Environmental Science: Atmospheres

ROYAL SOCIETY OF CHEMISTRY

PAPER

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Cite this: Environ. Sci.: Atmos., 2026, 6, 377

# Implications of daily thermal variations in the ventilation and indoor $CO_2$ levels in the karstic system of the Altamira Cave

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Received 5th September 2025
Accepted 29th December 2025

DOI: 10.1039/d5ea00107b

rsc.li/esatmospheres

Within the Preventive Conservation Plan framework established for the Cave of Altamira, the continuous monitoring of environmental variables constitutes one of the focal points for preserving the parietal art contained therein. This paper presents new aspects of the ventilation of the Cave of Altamira derived from detecting short-period thermal fluctuations observed in different areas inside the cave. For 2021 and 2022, there are periods with daily air temperature oscillations, mainly in the summer and early autumn, corresponding to day/night thermal variations. The concentration of $CO_2$ was considered as a passive tracer to investigate air exchange dynamics. We observed temporally correlated fluctuations in $CO_2$ levels across three interior rooms (Hall, Crossing, and Polychromes Room). This pattern suggests the influence of a shared ventilation pathway or a common driver of gas exchange with the exterior. The correlations between these fluctuations and the variations of the indoor/outdoor air thermal gradient in each area indicate that these gradients could explain, to a large extent, the variations of $CO_2$ concentration during the period analysed. These results allow us to know more precisely the behaviour of the concentration of this gas inside the cave and to better characterise the cave's ventilation.

### Environmental significance

The preservation of cave art such as Altamira relies on maintaining stable microclimatic conditions that prevent physical, chemical, and biological alterations to the prehistoric art. Understanding ventilation processes is essential because they directly control gas concentrations, humidity, and temperature factors that influence the conservation state of parietal paintings. This study provides new insights into short-period ventilation dynamics of the Cave of Altamira by linking daily thermal oscillations with correlated fluctuations in $CO_2$ levels across different chambers. By identifying the environmental drivers of gas exchange, our results contribute to refining conservation strategies and to developing more accurate predictive tools for monitoring sensitive subterranean cultural heritage sites under current and future climate variability.

## 1. Introduction

The Cave of Altamira contains one of the world's most impressive sets of rock art.[1,2] Awareness of the need to implement measures to ensure the preservation of the paintings arose almost immediately upon their discovery at the end of the 19$^{th}$ century. However, it was not until the 1980s that preservation measures based on scientific knowledge of the physical, chemical and biological variables most directly linked to the state of preservation of paintings began to be applied.[3] Since the mid-20$^{th}$ century, when the number of visitors increased considerably, a great deal of scientific attention began to be focused on the problems of conservation of the cave art linked both to the natural and inexorable deterioration of the paintings and to the anthropic influence on this deterioration. Among the most decisive environmental aspects in the deterioration mechanisms identified, such as the dissolution and dragging of pigments, the temperature field and variations in the concentration of interior $CO_2$ stand out. From 2014 to the present day, the preservation of the art contained in Altamira has been systematised in a set of protocols and procedures known as the Preventive Conservation Plan.[4] Within the area of environmental monitoring, the monitoring of temperatures outside and in all the interior areas of the cave is its central focus.

Continuous monitoring of the temperature field in caves containing cultural and artistic heritage is an essential tool in any preventive conservation programme.[5,6] The temperature field means the set of values of this magnitude both in the atmosphere inside and outside the cave environment, and in the walls, ceilings and floors that delimit the cavity. A precise knowledge of the temporal dynamics of the temperature field is a significant contribution from different points of view.

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The environmental conditions that have allowed wall paintings to reach our days in a good state of preservation are usually unknown. Currently, there is no sufficiently reliable method that allows us to know them to the point of defining them as preservation standards in each case. Continuous monitoring of the temperature field, together with other relevant variables such as relative air humidity or the concentration of $^{222}$Rn and $CO_2$ in air,[7,8] allows the establishment of reference conditions for preservation based on historical values, whose robustness increases with the quantity and quality of accumulated data. Furthermore, with continuous temperature monitoring at adequate temporal resolution, a detailed analysis of the impact of human presence on sensitive microclimatic systems like the Cave of Altamira can be conducted.[1,9,10]

It is also remarkable that there is a need for precise knowledge of the temperature field in a cave when the atmospheric dynamics are to be studied. As pointed out in other studies,[11–14] the air mass exchanges between the interior and exterior in caves are directly related to air density gradients that ultimately depend on thermal gradients. This relationship has been particularly well described in shallow caves.[15–17] Again, in the case of particularly vulnerable artistic heritage, the monitoring of atmospheric dynamics is of utmost importance to understand the periods of the most significant risk of entry of biological pollutants (such as spores, fungi, bacteria, *etc.*) that may threaten the preservation of sensitive areas.[18–20]

A final element of interest in obtaining high-quality temperature time series is their potential use in studying meteorological and climatic disturbances in the cave environment.[18] The thermal signal recorded inside caves is heavily filtered by the rock interface, eliminating noisy or short-period variations in outside air temperature, such as those caused by wind or precipitation, which would otherwise make it difficult to identify changes accurately.[21]

The extraordinary relevance of the Altamira paintings and engravings makes it essential to use highly sensitive sensors subjected to rigorous periodic quality controls, as shown in the following section. The study presented in this article is based precisely on analysing the aerodynamic implications of thermal fluctuations observed in different areas of the cave interior. At Altamira, the seasonal thermal oscillations of the interior air temperature are well known[3] and have been explained by the transmission of the annual external thermal wave through the rock interface that defines the cave. However, particularly during the summer, daily fluctuations in air temperature are observed that cannot be adequately explained by the annual thermal wave. Since the temperature indoors shows clear daily oscillations from mid-spring to early autumn, it was hypothesised that they were temporally linked to those observed outdoors and could be explained based on gaseous exchanges produced by short-lived discharge and regasification events between the indoor and outdoor atmospheres.

The most evident observation of thermal fluctuations was found in the area known as the Crossing, as well as in adjacent areas such as the Entrance or Hall area and the Polychromes Room, the place with the highest content of pictorial representations in the cave. In order to analyse the possible influence of air exchanges between these rooms on the observed oscillations, we conducted a correlation study of the air temperatures between the three rooms and each of them with the outside air temperature. In addition, the correlations between the indoor–outdoor thermal gradient and the carbon dioxide concentration in each of the areas above have been analysed. As demonstrated in previous work,[9,14,22] these correlations can satisfactorily explain direct exchanges between each room and the outside atmosphere.

This work has two main objectives, related to the atmospheric dynamics in the cave (ventilation) and the presence of $CO_2$ in the interior. Given the direct relevance of the concentration of this gas in the air to the deterioration processes, we have sought to deepen our knowledge of the short period variations experienced by its concentration in certain periods of the year. The aim is to make a significant contribution to a more detailed knowledge of the temporal evolution curve of this variable. The second research objective was to study the aerodynamic fluctuations of the air exchange with the outside of the cave, and the degree of synchrony between different interior rooms.

