No. 4 (upper measuring point #4) were selected for the subsequent comparative analysis.

Temperature and relative humidity

The annual distributions of the occurrence times of the daily extreme T and RH (maximum and minimum) are shown in Figs. 6, 7. Classify days 90–270 as the warm season and the remaining days of the year as the cold season, the summary of extreme times is shown in Table1.

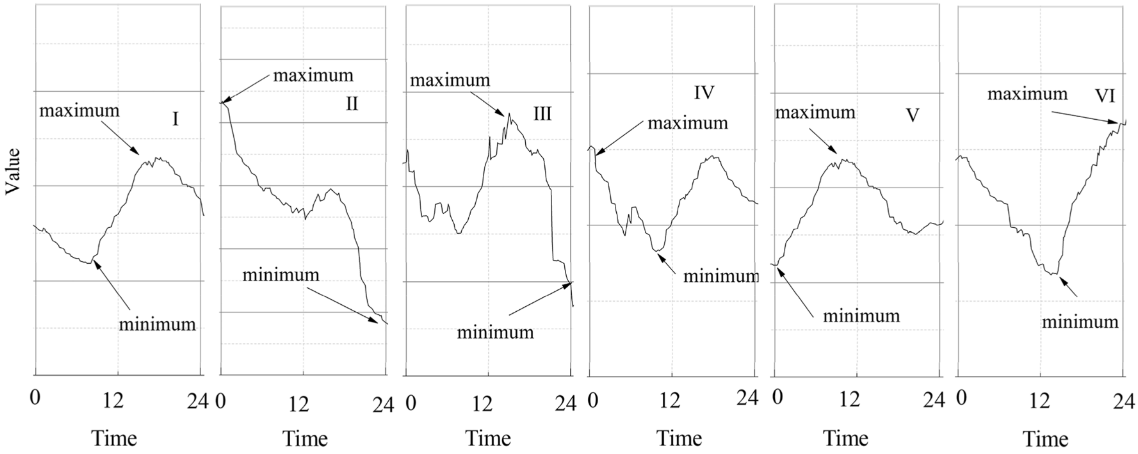

Fig. 5 Six distribution types of the daily extremum time

As shown in Fig. 6, Table 1, the occurrence times of the daily outdoor maximum T and minimum T are mainly distributed between 4 pm ~ 7 pm and 7 am ~ 10 am. During days 90 ~ 270, the times of the daily outdoor minimum T were more concentrated than the occurrence times during days 1 ~ 90 and days 270 ~ 365, which were scattered. The indoor T generally reached its maximum from 4 to 12 pm. The occurrence times of the minimum T were mainly distributed in the range of 6 ~ 10 am, and the average value was 8 am. Further statistical analysis showed that the average times of the indoor maximum T (average of No. 1 and No. 4) and outdoor maximum T values were 5:38 pm and 5:18 pm, respectively. The average occurrence time of the daily indoor minimum T was 8:34 am, while that outside the cave was 7:30 am.

The times of the outdoor maximum RH mostly varied between 4 and 8 pm, with an average of 6 pm. The times of the outdoor minimum RH mainly varied between 6 and 10 am, but it varied seasonally. During days 90 ~ 285, most of the times were distributed between 5 and 8 am. The times were scattered from 4 ~ 10 am during the rest of the year (days 1 ~ 90 and days 285 ~ 365). The occurrence times of indoor maximum RH were scattered. However, it also exhibited slight seasonal characteristics. Notably, the maximum RH more likely occurred from 8 am ~ 12 am and 6 pm ~ 12 pm but rarely occurred between 2 am ~ 6 am and 12 am ~ 4 pm. The time distribution of the minimum RH also revealed seasonal characteristics. In the cool season, the times were mainly distributed between 8 am ~ 12 am. In the warm season, the indoor RH likely reached its minimum from 6 pm ~ 10 pm. When the RH gradually has been increasing or decreasing all day, the maximum or minimum RH occurred at 0 or 24 o'clock, respectively.

Temperature difference and relative humidity difference (indoor T minus outdoor T)

The annual distributions of the occurrence times of the extreme T differences are shown in Fig. 8, Table 2. The time distribution of the extreme T difference of No. 1 was almost the same as that of No. 4, as was that of the RH difference.

The time distribution of the maximum T difference significantly varied with the season, which could be manifested as 6 am ~ 9 am during the cold season and 4 pm ~ 6 pm during the warm season. The time distributions of the minimum T differences exhibited roughly the opposite trend to that of the maximum T difference, namely, the times mostly ranged from 4 pm ~ 6 pm in the cold season and 6 am ~ 9 am in the warm season. The times of the extreme RH differences were obtained, as shown in Fig. 9, Table 2.

