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Carbon dioxide concentration in air within the Nerja Cave (Malaga, Andalusia, Spain)

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Abstract:

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From 2001 to 2005 the CO_2 concentration of the air in the interior and exterior of the Nerja Cave was studied and its relation with the air temperature and visitor number. The average annual CO_2 concentration outside of the cave is 320 ppmv, whilst inside, the mean concentration increases to 525 ppmv during autumn and winter, and in the order of 750 ppmv during spring and summer. The temporal variation of CO_2 content in the air of the cave is strongly influenced by its degree of natural ventilation which is, in turn, determined by the difference between external and internal air temperatures. During autumn, winter and spring, a positive correlation between the CO_2 content of the air inside the cave and the temperature difference between the external and internal air was observed, such that when this difference increased, there was a higher level of CO_2 within the cave. Then, the ventilation is high and CO_2 levels are mainly of human origin. During summer, there was a negative correlation between CO_2 and the temperature difference between the air outside and that inside the cave: when the temperature difference increases, the CO_2 content within the cave is lower. At this time of the year, the renovation of the air is much slower due to the lower ventilation. A positive correlation between CO_2 concentration of the air in the cave and the visitor number can only be observed during August, the month that receives the most visits throughout the year averaging 100,000.

Keywords: carbon dioxide, Nerja Cave, air temperature, visitor number, cave ventilation.

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INTRODUCTION

In caves adapted for tourism, the control of carbon dioxide levels is crucial for the cave's conservation as well as for public health, so that an adequate air quality is maintained for the visitors. On one hand, the CO_2 concentration in the air in karstic caves conditions the development of different speleogenetic processes within these caves given that it directly influences the precipitation/dissolution of carbonates (White, 1988, 1997; Dreybrodt, 2000; Dreybodt & Eisenlohr, 2000). On the other hand, the CO_2 concentration determines the cave's air quality, as elevated CO_2 concentrations above 5000 ppmv are noxious to human health (Halbert, 1982).

Numerous authors have studied CO_2 from diverse standpoints. Pioneering studies have been made on the presence and dynamics of CO_2 in caves with respect to the exterior environment, for example Renault (1968), Ek (1968, 1979, 1981), James (1977) and Troester & White (1984). Other authors have focused on studying the spatial and/or temporal distribution of CO_2 (Atkinson, 1977; Wood & Petraitis, 1984; Wood, 1985), or the dynamics within the caves (Ek & Gewelt, 1985; Bourges et al., 2001; Batiot, 2002; Baldini et al., 2006; Batiot et al., 2006). The human impact on tourist caves, using CO_2 content as one of the reference parameters, is another research line that has been widely developed in recent decades (Villar et al., 1986; Dragovich & Grose, 1990; Craven, 1996; Hoyos et al., 1998; De Freitas & Banbury, 1999, Liang et al., 2000; Carrasco et al., 2002; Zelinka, 2002). Other interesting recent references dealing with CO_2 are: Spötl et al., 2005; Denis et al., 2005; Faimon et al., 2006 ; Bourges et al., 2006; Fernández-Cortés et al., 2006 and Batiot-Guilhe et al., 2007.

CHARACTERISTICS OF THE STUDY AREA

The Nerja Cave is located in Andalusia (southern Spain), in the province of Malaga, about 5 km east of the coastal town Nerja. The climate outside the cave is typically Mediterranean, with a wet season from October to February and a long dry season that is especially notable during the summer. The mean annual values for rainfall and temperature are 490 mm and 18.8 °C respectively.