The results obtained in this study will contribute to a more efficient conservation of the rock art, based on environmental data, which constitute a solid base for the future validation of predictive models of the interior $CO_2$ concentration that allow us to distinguish the variations produced by anthropic action from those observed by environmental dynamics. Here we show, on the one hand, the existence of convective exchange pathways between each of the rooms studied and the exterior, and on the other hand, this study provides relevant information for a more complete understanding of the evolution curve of the $CO_2$ concentration in the air, also continuously monitored in all the rooms as part of the environmental monitoring of the cave, both for its direct influence on the state of preservation of the paintings and for its usefulness as a tracer gas for air mass exchanges.[10,23–26]

## 2. Materials and methods

### 2.1 Description of the Cave of Altamira

The Cave of Altamira is located in the upper part of a limestone hill in the town of Santillana del Mar, on the western coast of Cantabria (northern Spain). Its geographical coordinates are 43°22′37″N 4°07′11″W. It is a shallow cavity with a north-facing entrance at an elevation of 152 m. It develops in S-shaped passages and has a total length of approximately 270 m, with the lowest point at about 16 m from the entrance.

Geologically, the cave was formed in an environment of Upper Cretaceous calcareous rocks, characterised by their high solubility in slightly acidic water. This chemical dissolution process, known as karstification, has been fundamental in the cave formation.[1] Fig. 1 shows the map of the initial part of the cave, which includes the Hall, the Crossing and the Polychromes Room.

### 2.2 Description of the measurement stations, corrections and calibration

The Cave of Altamira has a total of 6 measurement stations: one outdoor and five indoor stations distributed among the main

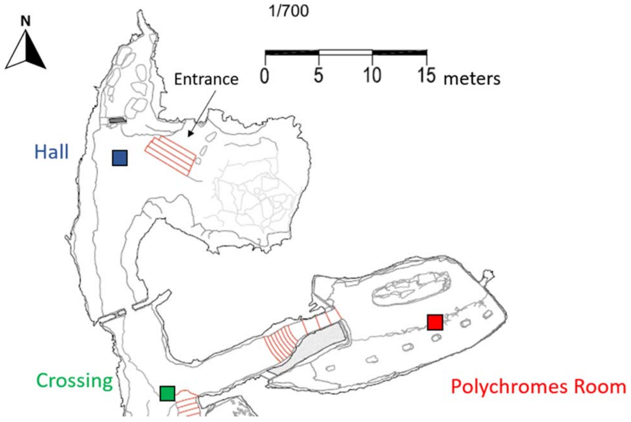


Fig. 1 Map depicting the initial section of the Cave of Altamira, including orientation (north arrow), the numeric scale (1/700) and the scale bar. Coloured squares denote the precise locations of the Hall, Crossing, and Polychromes Room measurement stations.

rooms of the cave. These stations comprise different measurement probes connected to dataloggers that send data packets to an external server. These data can be downloaded remotely. The variables these stations monitor are air temperature, rock temperature (soil and roof), relative humidity and $CO_2$ concentration in the air (Fig. 2). Data are recorded every 15 minutes in all cases, except for the station in the Polychromes Room, where the frequency of data acquisition is higher, with data recorded every minute. For the study presented in this article, data on $CO_2$ concentration and air temperature at mid-elevation from the outdoor station and from the three stations located in the most external rooms of the cave, Hall, Crossing and Polychromes Room, were used. The air temperature probes, both internal and external, are Pt100 models with a resolution of 0.01 °C and an accuracy of ±0.06 °C. $CO_2$ concentration is measured using EE82 Series instruments, which offer a resolution of 1 ppm and an accuracy of ±100 ppm. The $CO_2$ sensor accuracy is conservatively reported according to the manufacturer's specification for high concentration levels (>5000 ppm), which represents the maximum error. Measurement accuracy is defined as the sum of two components: a fixed offset (100 ppm) and a percentage of the measured value (5%), so that at low concentrations the offset predominates, while at higher concentrations the error increases proportionally.

In accordance with the Preventive Conservation Plan for the Cave of Altamira,[4] the probes are periodically calibrated, and the electronic thermometers are compared every two weeks with high sensitivity Hg thermometers (0.05 °C) in order to guarantee the quality of the data obtained.

## 2.3 Preparation of the time series

This study used data from the four stations mentioned above for 2021 and 2022. Before being used for analysis, the data were reviewed and cleaned by removing outliers. Considering that the available data from the Polychromes Room had been stored more periodically, the corresponding data were taken from the series, which coincided with the data available in the rest of the stations every fifteen minutes.

We then made a graphical representation of each variable for the entire available period to identify oscillations of approximately daily frequency. As previously observed, such oscillations were identified in the crossing area during the summer months of July, August, and September in both years. In addition, it was found that such oscillations also occurred in the same period, albeit to a varying degree, in the Hall and Polychromes Room areas. Finally, almost simultaneous fluctuations in $CO_2$ concentration were also identified in the three rooms mentioned above.

Monthly basic statistics were also evaluated for air temperature and $CO_2$ concentration variables for each station considered. We conducted this analysis to detect outliers in the time series used and obtain descriptive statistics on the variables. We represented all this by boxplot diagrams, which provide a clear synthesis of the central tendency of the dispersion and the skewness of the data.

## 2.4 Correlation analysis

To perform the correlation analysis, we grouped the values of each variable by weeks for the months from 1 June to 31 October

Fig. 2 Measurement stations from the exterior (left) and the mid-section of the Hall (right), as examples, with $CO_2$ and air temperature sensors marked in red.

2021 and 2022, obtaining Pearson correlation coefficients ($r$) and the corresponding $p$-values between the pairs of variables of interest. The $r$ values are always between −1 and 1, with 1 corresponding to a perfect positive correlation (the variables oscillate in the same direction simultaneously) and −1 to a perfect negative correlation (the variables oscillate simultaneously in opposite directions). The intermediate value of 0 indicates no linear correlation.[27]

A student's $t$-test was used to assess the statistical significance of the correlations found.[28] In this type of test, the confidence level with which a null hypothesis ($H_0$) can be rejected is tested. In this case, it consists of stating that there is no significant correlation between the pairs of variables corresponding to the two time series being compared. We used a confidence level of $\alpha = 0.01$, which represents the maximum probability of rejecting the null hypothesis when it is true, in this case 1%. Thus, if the $p$-value found is less than $\alpha$, we can conclude that the null hypothesis is rejected, indicating that the correlation obtained is significant.

With the analysis of the correlations between the monitored variables, the hypothesis of a common dominant mechanism explaining the degassing and recharging observed in each of the cave rooms has been tested. As a preliminary step, we analysed the synchrony between the variations in air temperature outside and in the three rooms. In the same way, we studied the relationship between the $CO_2$ concentration variations of the different indoor rooms. Subsequently, we calculated correlation parameters between the $CO_2$ concentration in each area and the thermal gradient between the air in each room and the outside atmosphere.

After obtaining the Pearson coefficients, we computed the number in each of the following intervals [−1, 0.5), (−0.5, 0), (0, 0.5) and (0.5, 1] and then analysed these correlation values together with the $p$-values to discard those values due to chance.

Data processing and obtaining graphs, correlation coefficients and $p$-values were carried out using a Python code programmed ad hoc. The code used is available on GitHub at https://github.com/IreneeMM/TFG_Altamira/blob/main/CCsTemperaturasCruceHallExterior.ipynb

## 3. Results and discussion

### 3.1 Time trends of the studied variables

Fig. 3 shows the evolution of the continuous series of air temperatures in the different indoor areas and outdoors from 2021 onwards.

