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Monitoring present day climatic conditions in tropical caves using an Environmental Data Acquisition System (EDAS)

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Abstract

This paper presents data from automatic stations which have been installed for monitoring climatic parameters in caves in two areas of Brazil. These devices, initially developed at the Royal Observatory of Belgium to monitor environmental parameters in geophysical observatories, were adapted in our study to operate under tropical cave conditions and to measure temperature, atmospheric pressure and drip rate of stalactites. Similar devices were installed at the surface near to the caves to measure air temperature, atmospheric pressure and rainfall.

The results reveal that the drip rate at the tip of stalactites is related to the effective rainfall (water excess). The stable drip regime observed during the dry season seems to be reproducible from one year to the other and could be related to the infiltration of water which has a long residence time in the aquifer.

Regular pressure oscillations, with amplitude ranging between 1 and 2 mb, are observed in both of the monitored caves. Spectral analysis of the data suggests that these oscillations are linked to the diurnal and semi-diurnal solar tides (S1 and S2). In one cave, very small temperature variations (0.02–0.05 °C) are also observed with a similar diurnal and semi-diurnal pattern, and we argue that the generating process of the thermal components of the S1 and S2 frequencies is a mixture of thermal convection produced by the surface meteorological variations and of an adiabatic induction of the S2 atmospheric pressure modulation.

A very large annual thermal amplitude (13 °C) is observed in the other cave; this is a great motivation to study the stable isotope geochemistry of its speleothems as they probably have recorded past temperature fluctuations linked to paleoclimate variations in this area of south-western Brazil.

Keywords: Cave monitoring; Cave meteorology; Stalactite; Drip rate; Brazil

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1. Introduction

The use of cave deposits, such as speleothems or clastic sediments, has proven to be a powerful tool to study past climatic and environmental changes. More specifically, carbonate speleothems, mainly stalagmites, are often studied for palaeoenvironmental interpretations (see references in Gascoyne, 1992; Lauritzen, 1996). The noteworthy properties of climate recorded by these cave formations result from their formation's mineralogy, their mode of occurrence and from their content of trace elements, fluid inclusions, pollen, etc. In some instances, they present annual laminæ analogous to those found in corals or in tree rings, and it has been proved that the sequential study of this lamination is a powerful tool for paleoclimatic reconstructions (Baker et al., 1993; Genty and Quinif, 1996; Kaufman et al., 1998; Railsback et al., 1994). Some authors have reported that formation of laminæ is, or might be, annual (Genty and Quinif, 1996; Holmgren et al., 1999; Railsback et al., 1994). Study of such well laminated speleothems thus could help in high-resolution reconstruction of past climate changes. Other parameters measurable in speleothems are $\delta^{18}O$ and $\delta^{13}C$ (Bar-Matthews and Ayalon, 1997; Holmgren et al., 1999; Repinski et al., 1999; Talma and Vogel, 1992), trace element content (Hellstrom and McCulloch, 2000; Railsback et al., 1994; Roberts et al., 1998; Roberts et al., 1999; Verheyden et al., 2000), or luminescence (Baker et al., 1998; Hellstrom and McCulloch, 2000; Perrette et al., 1999), with possible inference on paleotemperature and vegetal cover reconstructions.

Calibration of the chosen proxy is essential for reliable interpretation of the data. The main factors that govern stalagmite growth rate, chemical composition and laminae formation are rainfall, water chemistry, percolation rate, atmospheric pressure, CO_2 partial pressure and air temperature (Baker et al., 1998; Dreybrodt, 1981; Genty and Deflandre, 1998; Genty and Quinif, 1996). In caves, air temperature has a fundamental relationship with atmospheric density and with the processes of evaporation and condensation of water (Andrieux, 1978). The dynamics of gas exchange are therefore under the direct control of pressure and temperature. Inside a cave, it has been shown that temperature may vary from one place to another and that heat may enter either from the overlying or underlying rock, or from air or water flowing into the cave (Davis, 1960; Nepstad and Pisarowicz, 1989; Wigley and Brown, 1976). Except for the very complete work of Genty and Deflandre (1998), the use of permanent automatic devices in paleoenvironmental cave studies has rarely been undertaken until now; it is more often used for the management of caves visited by tourists (Cigna, 1993; Pulido-Bosch et al., 1997).