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From the geological viewpoint, the Nerja Cave is situated on the southern border of Sierra Almijara, within the Alpujarride Complex of the Betic Cordillera. It is developed within a highly fractured medium and coarse-grained dolomite marbles, from the Middle Triassic (Fig. 1A). The marbles are permeable due to fracturing and karstification and, thus, constitute a carbonate aquifer. As a result of the Plio-Quaternary tectonic activity which affected this area, the cave is currently located in the unsaturated zone of the aquifer, above the piezometric level. The thickness of the unsaturated zone above the cave is highly variable, from 4 to 50 m in the external part, while in the internal area it exceeds 90 m. Except for the gardens near the entrance, only low shrubs or soil are found above the cave.The cave has three entrance points, two of them are sinkholes (at 161 and 162 m.a.s.l.) and the third is a wider entrance which is equipped for tourist visits, found at 158 m.a.s.l. The cave extends almost horizontally between limits of 123 and 191 m.a.s.l. and occupies a volume of about 300,000 m^3, a third of which is prepared to receive tourist visits (Figs. 1B y 1C). The Nerja Cave is one of the most visited natural sites in Andalusia (Carrasco et al., 1999), receiving an average of 500,000 visitors yearly.

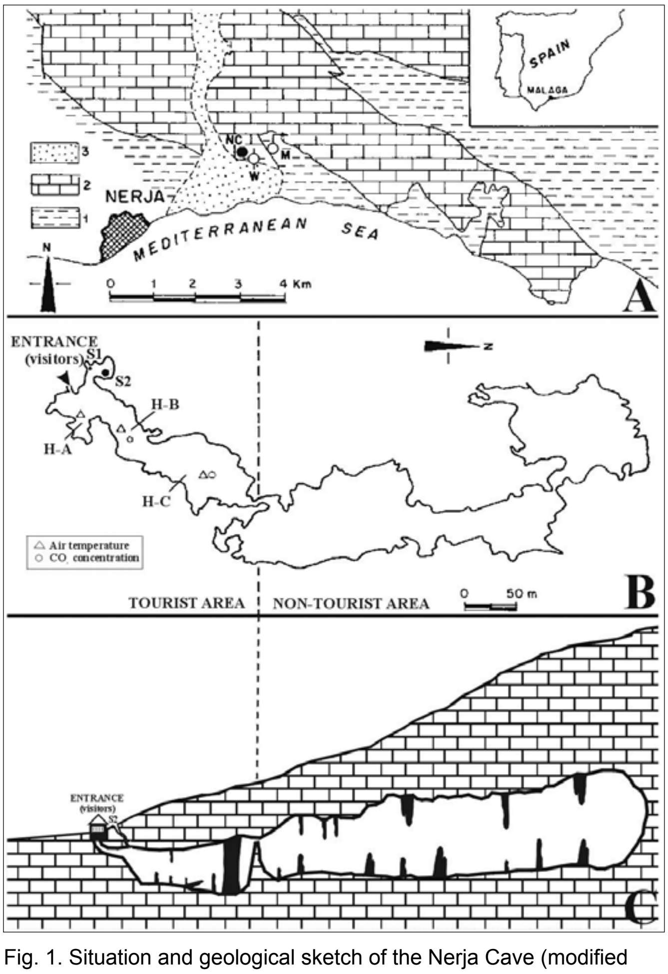

Fig. 1. Situation and geological sketch of the Nerja Cave (modified from Carrasco et al., 1995). A: 1, metapelites; 2, carbonates; 3, Pliocene and Quaternary deposits; NC, cave entrance; M, Maro spring; W, cave well. B: location of the sensors in the cave. H-A: Hall of the Nativity, H-B: Hall of the Cascade, H-C: Hall of the Cataclysm, S1 and S2: natural entrances (sinkholes). C: cross-sectional sketch (not to scale) of the Nerja Cave.

Since 1993, the tourist galleries inside the cave have been fitted with a complete network for specialised monitoring (Liñán et al., 2004) that makes the continuous monitoring (at an hourly rate) of the most significant environmental parameters within the cave possible, such as the temperature, relative humidity and concentration of CO_2 in the air, and also to evaluate the human influence on the subterranean microclimate.