As seen in the example for the Polychromes Room in Fig. 4, the boxplot diagrams show remarkable thermal stability, considering that the air temperature shows an annual variation of about 1.5 °C in the two years depicted. The annual variation of this temperature shows a seasonal oscillation, with minima at the beginning of summer and maxima around December, initially described in the 1980s[3] and corroborated by monitoring in subsequent years.[9,14,29] The boxplots for each month

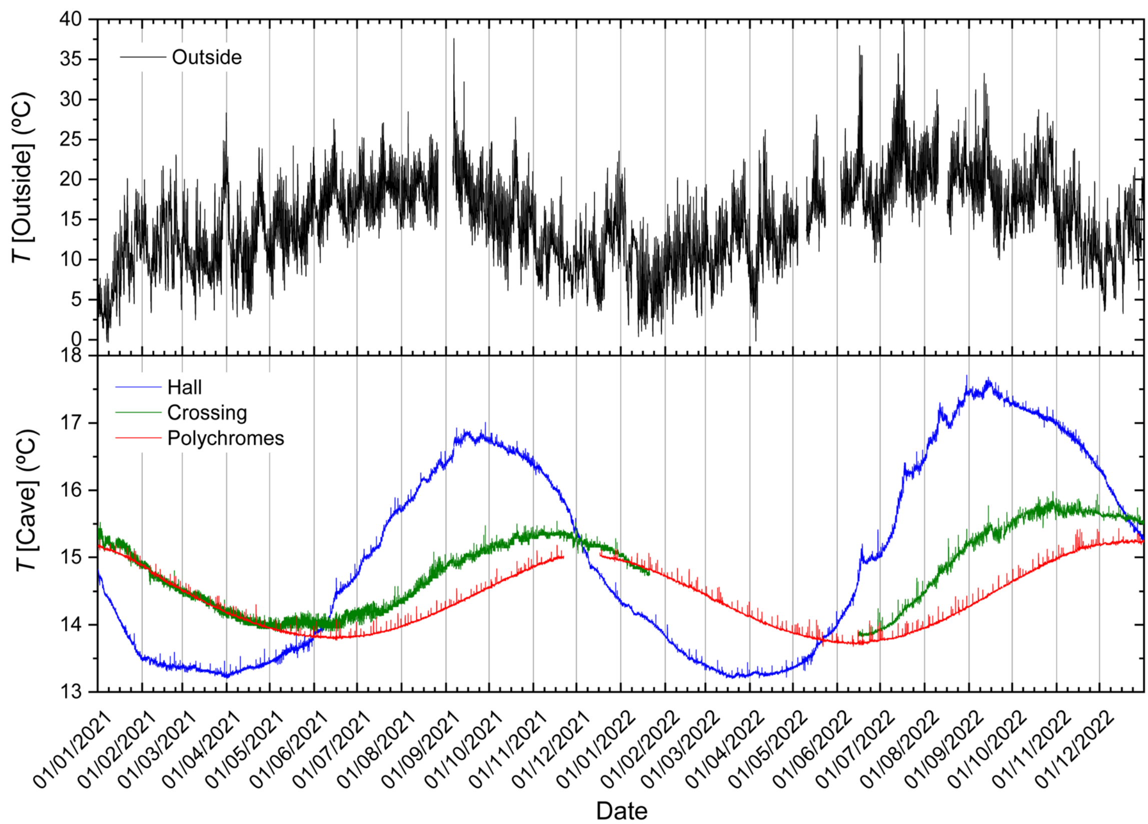


Fig. 3 The temperature at half height inside and outside the cave for the period 2021–2022.

 

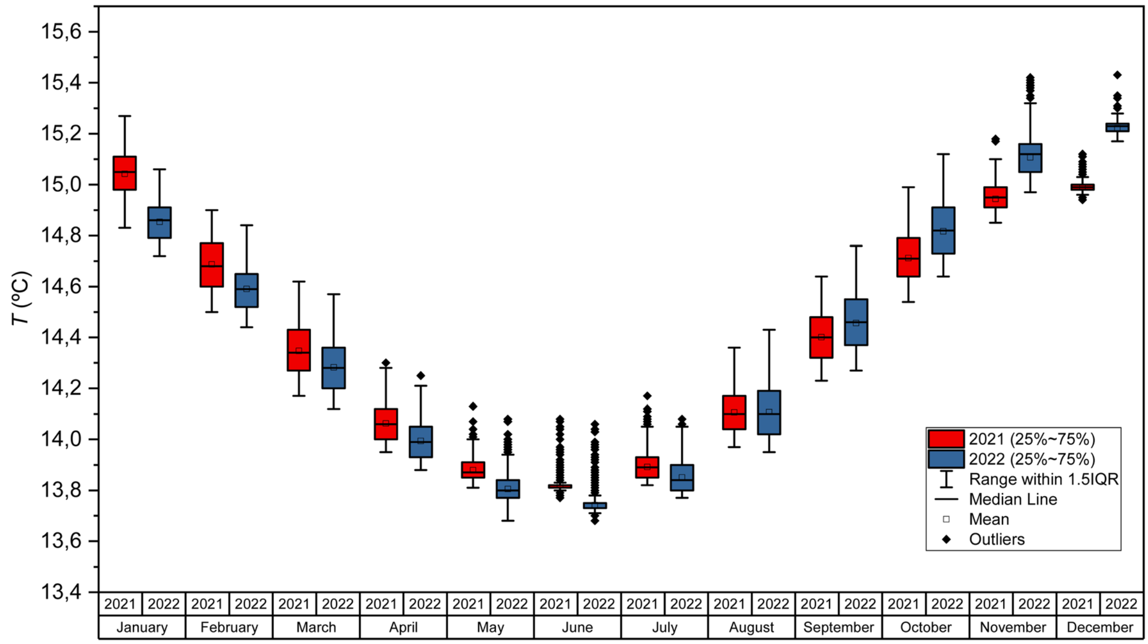


Fig. 4 Boxplot of the air temperature in the Polychromes Room.

show a remarkable symmetry around the median, indicating a distribution of values without prominent skewness, approximately normal. Considering the size of the monthly boxes represented, we observe that the temperature variability is minimal in the turning point months, June and December, and maximal in the intermediate months with a downward or upward seasonal trend, as in the case of March and September, respectively. The reason for this can be determined by examining the slopes of the temperature time evolution in Fig. 3. Finally, the points representing outliers deserve attention, which are always above the maximum value for each month and correspond to people's entries for research and maintenance tasks. These values can be clearly visualised in the representations shown in the monthly graphs below as short-lived, one-off increases.

The lack of perfect repeatability between the two years analyzed can be explained by two main factors. First, human presence inside the cave introduces short-term disturbances that vary depending on the number of people and the duration of their stay. These events, associated with research and maintenance activities, are reflected as outliers in the dataset and correspond to brief temperature increases, as shown in Fig. 4. Second, external meteorological conditions differ from year to year. Although the overall seasonal pattern remains stable, the amplitude of thermal oscillations can vary according to the intensity of external thermal waves, such as warmer summers or milder winters. These factors account for the observed discrepancies while preserving the general consistency of the long-term trend.