In this study, we will present the results of climate monitoring in two caves from Central Western Brazil using the Environmental Data Acquisition System (EDAS) developed at the Royal Observatory of Belgium. The system constantly records air temperature, atmospheric pressure, rainfall, and drip rate at a fixed sampling rate. The main aim of this monitoring was a better understanding of the relative importance of the parameters governing speleothem growth and of the seepage dynamics in karst environments.

2. Study area

Karstic terrains related to Meso-and Neoproterozoic carbonates occur in different areas of central Brazil (Fig. 1). They contain numerous caves with speleothems (Lino and Allievi, 1980) especially in the Serra das Araras (Mato Grosso State) and in the Serra da Bodoquena (Mato Grosso do Sul State), in the Nordeste and in many places of central and south Brazil (Goiás, Minas Gerais and São Paulo states). In the first step of this study we selected two areas with distinct climatic patterns:

(1) The area of Brasília (Federal District and surrounding Goiás State, 15–16°S, 47–48°W) situated in the Brazilian Central Plateau (altitude from 700 to 1,100 m). This area is covered by arboreal savanna ('cerrado'). The climate is tropical and humid with moderate water deficit (Instituto Brasileiro de Geografia e Estatística, 1992). It is characterized by a mean annual temperature between 21 and 22 °C, rainfall ranging from 1,400 to 1,600 mm $year^{-1}$, and a five months dry and cold season (from May to September). The mean annual thermal amplitude is relatively low (from 19 to 22.5 °C) (Departamento Nacional de Meteorologia, 1992). The Paineira cave (120 km NE of Brasília, see Fig. 1) which was