Previous research carried out in the Nerja Cave (Carrasco et al., 1999, 2002; Liñán et al., 2000; Liñán et al., 2004) examined the mean daily concentrations of CO_2 in the tourist galleries and analysed their spatial and temporal variations with respect to the visitor number, the natural ventilation within the cave (Cañete, 1997; Dueñas et al., 1999), the greater or lesser dripwater volume and the dimensions of the galleries (Benavente et al., 2005). The present paper presents an analysis of the concentration of CO_2 in the exterior and the interior of the cave during the years 2001 to 2005 and its relation with other parameters measured inside and outside the cave. In particular, the authors seek to provide new data on the close relation between the CO_2 content within the cave and the air temperature, as well as the significant effects of the natural ventilation of the cave.

METHODOLOGY

Commercial OLLARTE sensors were used to measure the exterior and interior temperatures and the CO_2 content within the cave. The CO_2 sensor employed an infrared non-dispersive measuring technique. Its working range was from 0 to 3,000 ppmv with a resolution of 1 ppmv. The temperature was measured using sensors fitted with a platinum thread sensor element, with a variation range of 0 to 40 ºC and a resolution of 0.05 ºC.

To measure the CO_2 content of the air outside the cave, a TESTO commercial sensor was used. This employed the infrared non-dispersive technique to obtain readings, and had a measurement range of 0-10,000 ppmv, a resolution of 1 ppmv and an accuracy of ± 50 ppmv ± 2 % of the volume measured.

RESULTS AND DATA ANALYSIS

Outside the Nerja Cave, the mean concentration of CO_2 in the air was found to be 318 ± 21 ppmv (Fig. 2). Minimum values were recorded during the summer (from June to September) and maximum values corresponded to the winter and spring (from December to April).

In the autumn, winter and spring, the mean monthly concentration of CO_2 outside the cave is fairly constant, between 340 and 320 ppmv, while in the summer it is somewhat lower, at around 290 ppmv. Minimum and maximum mean monthly values were recorded in August (288 ± 29 ppmv) and March (347 ± 14 ppmv), respectively.

Inside the Nerja Cave, the concentration of CO_2 in the air varies seasonally (Carrasco et al., 1999; Benavente et al., 2005), but in this case the minimum values of CO_2 are recorded during the autumn and winter and the maximum values