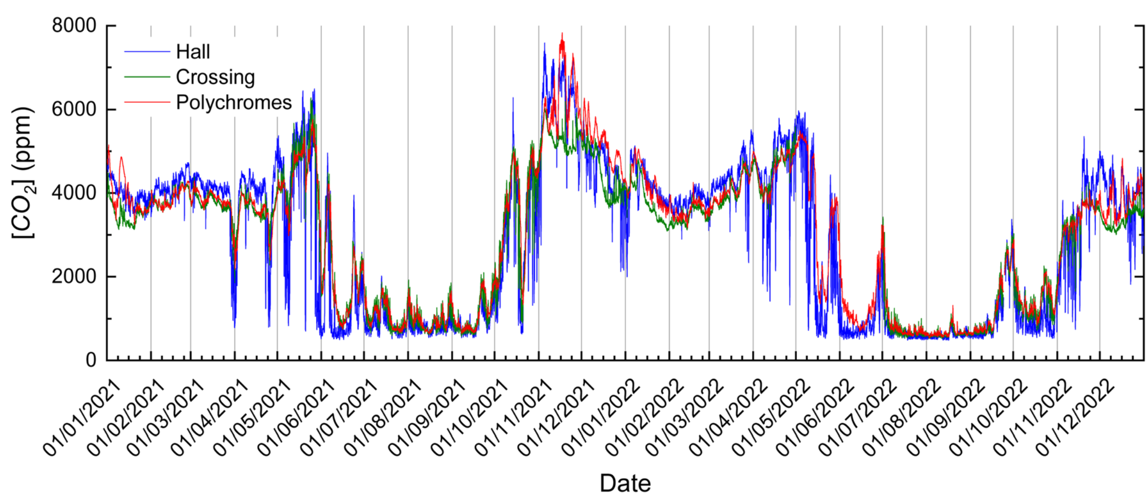


Fig. 5 $CO_2$ concentration graph in the Hall, Crossing, and Polychromes Room.



 

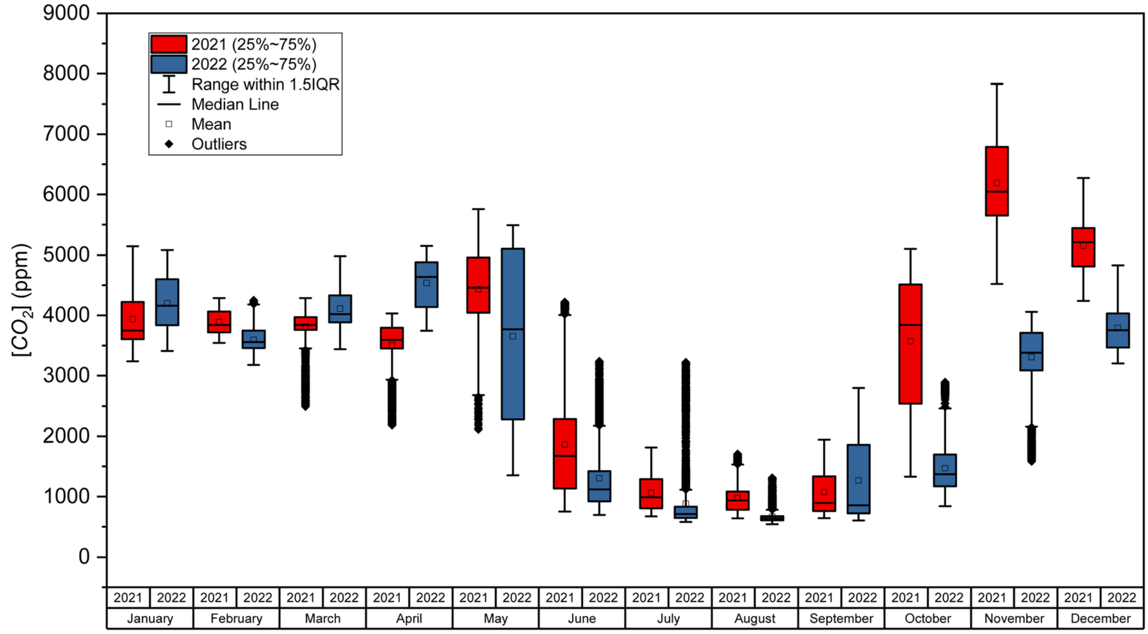


Fig. 6 Boxplot of $CO_2$ concentration in the air of the Polychromes Room.

Regarding $CO_2$ concentration, its continuous evolution in the three rooms (Hall, Crossing and Polychromes Room) is represented in Fig. 5.

Fig. 6 shows the statistical summary of the monthly $CO_2$ concentration values (ppm) for the Polychromes Room. The remarkable parallelism observed in Fig. 5 between the evolution of $CO_2$ in the three rooms makes the following comments on the Polychromes Room applicable in practice to the Hall and Crossing. The $CO_2$ concentration inside the cave shows a considerable seasonal variation, with differences of more than 7000 ppm between the months of greatest isolation from the outside atmosphere, typically December and January, and those of greatest aerodynamic connection with the outside, July and August. As in the case of temperature, these seasonal dynamics have been observed and described from the 1980s to the present day. The symmetry of the monthly boxes is highly variable, with notable differences between the mean and the median, indicating distributions that may be skewed or multi-modal. The size of the boxes is also variable. However, it is possible to distinguish periods of stability, such as January–April and July–August, and periods of more significant oscillations, such as May–June and September–December. The numerous outliers observed provide valuable information on degassing and recharging of short duration (days) that can occur at any time but are predominantly observed during spring and early summer.[14]

Fig. 7 shows, as an example, the parallel monthly changes in outdoor temperature, indoor temperature, and $CO_2$ concentration in the air for the Entrance or Hall, Crossing and Polychromes Room in July 2022. Preliminary observation of these shows periodic oscillations in the three variables depicted, and it is more evident in the outdoor air temperature and the respective $CO_2$ concentrations in the air of the rooms.

There are some aspects of the above figures that merit comment. It can be observed that the outside temperature during this period of the year shows clearly visible day/night fluctuations, ranging in magnitude from about 5 °C to more than 15 °C. These oscillations occur with nearly the same frequency in the $CO_2$ concentration of the air in the three rooms under study. The concentration of this gas, which decreases during the summer due to seasonal outdoor thermal variation,[3,9,30] shows variations ranging from a few hundred ppm to almost 2000 ppm. As indicated in previous work,[14] bearing in mind that indoor $CO_2$ concentration can be influenced by a complex interaction of several factors, including air exchange rates, soil respiration, human activity and the presence of infiltration water, the most significant influencing factor of these variations can be explained with a fair degree of certainty as a function of the thermal gradients between the indoor and outdoor air. The three rooms show a noticeable trend of rising indoor air temperature, which is typical during summer. This can be attributed to the delayed and damped transmission of the annual external thermal wave through the varying rock thicknesses forming each of the internal rooms examined.[3,31]

The time evolution of the air temperature in the exterior, the Hall, the Crossing and the Polychromes Room for July 2022 shows a variable degree of synchrony between the daily thermal oscillations observed at each station. Due to its higher thermal stability, the Polychromes Room shows the least evident short-period thermal oscillations. Evidence of such stability can be seen in the almost one-off increases of between 0.1 and 0.2 °C due to short-term human entries, either for public visits or for visits related to preservation and research.