The seasonal characteristic of the time distribution of the maximum RH difference was similar to that of the T difference, namely, the times ranged from 4 am ~ 12 am during the cold season and 4 pm ~ 8 pm during the warm season. The time distributions of the minimum T differences were roughly opposite to those of the maximum RH differences, namely, the times mostly occurred in the range of 4 pm ~ 10 pm during the cold season and 4 am ~ 10 am during the warm season.

Microclimate fluctuation in the cave caused by door opening

Attributed to the valley topography and windbreak forest in front of the Mogao Grottoes, the average annual wind speed is only 0.6 m/s [31]. Cave 87 can be defined as a building with a single rectangular opening. Therefore, the indoor-outdoor air exchange of Cave 87 is largely driven by thermally induced natural convection flow.

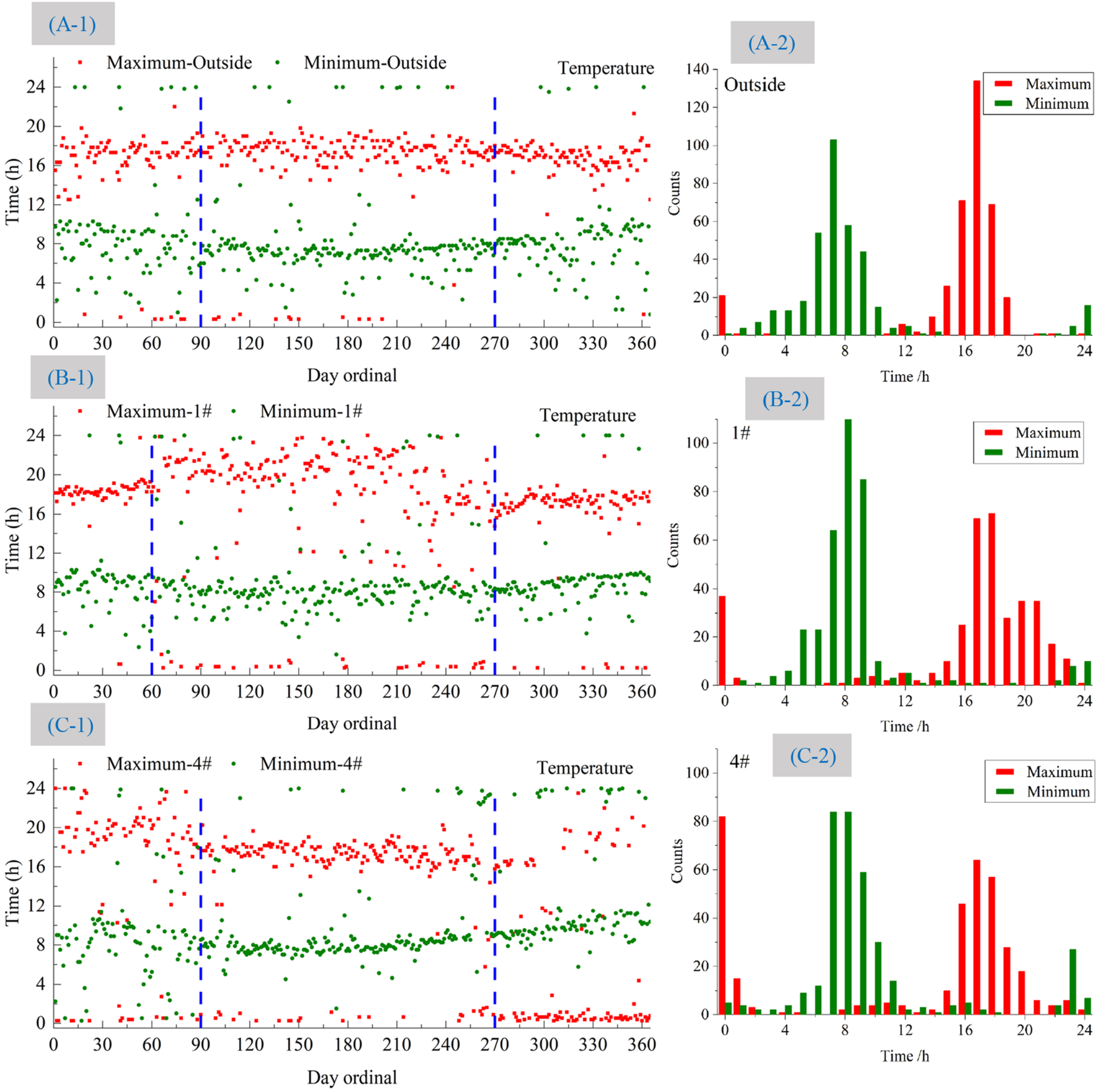

Fig. 6 Annual distributions of the daily extreme times of the temperature and their statistics. The maximum value: red, the minimum value: green. **A–1** is annual distributions of outside. **A–2** is statistics of outside. **B–1** is annual distributions of location No.1. **B–2** is statistics of location No.1. **C–1** is annual distributions of location No.4. **C–2** is statistics of location No.4

Researchers demonstrated that the relationship between the airflow velocity (air exchange capacity) and the T difference between indoors and outdoors(ΔT) exhibits a power exponential function relationship, which can be expressed as Eq. (1) [32, 33].

$$Q = \frac{1}{3} C_d A \sqrt{gH\frac{\Delta T}{T_i}} (\mathrm{m3} \cdot \mathrm{s}^{-1}) \quad (1)$$

where C_d is the flow coefficient, A is the opening area (m^2), g is the acceleration of gravity, ΔT is the T difference between indoors and outdoors, T_i is the indoor air T, H is the opening height (door height), the total area of the two shutters is only 1/4 of the door area.

For example, on August 26th, the daily T fluctuation in the cave is not more than 0.5 °C, and the daily fluctuation in the RH is less than 5% (Fig. 10). Once the cave