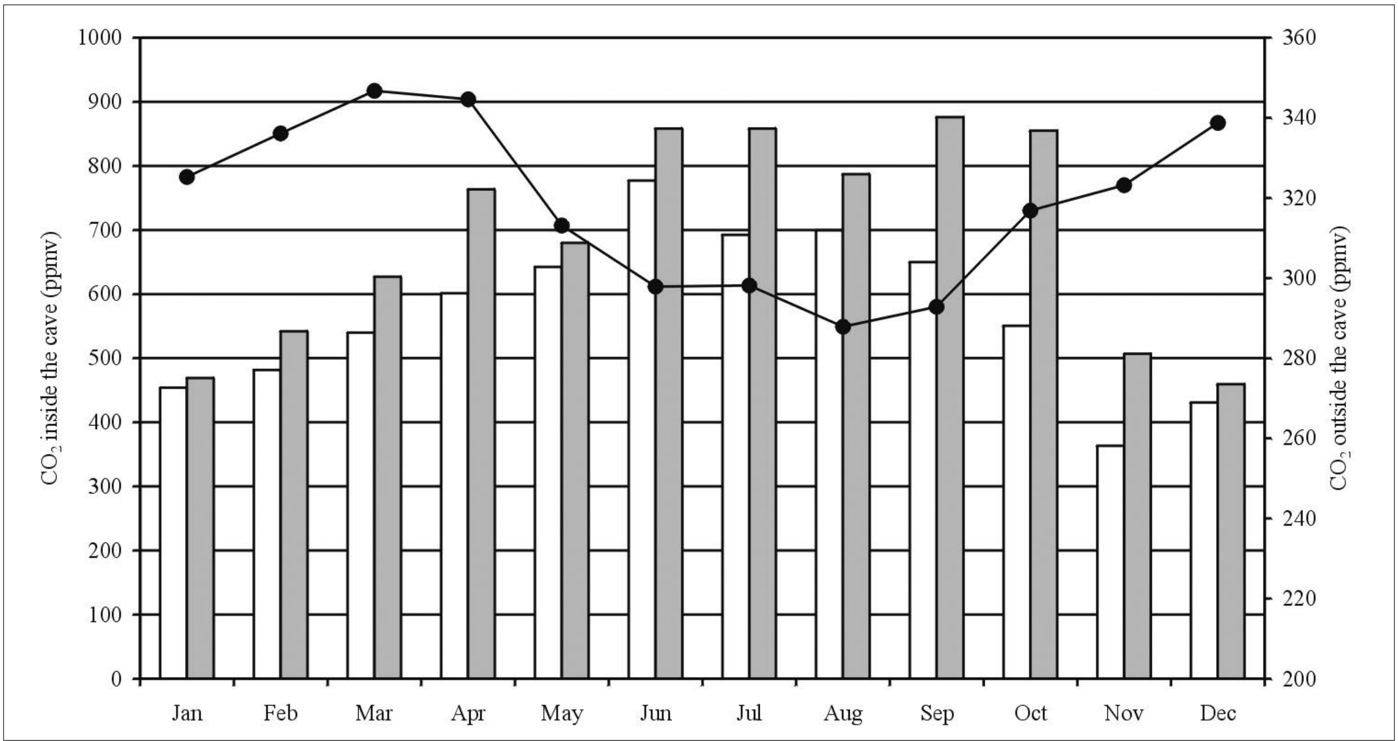

Fig. 2. Monthly CO_2 concentrations averaged for last five years (2001-2005), outside the Nerja Cave (black line) and inside it, in H-B (in white) and H-C (in grey).

are recorded during the summer period (Fig. 2). During the autumn and winter, the mean monthly concentration of CO_2 within the cave is around 525 ppmv while in the spring and summer; this value rises to 750 ppmv.

On an annual scale, the variations in CO_2 content in the subterranean atmosphere are generally similar to those of the number of visits to the cave and to those of the air temperature, both outside and inside the cave. All these parameters fit an undulating curve, with maximums in the spring and summer and minimums in the autumn and winter (Fig. 3). In general, during the autumn, winter and spring, the exterior temperature is lower than that recorded inside the cave while, during the summer, the temperature outside the cave exceeds that recorded inside (Fig. 3). The greatest temperature difference between the exterior and interior of the cave is recorded between December and February and during the summer, from June to August.

If a further analysis is carried out, at a monthly scale, it is observed that during some months of the year the temporal evolution of the mean monthly CO_2 concentration in the air inside the cave is identical to the exterior air temperature, meanwhile during other months it is clearly similar to the visitor number (Fig 4).

In order to determine the relation between the air temperature and the visitor number with respect to the CO_2 content of the air inside the cave, for each of the months examined during the study, the following correlation diagrams were made: CO_2 and external/internal temperature difference, and CO_2 and visitor number. Thus, the corresponding correlation coefficients were obtained (Table 1).

The correlation curves obtained (Fig. 5) and the coefficients shown in Table 1 reveal the following:

- A significant correlation between the CO_2 content within the cave and the visitor number.
- A significant positive correlation between the CO_2content within the cave and the external/internal temperature difference between January and May (except in February) and from October to December, although during this month there was a clearer correlation with the visitor number.
- A significant negative correlation between the CO_2content inside the cave and the external/internal air temperature during some summer months (June to September).
- In some months characterised by high visitor numbers, such as May (monthly average of 52,000 visitors) the only correlation observed was between the CO_2 content of the air and the external/internal air temperature difference.
- In months characterised by low visitor numbers, such as February (about 21,000 visitors on average) the only correlation observed was between the CO_2content within the cave and the visitor number.