The variations in $CO_2$ concentration in the three interior zones of the cave are finally shown in Fig. 8 for October 2021. There, the envelopes or trends of the curves corresponding to

 

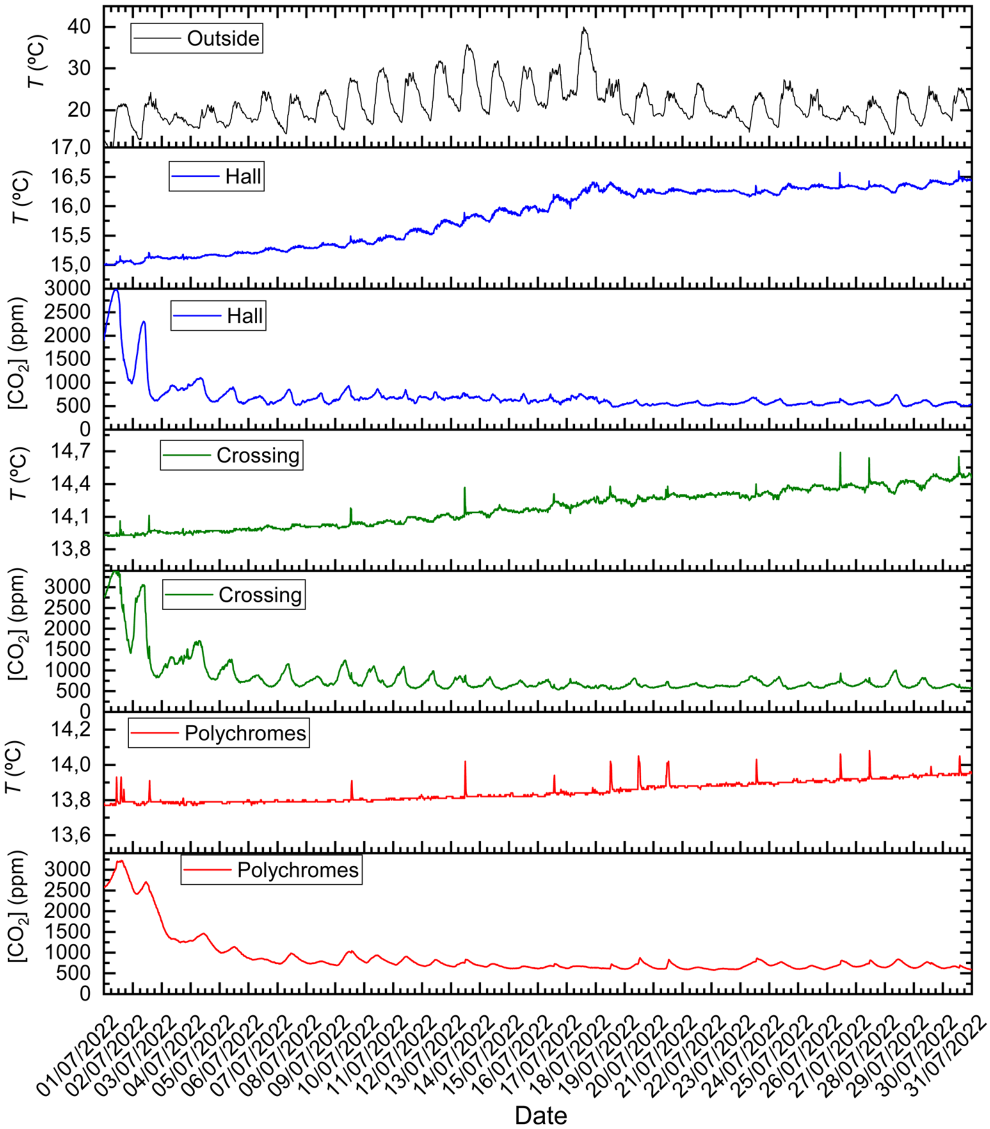


Fig. 7 Outside temperature, indoor temperature and $CO_2$ concentration in the Hall, Crossing and Polychromes Room during July 2022.

the interior rooms display remarkable parallelism, indicating the existence of a common mechanism that can account for them. An indication of this mechanism can be clearly seen in the large variation in $CO_2$ concentration between the 18th and 25th day of the month depicted. In that period, the outside air temperature trend line experiences an increase of about 12 °C followed by a decrease of almost 20 °C. Considering that the thermal oscillations inside the cave do not exceed 2 °C in that period, the internal thermal gradient inside the cave is so intense that it is capable of favouring degassing of more than 3000 ppm in a period of a few days, confirming what was previously indicated.[10] However, the action of this mechanism is not that evident in the daily variations, which, despite a similar periodicity, show variations of different magnitudes.

The SI accompanying this article contains summarized graphs for the period containing data from July to October of both years 2021 and 2022. They show the variations in outdoor and indoor air temperature and $CO_2$ concentration recorded by the measuring stations used in this study.

### 3.2 Correlation study

The correlation study has been carried out weekly from 1 June to 31 October during 2021 and 2022. Its graphical representation is shown in the heat maps below. The numerical values in each case are included in the supplementary material.

Fig. 9 shows the Pearson coefficients ($r$) corresponding to the thermal ratios between each indoor room and the outdoor atmosphere records, evaluated per week, as well as the correlation between rooms. A high positive correlation is evident between the variations of the two temperatures for the whole studied period, which is corroborated by low $P$-values.

Between 70% and 80% of the correlations of the weekly temperatures analysed are significant, except in the case of the Polychromes Room, where they are significant at around 45%.