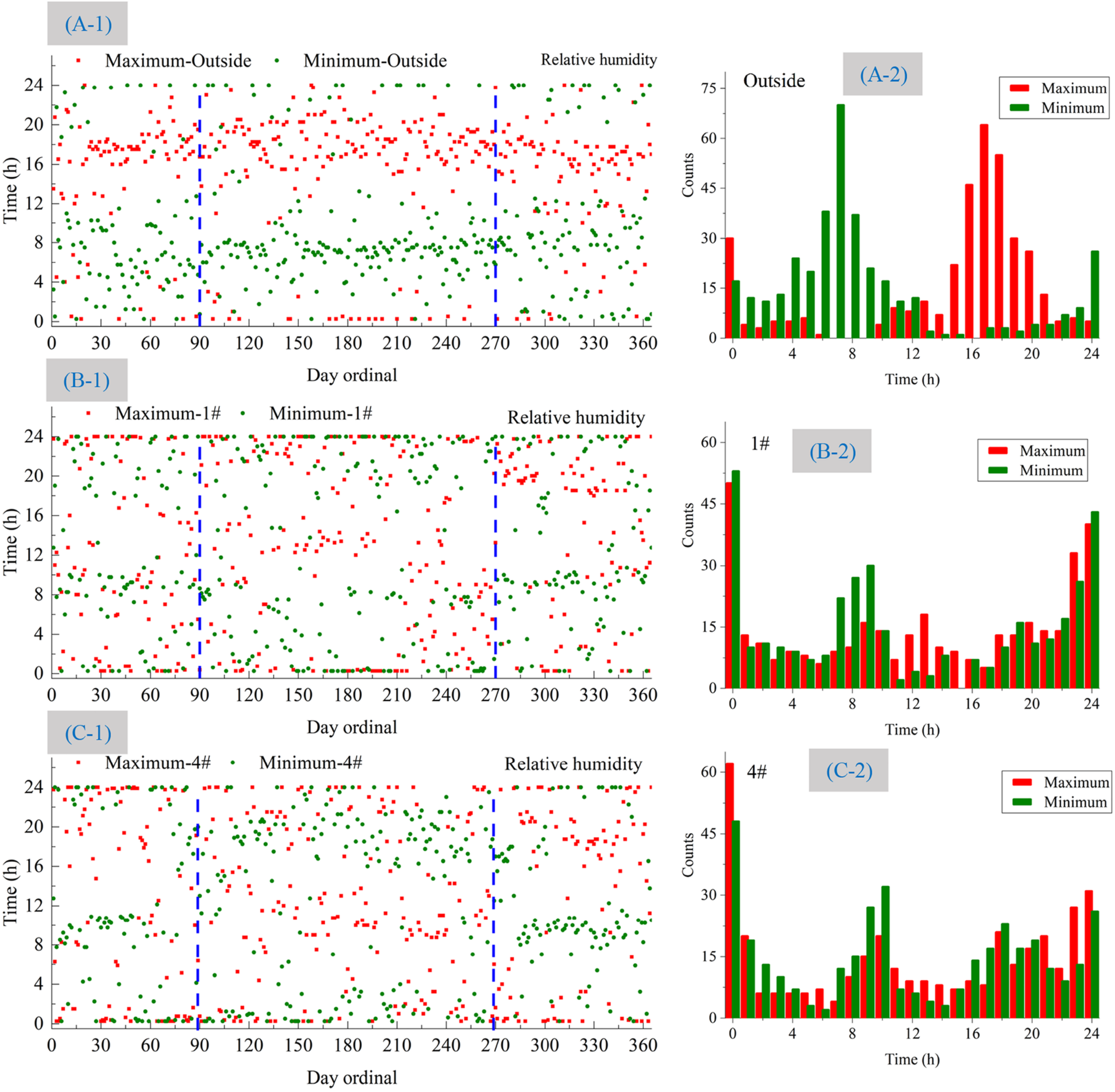

Fig. 7 Temporal annual distributions of the daily extreme relative humidity and their statistics. The maximum value: red, the minimum value: green. **A–1** is annual distributions of outside. **A–2** is statistics of outside. **B–1** annual distributions of location No.1. **B–2** is statistics of location No.1. **C–1** is annual distributions of location No.4. **C–2** is statistics of location No.4

door is opened, A and H in Eq. (1) increase by several times, and the small fluctuations in the relatively stable initial microclimate can be greatly aggravated. As shown in Fig. 10, seven indoor fluctuations in T and RH caused by door openings are denoted as a–g. It is obvious that the larger the T difference (August 26th and 28th), the greater the fluctuation. Rapid air exchange inevitably brings fluctuations in the RH within the cave. Moreover, the externally hotter air enters the cave through the upper shutter and is cooled in the cave, resulting in larger fluctuations at the upper sites (No. 4).