DISCUSSION

The CO_2 within caves is derived from different sources: (1) external atmosphere, (2) soil overlying the caves, where biological activity produces CO_2 that is transported by water seeping through the soil and network of rock voids, (3) oxidation by bacteria of organic matter in carbonated rocks or cave deposits, (4) deep gas diffusion or transport and (5) human activity (the respiration of visitors within the cave).

The temporal variation in the CO_2 content of the air outside the cave presents minimum values during the summer months, coinciding with maximum values of the external air temperature. This summer decrease

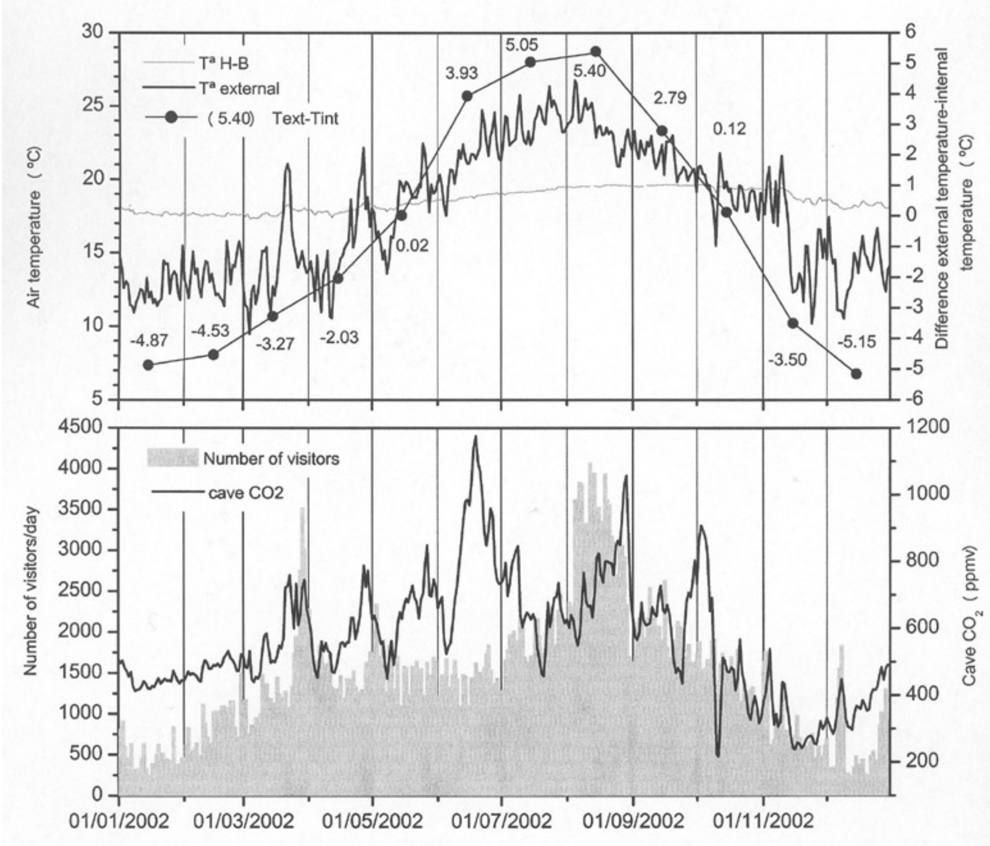

Fig. 3. Annual visitor number, CO_2 concentration inside the cave (H-B), external and internal (H-B) air temperature during the year 2002, and monthly temperature differences averaged for last five years (2001-2005).