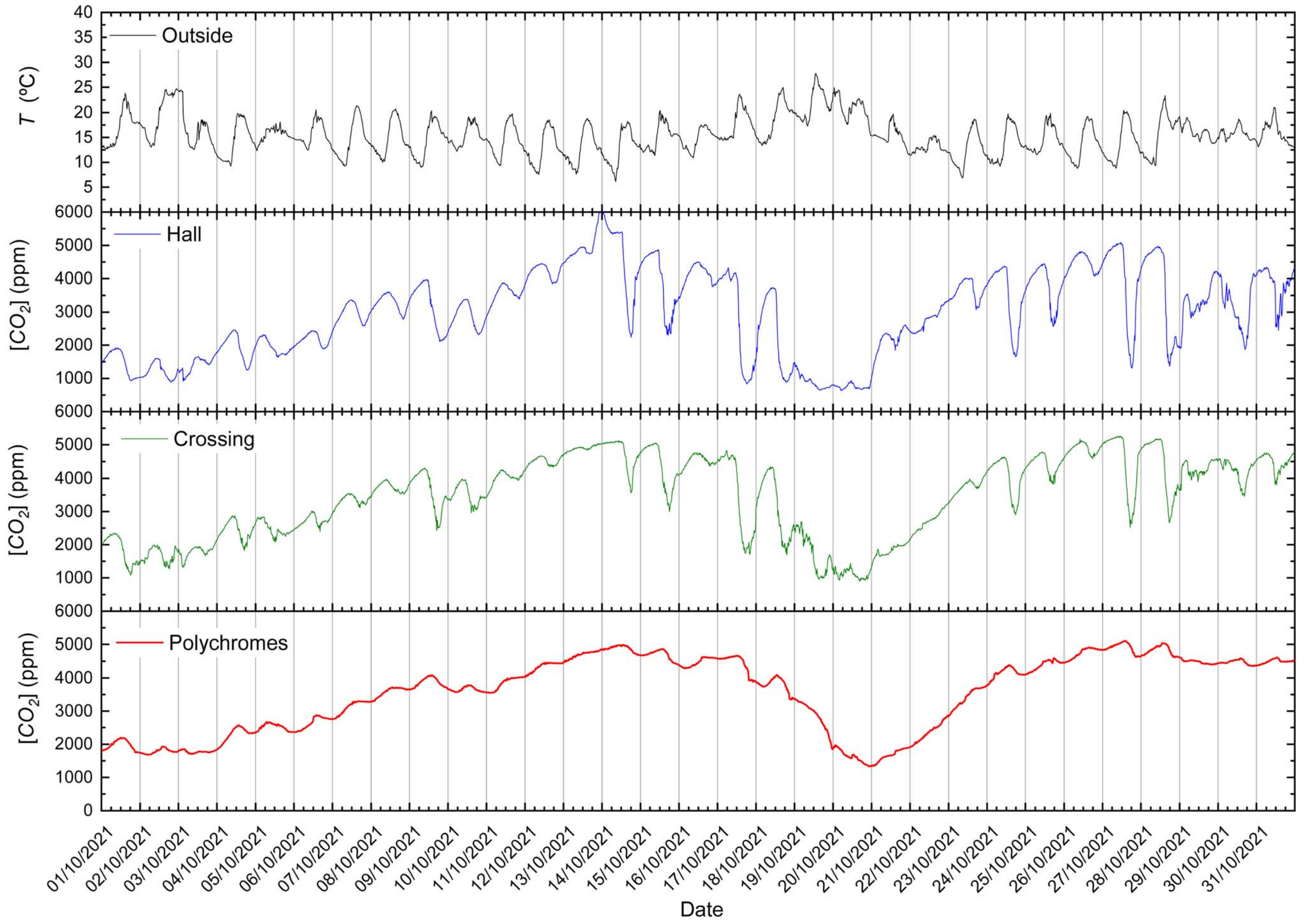


Fig. 8 Outdoor temperature and $CO_2$ concentration in the Hall, Crossing, and Polychromes Room during October 2021.

The correlation between the temperatures of the Crossing and the outside is positive in 82% of the weeks analysed, with more than half of the coefficients being higher than 0.5. The thermal correlations between the air in the Hall and the outside air are even more evident. In this case, up to 97% of the coefficients have shown positive values, with 54% of the total greater than 0.5. The few negative values found were accompanied by high $p$-values, making it possible to dismiss them. The correlations found between the Polychromes Room and the outdoor atmosphere are also primarily positive and significant, approximately in 75% of them, although they are somewhat weaker than in the previous cases, as 70% of the $r$ values are between 0 and 0.5.

The correlation between the Crossing and Hall temperatures is positive and significant at 83%. More than 95% of the correlations between the temperature at the Crossing and the temperature recorded in the Polychromes Room are positive, with almost half higher than 0.5. Again, the $p$-values associated with the negative coefficients found are high, indicating low statistical significance. We found similar results when calculating the thermal correlations between the Hall and the Polychromes Room. Almost 60% of the values obtained were positive, with 44% above 0.5.

Regarding the evolution of $CO_2$ concentrations, Fig. 10 shows the correlation coefficients found for each week of the period analysed between the different rooms inside the cave.

It is noteworthy that there is a high degree of correlation between the evolution of the concentration of this gas in the Hall, the Crossing, and the Polychromes Room. Practically all the coefficients evaluated were positive and significant, above 85%, with around 70% above 0.5.

Finally, Fig. 11 shows the coefficients resulting from crossing the thermal gradients with the outside atmosphere and the $CO_2$ concentrations in the different zones inside the cave.

When examining the correlation between the air temperature gradient between the outside and each room and the $CO_2$ concentration in the rooms, mostly negative and reliable $r$ coefficients were found, indicating dynamic consistency with previous studies.[14] Between 80% and 100% of the values showed a negative correlation for the Crossing and the Hall cases. The highest percentage of values below −0.5 was found at the Crossing, with 51% of the total, followed by the Hall with 19%. In the case of the Polychromes Room, 33% of the coefficients were found to be negative, with less than 5% of the coefficients being under −0.5, indicating a less obvious correlation.

The dominant mechanism explaining the thermal oscillations and $CO_2$ concentration variations in Altamira is based on

 