The thermal pressure inevitably causes air exchange between indoors and outdoors [9, 32–34]. The larger the T difference is, the higher the air exchange rate and the greater the microclimate fluctuation inside the cave. However, the T difference is not constant throughout the year. The significant characteristics of the T difference are embodied in a larger difference in winter and summer and a smaller difference in spring and autumn. Similarly,

Table 1 Occurrence times of the daily extreme T and RH

	T			**RH**		
	Outdoor	**No.1**	**No.4**	**Outdoor**	**No.1**	**No.4**
Maximum						
Annual average	4 pm ~ 7 pm	4 pm ~ 8 pm	4 pm ~ 8 pm	4 pm ~ 8 pm		
Warm season	6 pm	6 pm ~ 10 pm	4 pm ~ 8 pm	4 pm ~ 8 pm	8 am ~ 12 am	
Cool season	5 pm	4 pm ~ 8 pm	6 pm ~ 10 pm	4 pm ~ 7 pm	6 pm ~ 12 pm	
Minimum						
Annual average	6 am ~ 10 am	6 am ~ 10 am	6 pm ~ 10 am	6 am ~ 10 am		
Warm season	7 am ~ 8 am	6 am ~ 10 am	7 am ~ 9 am	4 am ~ 10 am	8 pm ~ 12 pm	
Cool season	6 am ~ 10 am	7 am ~ 9 am	6 am ~ 10 am	6 am ~ 10 am	8 am ~ 12 am	