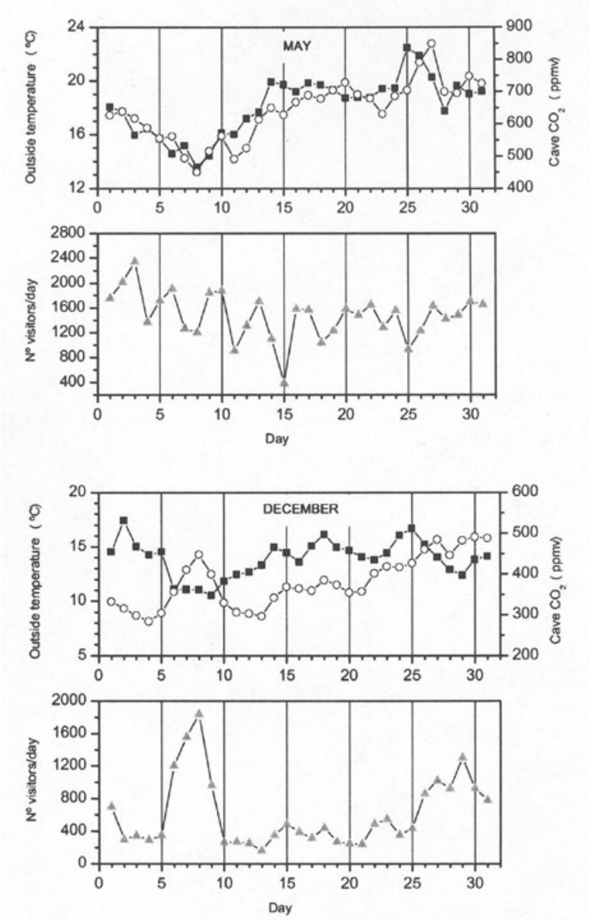

Fig. 4. Monthly variation in CO_2 concentration in the air inside the cave (white marker), external air temperature (black marker) and visitor number (grey marker) during May and December 2002, respectively.

in atmospheric CO_2 must be related to the reduction in the plant cover of the immediate surroundings of the cave, as many species lose their leaves as a mechanism of adaptation to the very dry conditions normally encountered during this season (Batiot et al., 2003) and to the reduction in the plants' vital activities.

The correlation diagrams reveal the close relation, maintained practically throughout the year and irrespective of the visitor number, between the CO_2 content of the air within the cave and the temperature difference between the exterior and the interior of the cave. This same relation has been described by other authors for the Altamira Cave (Villar et al., 1983). The temperature difference between the exterior and the interior of the cave influences the exchange of air and favours its natural ventilation.

The ventilation in the Nerja Cave was measured by means of a study of the concentration of radon inside the cave (Cañete, 1997; Dueñas et al., 1999). The seasonal variation in radon concentration within the cave is similar to that of the external air temperature, with minimum concentrations of radon being measured in the autumn and winter, and maximum concentrations during the spring and summer. These authors described a positive linear correlation between the concentration of radon in the air inside the cave and the external air temperature; therefore, there is an inverse linear correlation between the ventilation of the cave and the external temperature. In the Nerja Cave, during the autumn and winter, the ventilation is high

	2001		2002		2003		2004		2005	
	A	B	A	B	A	B	A	B	A	B
January	0,60	0,52	-	0,77	0,73	0,61	-	0,76		
February	-	0,46	-	0,82			-	0,56	-	0,66
March	0,81	-	0,67	0,60			0,72	0,40	0,69	0,94
April	-	0,42	0,78	-	-	-	-	0,88	0,82	-
May	0,85	-	0,81	-	0,76	-	0,82	-	0,47	-
June	-0,47	-	0,58	-	0,56	-	-0,52	-		
July	-	-	-	-	-0,76	-	-0,71	-	-0,70	-
August	-0,48	-	-0,73	-	-0,42	-	0,37	0,79	-	0,69
September	-	0,40	-	-	-	-	-0,67	-	-	-
October	0,71	-	0,54	0,43	0,76	-	0,66	-	0,58	-
November	0,37	-	0,75	-	-	-	0,52	-	0,46	-
December	-	0,64	-	0,73	0,48	-	-	0,89	-	0,91

- : no significant correlation was observed; (empty box): no data were available

Table 1- Correlation coefficients between (A) CO_2 inside the cave and external/internal temperature differences and (B) CO_2 inside the cave and visitor number, during the period 2001-2005. The CO_2 and internal air temperature data correspond to the Cascade Hall (H-B).