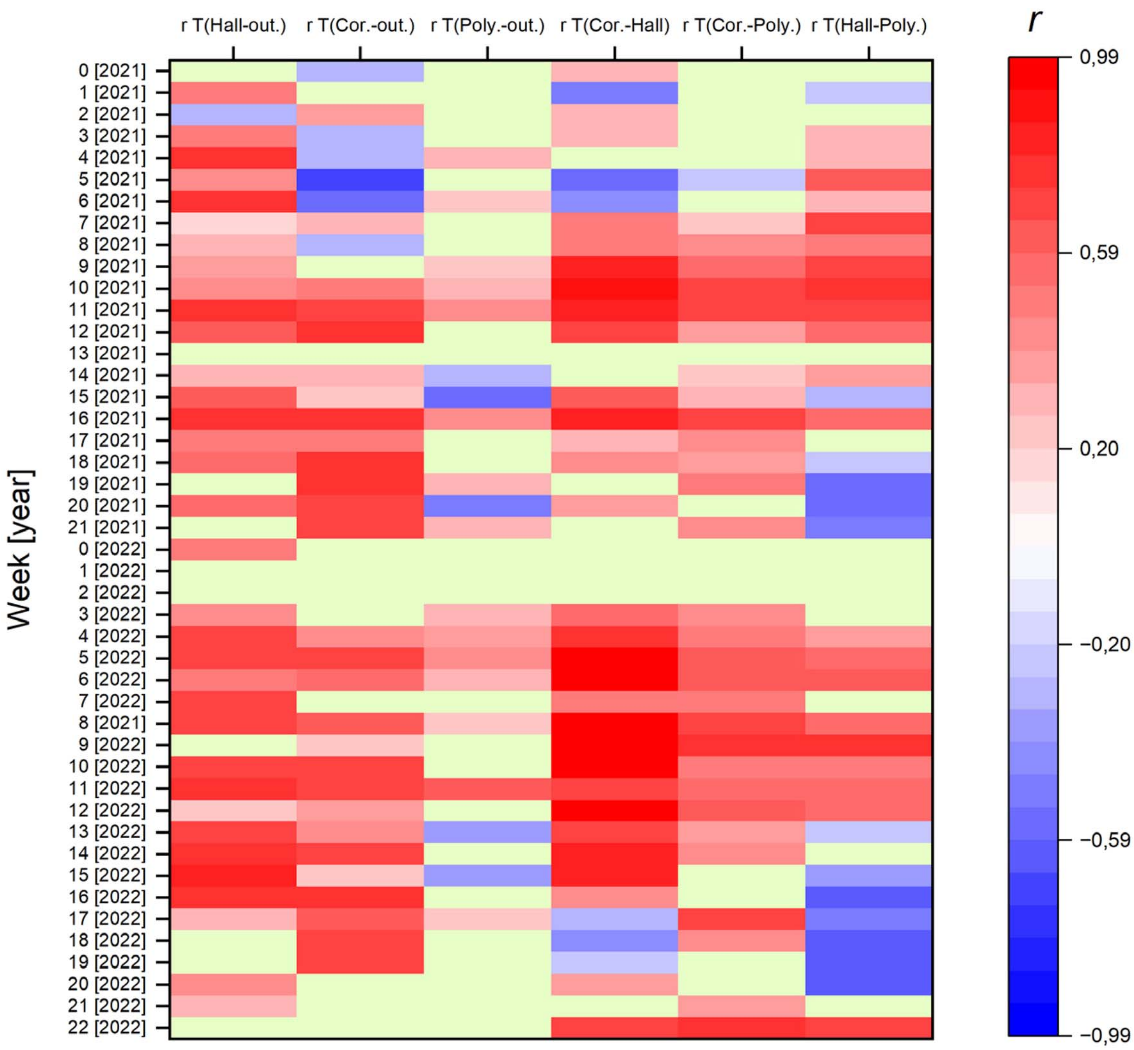


Fig. 9 Pearson correlation coefficients between the outside temperature (out.) and each of the rooms (Hall, Crossing and Polychromes Room), as well as the correlation of the rooms with each other. Correlations that are not significant ($p > 0.01$) are coloured light green.

the relationship between the indoor–outdoor thermal gradient and air density gradients. When the external temperature changes rapidly relative to the stable interior temperature, air density differences arise that induce convective movements through fissures and cracks in the karst system. This process promotes convective air mass exchange, triggering episodes of $CO_2$ degassing or recharge within the cavity. Previous studies in Altamira identified the influence of seasonal thermal gradients on ventilation,[10,14,30] while others provided detailed insights into convective and diffusive transport processes governing gas exchange in shallow karst systems.[9,12] Our findings add evidence that this mechanism also operates at daily scales, synchronized with diurnal cycles. Similar phenomena have been reported in other caves, such as the Chauvet,[24,25] Jiguan Cave,[19] Ballynamintra Cave,[32] and Brazilian systems,[16] reinforcing the interpretation that thermal gradients are a universal driver of microclimatic regulation in shallow karst cavities.[11]

These results confirm and expand previous observations on ventilation dynamics in Altamira, where the role of seasonal thermal gradients in air circulation and $CO_2$ concentration has been documented.[10,14,30] Our work provides detailed evidence of short-term thermal oscillations (daily) and their correlation with $CO_2$ variations, enabling a more precise characterization of convective mechanisms that were not previously analyzed at this temporal resolution. Comparatively, studies in other caves such as Chauvet and Jiguan Caves have shown similar ventilation patterns controlled by thermal gradients, although with differences in amplitude and periodicity due to morphological and depth-related factors.[19,24,25] Research in Brazilian caves also highlights the significance of diurnal cycles in ventilation, supporting the notion that these mechanisms are common in shallow karst systems, even though their impact on rock art conservation depends on local factors such as external connectivity and relative humidity.[16]

The findings of this study have direct implications for the protection of cave geological heritage and associated rock art. By identifying short-term thermal oscillations and their strong correlation with $CO_2$ dynamics, we provide evidence of ventilation mechanisms that can significantly influence microclimatic stability. Understanding these processes is essential for

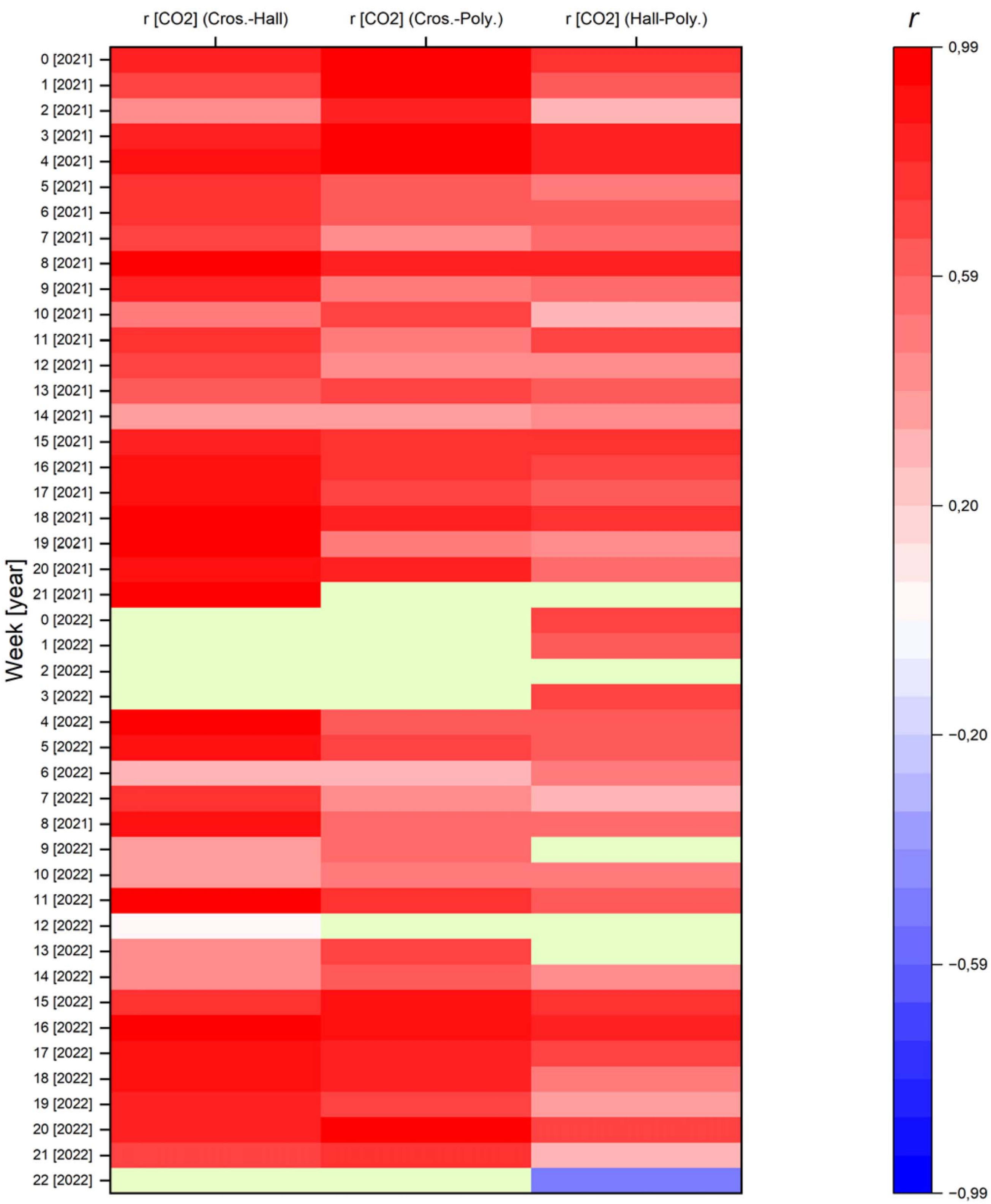


Fig. 10 Correlations between $CO_2$ concentrations in the indoor rooms. Correlations that are not significant ($p > 0.01$) are coloured light green.