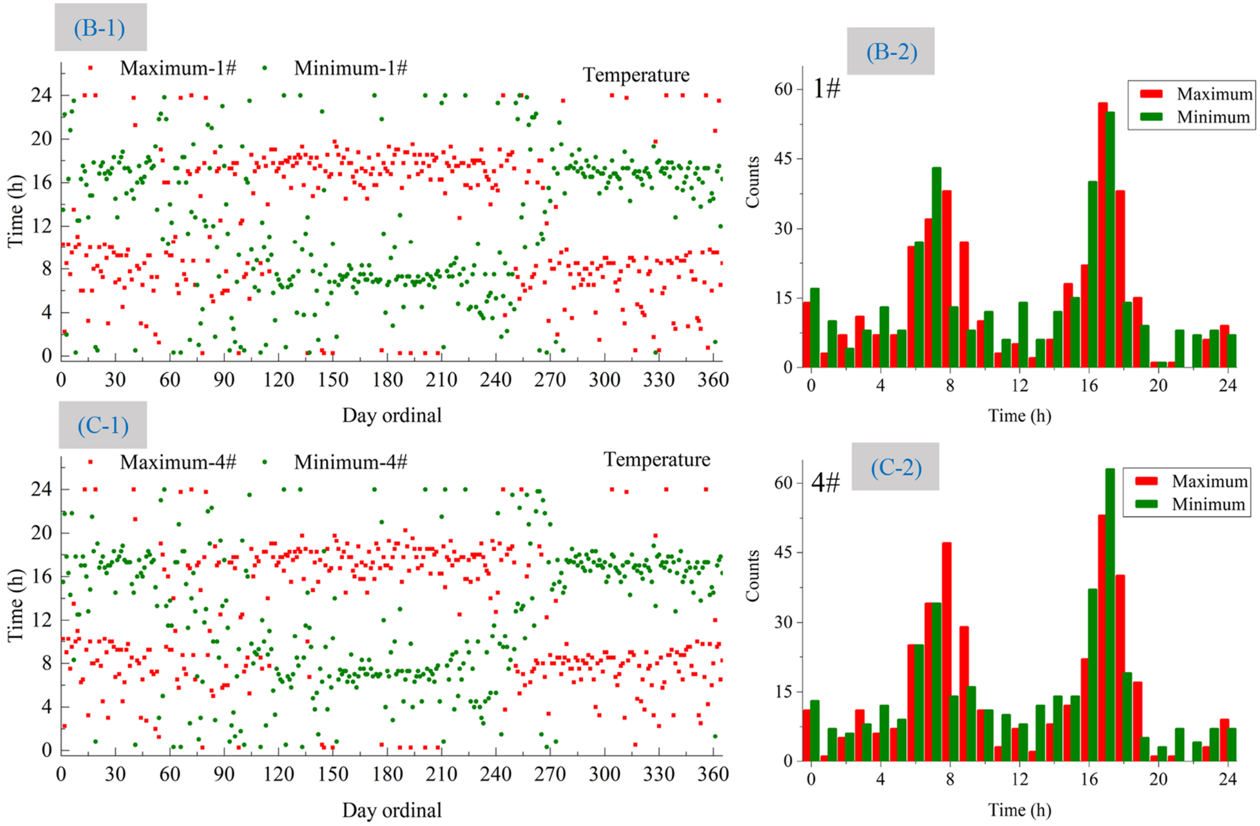

Fig. 8 Annual distributions of the daily extreme times of the temperature difference and their statistics. The maximum value: red, the minimum value: green. **B**–**1** is annual distributions of location No.1. **B**–**2** is statistics of location No.1. **C**–**1** is annual distributions of location No.4. **C**–**2** is statistics of location No.4

there must be a maximum and minimum indoor-outdoor T difference value during the day, and the time distribution of the daily extreme T differences changes with the seasons. Finding the statistical distribution law of this extreme moment will help to design a more reasonable time for the daily management of caves, and reduce the impact of human activities on the environment in caves as much as possible. It is necessary to further analyse the seasonal distribution characteristics of the occurrence times of the extreme T and RH differences.

Discussion

Previous studies have demonstrated that air exchange caused by the T difference can exert an appreciable effect on indoor moisture fluctuations, frequent RH fluctuations could produce high risks of cracking, flaking, salt

Table 2 Occurrence times of the daily extreme T differences and RH differences

	T difference	RH difference
Maximum		
Warm season	6 am ~ 9 am	4 pm ~ 8 pm
Cool season	4 pm ~ 6 pm	4 am ~ 12 am
Minimumn		
Warm season	4 pm ~ 6 pm	4 am ~ 10 am
Cool season	6 am ~ 9 am	4 pm ~ 10 pm

efflorescence, swelling, disaggregation, surface layer detachment, and even microbe diseases [5, 35–37]. There is a common view that fluctuating T and RH are considered greater risk than a stable T and RH. It is necessary to identify the time when the T and RH differences between inside and outside the cave are relatively low.

Because of different air exchange patterns between inside and outside the cave in different seasons, there is a slight difference between No. 1 and No. 4. As we know, external temperature fluctuations are much greater than that of internal. In the cold season, the external temperature is lower than that inside the cave, outside cold air enters the cave through the lower shutters and leaves from the upper shutters after being heated inside the cave. This causes a greater fluctuation of the lower measuring point (No.1) than that of the upper measuring point (No.4) (Fig. 11). In the warm season, the air exchange mode is the opposite, the warm external air enters the cave from the upper shutters, and the internal cold air escapes from the bottom. Thus, the fluctuation of the upper measuring point is greater than that of the lower measuring point (No.1) (Fig. 12). While, this study focuses on the T difference between inside and outside the cave, therefore, these subtle differences between internal measurement points do not impact the results of this study. So only No. 1 was selected.