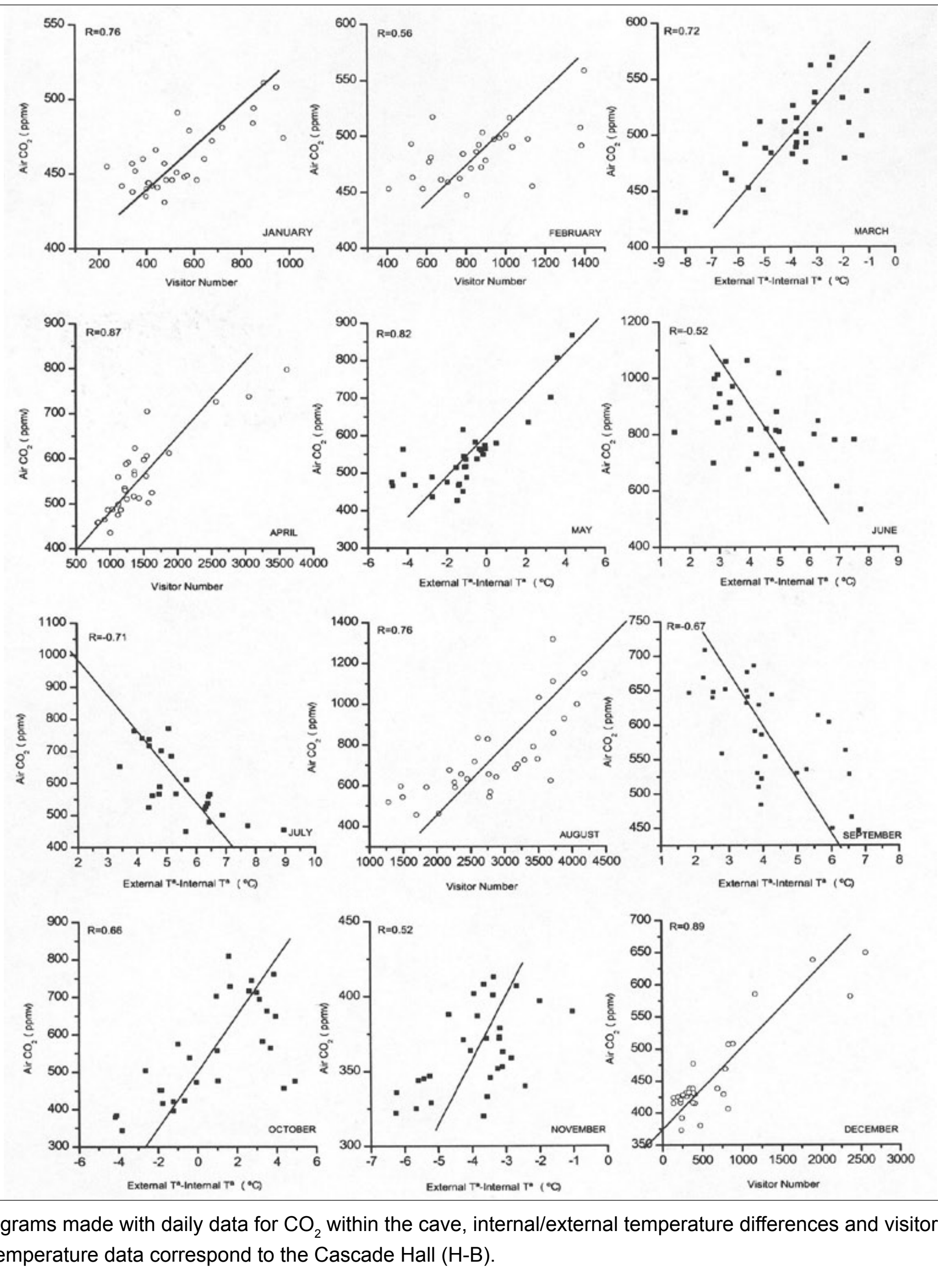

Fig. 5. Correlation diagrams made with daily data for CO_2 within the cave, internal/external temperature differences and visitor number during 2004. CO_2 and internal air temperature data correspond to the Cascade Hall (H-B).

because the external air is colder and, therefore, more dense than that found within the cave, and so it enters the cave easily, displacing the internal air. During the spring and summer, the ventilation is low because the internal air is denser than the external air, and so air circulation is restricted or halted. This air circulation pattern would correspond to a "cold air trap" type of cave (Choppy, 1982; Buecher, 1999).

There is a positive correlation between the CO_2 content and the difference between external and internal air temperatures during the autumn, winter and spring; that is, when this difference increases, the CO_2 levels within the cave are higher. At first sight, this result seems contradictory, as a greater difference between the external and internal temperatures and the fact that the external temperature is lower than the internal one would mean a higher exchange of air, which would bring about a reduction in levels of CO_2. The degree of ventilation is considered as being high and the atmospheric CO_2 decreases sufficiently to enable the anthropogenic CO_2 contribution to be observed which originates from the respiration of visitors. This would be the reason underlying the high correlation observed between the CO_2 content of the air inside the cave and the visitor number in the winter months when visitor numbers are low, in December, January and February.

During summer, there is a negative correlation between CO_2 and the temperature difference between the external and the internal air, and thus when the temperature difference increases, the CO_2 content within the cave is lower. During this season, the air temperature is very similar in each of the cave's chambers, irrespective of their proximity to or distance from the entrance; furthermore, the external temperature is higher than the internal temperature, and so there are no convective-type movements of air masses and the renovation of the air is much slower, due to the lower ventilation (Cañete, 1997). During summer, a positive correlation between the CO_2 concentration in the air in the cave and the visitor number can only be observed in August, which is the month that receives the most visits in the whole year averaging 100,000 visits/month.