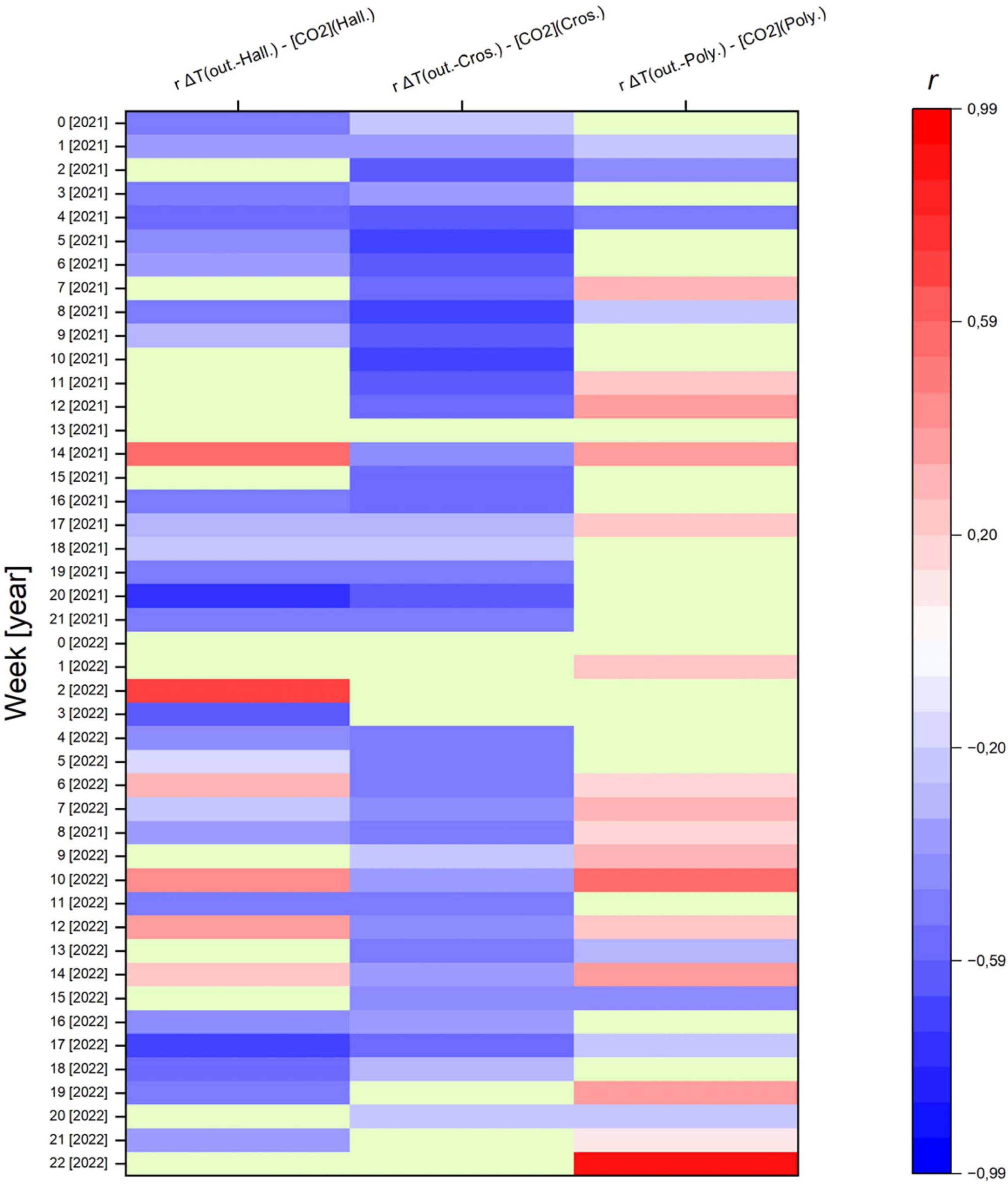


Fig. 11 Correlations between indoor/outdoor air temperature gradients and indoor $CO_2$ concentrations. Correlations that are not significant ($p > 0.01$) are coloured light green.

preventive conservation strategies, as fluctuations in $CO_2$ concentration and temperature gradients are closely linked to chemical and biological deterioration risks.

## 4. Conclusions

This study provides a detailed assessment of short-term thermal oscillations within the Hall, Crossing, and Polychromes Room of the Altamira Cave. The strong correspondence observed between these fluctuations and external day–night temperature cycles, together with the associated variations in indoor $CO_2$ levels, confirms the role of ventilation dynamics as a key driver of microclimatic changes inside the cave.

Although it is known that there is air circulation inside the cave,[9] the study of the evolution of the air temperature in each room has shown a synchrony which, together with that observed in the variations in $CO_2$ concentration, indicates the existence of a common ventilation mechanism that acts on the complete cave as a whole. For this reason, it can be stated that the short-period thermal oscillations are due to convective air transport through the karstic system of cracks and fissures, which each year presents its greatest degree of aperture during the months analysed here, in summer and early autumn.

This has significantly increased our knowledge of the $CO_2$ dynamics inside the cave, providing new evidence pointing to the temperature gradient between the outside and inside air as the main driver of the degassing and recharging found throughout the year. This mechanism, which is well characterised on a seasonal time scale,[12] can also quite accurately explain the degassing and recharging processes occurring over short periods.

Within the framework of the Preventive Conservation Plan for Altamira, this study highlights two critical aspects for heritage protection. First, understanding the temporal evolution of indoor $CO_2$ enables the establishment of reference levels to distinguish natural variations from those caused by human presence. Second, characterizing the intensity and periodicity of air exchange events with the exterior identifies periods of vulnerability when microorganisms or nutrients could enter, posing a biodeterioration risk to the paintings. These findings reinforce the need for continuous monitoring and adaptive management strategies to preserve the cave's cultural and geological heritage.

It must be considered that the $CO_2$ concentration inside the cave depends on other factors, such as the inflow of infiltration water in each interior area, which acts as a transport mechanism for this gas in dissolved form,[26] as well as the different degree of connection with the exterior of each room. The impact of human presence on indoor air $CO_2$ concentration is, at current occupancy levels, mainly due to research work, significantly lower than the observed natural variations. However, this contribution may be occasionally relevant at certain periods of the year, which will be analysed in detail in a new specific study.

## Author contributions

Carlos Sainz: conceptualization, methodology, writing – original draft, funding acquisition. Irene Morales: methodology, software. Daniel Rabago: conceptualization, methodology, software. Santiago Celaya: investigation, validation. Alicia Fernandez: investigation. Ismael Fuente: writing – review & editing. Enrique Fernandez: investigation. Jorge Quindos: investigation. Luis Quindos: supervision, writing – review & editing.

## Conflicts of interest

There are no conflicts to declare

## Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information is available. See DOI: https://doi.org/10.1039/d5ea00107b.

## Acknowledgements

This work was supported by the Spanish Ministry of Culture and Sport [grant number J200028].

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