Figure 13 shows that the times of the extreme T and RH differences were generally distributed in two ranges, namely, 6–12 am and 2–10 pm. It was found that both the T and RH differences are prone to reach their maximum values during the morning (6–12 am) in the cold season (October ~ December and January ~ March). When the T difference reached its minimum in the afternoon

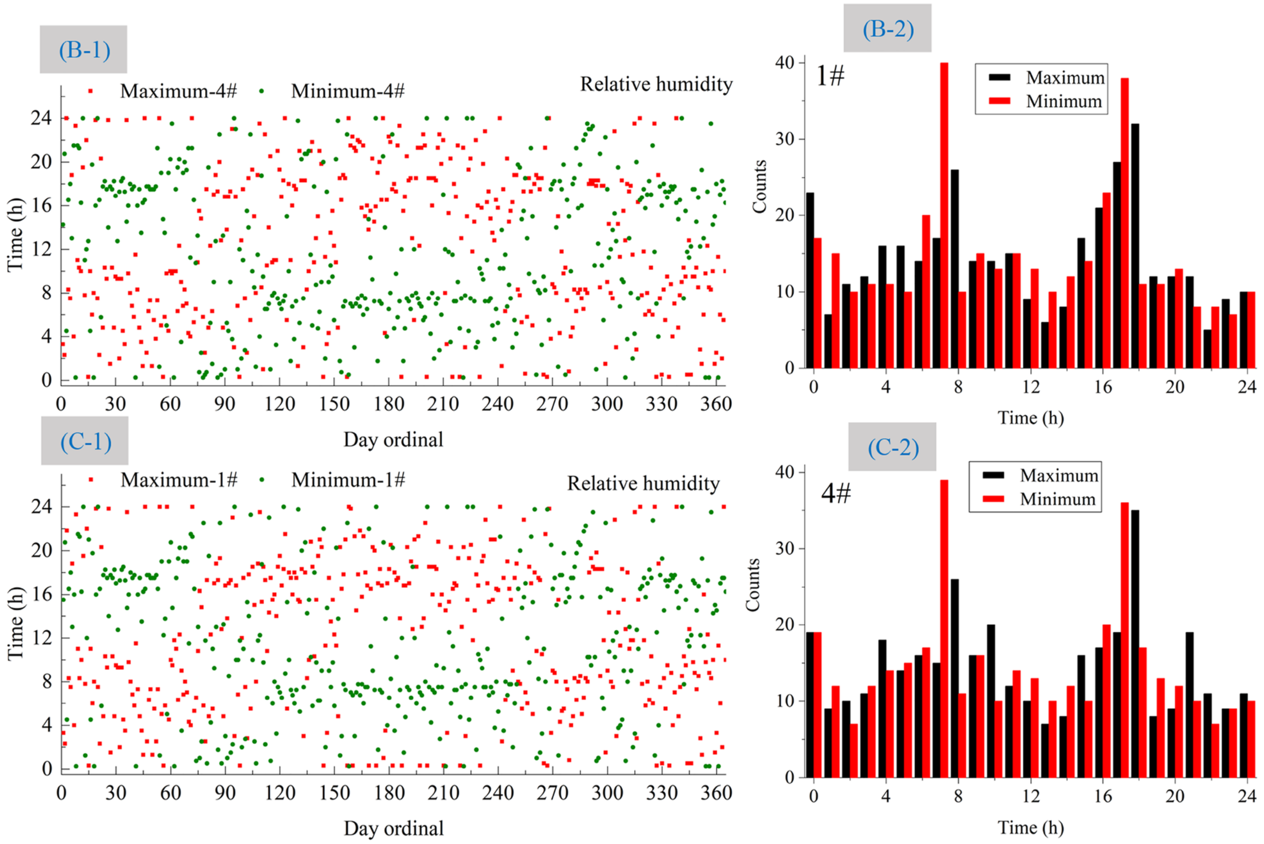

Fig. 9 Annual distributions of the daily extreme times of the relative humidity difference and their statistics. The maximum value: black, the minimum value: red. **B–1** is annual distributions of location No.1. **B–2** is statistics of location No.1. **C–1** is annual distributions of location No.4. **C–2** is statistics of location No.4