Therefore, the main cause of the temporal variation of the CO_2 content of the air of Nerja Cave must be the ventilation within the cave, that is, the exchange of air between the exterior and the interior of the cave, although the influence that other parameters may have on the evolution of the cave's CO_2 concentration in the air is considered, such as the dripwater rate, whose temporal variation, similar to that of the interior air CO_2, determinates a higher or lower contribution of biogenic CO_2 to the cave's interior.

CONCLUSIONS

The mean annual CO_2 content of the air outside the Nerja Cave was around 320 ± 21 ppmv during the study period (2001-2005). Analysis of the temporal variation of the CO_2 content of the air revealed the existence of a timelag of around 3-4 months between the maximum and minimum values of CO_2 measured outside and inside the cave.

The CO_2 content within the Nerja Cave is fundamentally related to the natural ventilation within the cave, this being determined by the difference in temperature between the air outside and that inside the cave. During autumn, winter and spring, a positive correlation between the CO_2 content of the air inside the cave and the temperature difference between the external and internal air was found, so that when this difference increased there was a higher level of CO_2 within the cave. Then, the ventilation is high and CO_2 levels are mainly of human origin.

During the summer, there was a negative correlation between CO_2 and the temperature difference between the air inside and the air outside of the cave: when the temperature difference increases, the CO_2 content within the cave is lower. At this time of the year, the renovation of the air is much slower due to the lower ventilation.

In future studies, an analysis of the ^{13}C content of air and water samples obtained within the cave would be highly useful in determining with greater precision the origin of the CO_2 within the cave, as has been suggested by various authors (Clark & Fritz, 1997, Batiot et al., 2006).

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