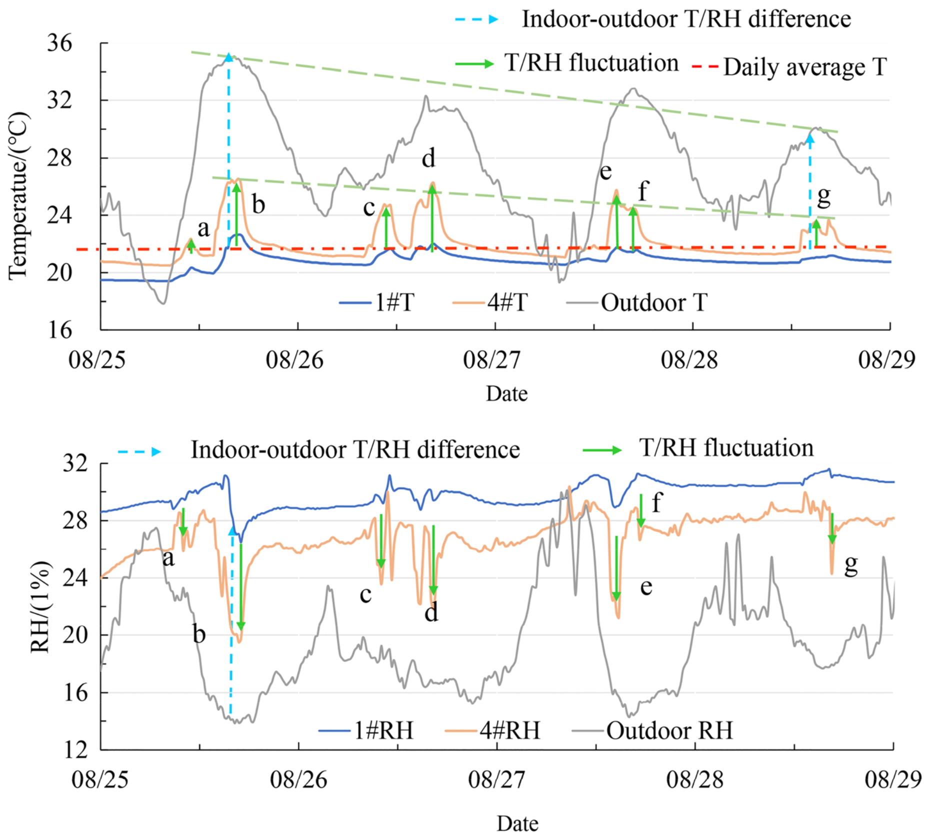

Fig. 10 Indoor T/RH variation under the influence of door opening

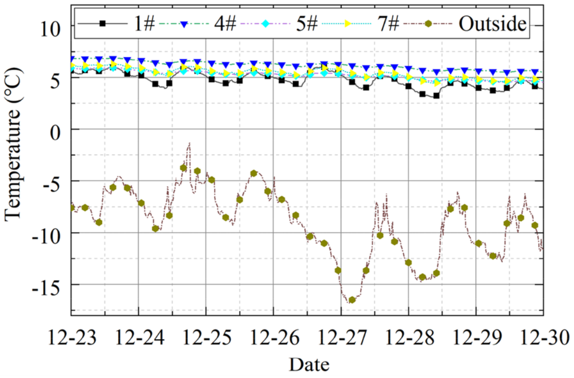

Fig. 11 Variation of T in December

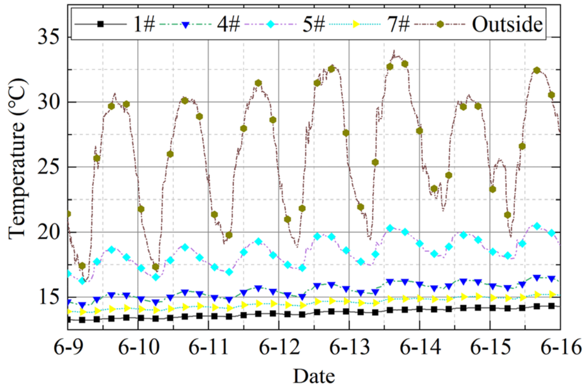

Fig. 12 Variation of T in June

(2 ~ 10 pm), the RH difference also reached its minimum. Therefore, in the cold season, investigation and maintenance should be arranged during the afternoon, and the morning should be avoided as much as possible. In fact, in the cold winter, the possibilities of workers accessing the cave to do their work after 8 pm are extremely low. Therefore, the opening time is limited to after 2 pm in the afternoon. The schedule during the warm season (April ~ September) should be the opposite of the winter schedule.

There is uncertainty that if the results are same in other caves (large caves, caves on different floors, etc.). Therefore, further experimental verification including data monitoring and analysis is undoubted essential, which is already added to our future research plan.

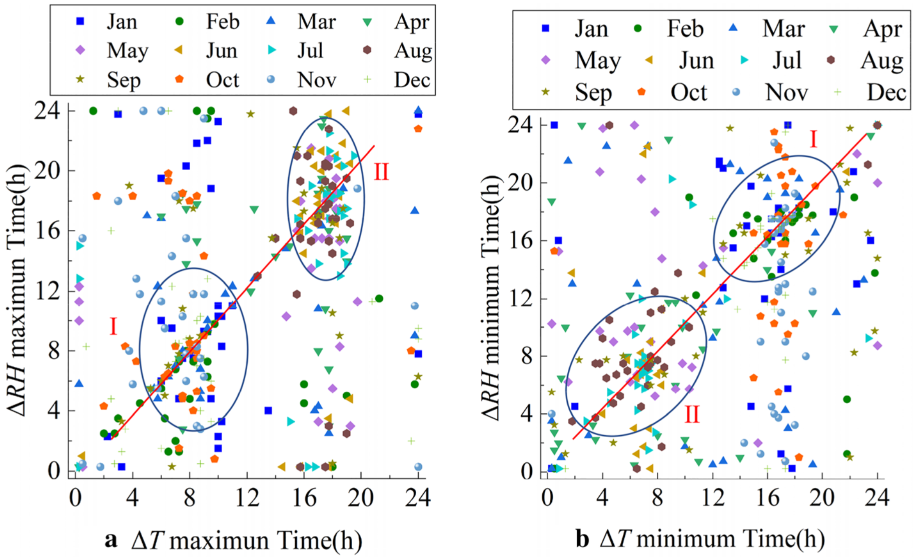

Fig. 13 Relationship between the extreme T (ΔT) difference time and extreme RH difference (ΔRH) time

Conclusion

The environmental differences between the indoor and outdoor areas of the Mogao Grottoes are characterized by obvious seasonal characteristics throughout the year and notable variations throughout the day. The indoor-outdoor air exchange of Cave 87 is mainly driven by thermally induced natural convection flow. Air exchange capacity depends on door openings and the T difference between indoors and outdoors. After the analysis of the microclimate difference between Cave 87 and its outside environment, the door opening times in different seasons were further optimized for conservators and managers, that is, the appropriate time for conservation activities is 2 ~ 10 pm in winter and 6 ~ 12 am in summer. Mural paintings have been preserved over thousands of years, benefiting from the stable microclimate in caves, so the rapid fluctuation of inside microclimate in a short time carries potential risks. While, there is a conflict between conservation activities and the stability of the indoor microclimate. Particularly, if the cave door is opened at an inappropriate time, conditions will worsen. Unfortunately, this has not been reflected in the conservation and management of heritage sites. Therefore, we suggest that managers develop a detailed maintenance schedule, and adjust the time in different seasons (2 ~ 10 pm in winter and 6 ~ 12 am in summer). Hence, this study is a significant attempt in this field and provides support and references for the management and preventive conservation of the wall paintings in the Mogao Grottoes. However, Cave 87 is a small-scale cave located on the ground floor of the Mogao Grottoes. Research on other caves requiring more microclimate data should be conducted.

Abbreviations

RH	Relative humidity
T	Temperature
AH	Absolute humidity
ΔT	Temperature difference (indoor T minus outdoor T)
ΔRH	RH difference (indoor RH minus outdoor RH)

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Author contributions

ZY wrote the main manuscript text and revised the manuscript repeatedly. ZY prepared Figs. 1, 9. WY selected the extreme values using ANSYS finite element software and prepared Figs. 2, 3, 4, 5, 6, 7, 8. WY revised the manuscript. I, and all co-authors have approved this manuscript version; AND we agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved. All persons who have made substantial contributions to the work reported in the manuscript, including those who provided editing and writing assistance but who are not authors, are named in the Acknowledgments section of the manuscript and have given their written permission to be named. If the manuscript does not include Acknowledgments, it is because the authors have not received substantial contributions from nonauthors.

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Availability of data and materials

All the original monitoring data and materials that are required to reproduce these findings can be shared by contacting the corresponding author, qawyj@lzu.edu.cn (WANG Yajun).

Declarations

Competing interests

The authors declare that we do not have any commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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