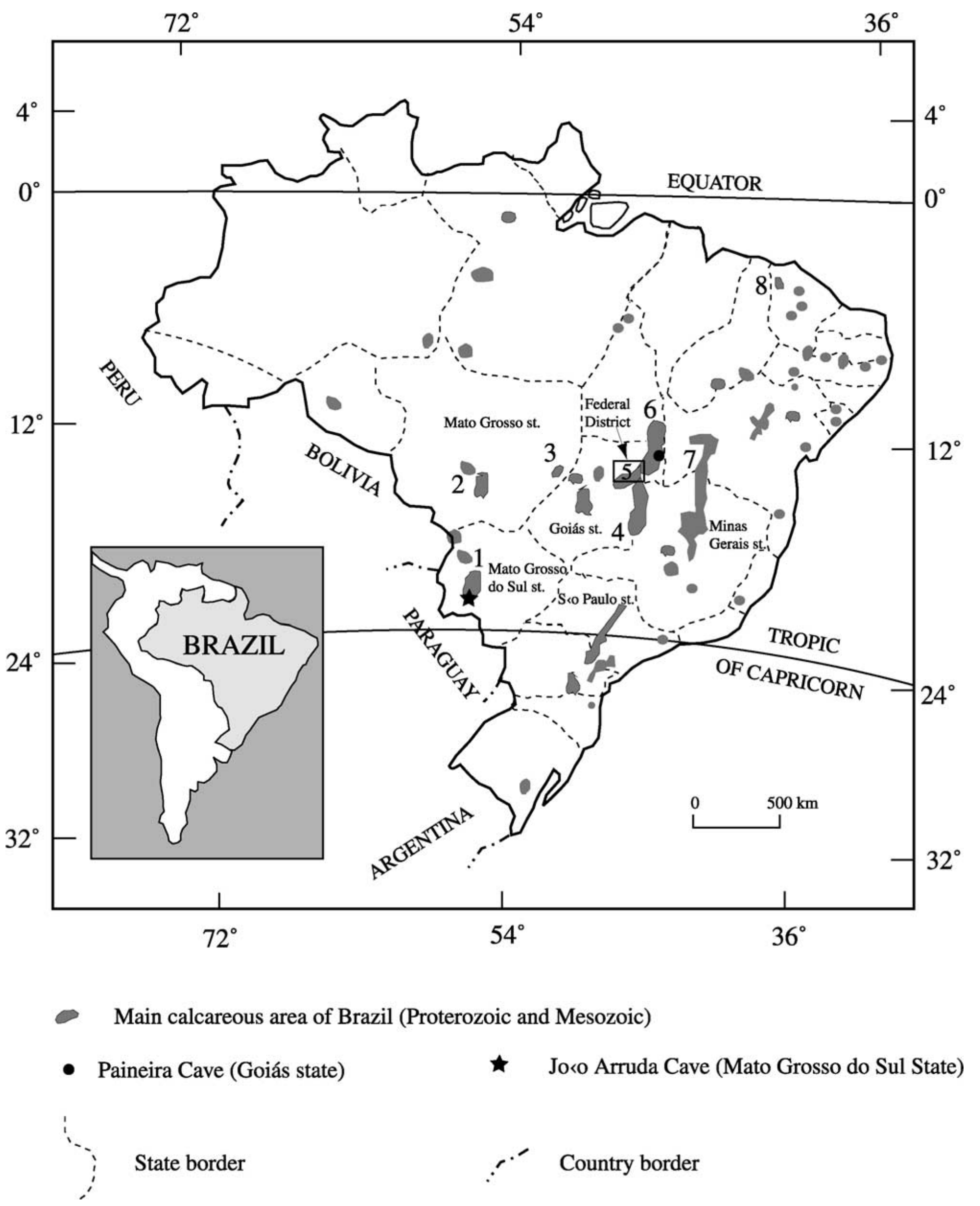

Fig. 1. Location of the main calcareous zones in Brazil and well-known speleological provinces of the 'Centro-Oeste' and 'Nordeste' of Brazil: 1-Serra da Bodoquena; 2-Serra das Araras-Alto Paraguai; 3-Cocalinho; 4-Paracatu-Vazante; 5-Brasília; 6-São Domingo; 7-Irecê; 8-Chapada de Ibiapaba (after Kartmann, in Lino and Allievi, 1980).

selected for this study is a 120 m long closed cavity that developed along the axis of chevron folded Mesoproterozoic limestones of the Paranoá Group. It consists of a succession of relatively voluminous rooms (5–7 m high) spreading along a main gallery. A small river with two siphons flows beneath part of the cave but it has no direct connection with the gallery. This cave, whose altitude is around 785 m at the entrance and 775 at the end, contains numerous speleothems (stalagmites, stalactites, columns and curtains). None of the sampled specimens was laminated. Soil development above the cave is very limited (a few tens of cm).

(2) The area of Bonito (21°S, 56°W, altitude around 300 m), Mato Grosso do Sul State, where the João Arruda Cave is located (Fig. 1). Situated in the southwest of Brazil, this area has a mean annual temperature of 22 °C and an average rainfall of 1,450 mm year^{-1} (Departamento Nacional de Meteorologia, 1992). The climate of the region is tropical, dry to sub-humid with slight water deficit (Instituto Brasileiro de Geografia e Estatística, 1992). It is under the influence of polar advection during the austral winter (June–September). Different authors have pointed out that El Niño-La Niña oscillations influence river discharges of the area (Grimm et al., 1998; Guetter, 1998), and that part of the climate variability of the region could also be linked to oscillations of the Atlantic dipole (Berri et al., 1998). This explains a large annual thermal amplitude (from 16 to 26 °C) and the fact that temperatures below 0 °C may occur during the winter (Departamento Nacional de Meteorologia, 1992). We selected the João Arruda cave, situated in Neoproterozoic dolomitic limestones of the Bocaina Formation (Corumba Group), as a site for installation of the EDAS device because it is well secluded from human activity and presents abundant speleothems. The cave consist of a sub-horizontal 100 m long gallery terminated by a small well. All the stalagmites sampled in this cave were well laminated (Bertaux et al., 2002). Above the cave, soil thickness is limited to a few tens of cm and a sub-mountaneous forest vegetation is present (Furtado et al., 1982).

3. The Environmental data acquisition system

3.1. The EDAS concept

The EDAS device was developed as a result of request from European geophysicists for a system to monitor environmental parameters in a geophysical observatory (van Ruymbeke et al., 1993).The probes designed at the Royal Observatory of Belgium were developed to monitor different environmental parameters, including air and water temperature, water level, gravity field, tilt, and sunlight (van Ruymbeke et al., 1997). In order to increase the precision of the sensors, passive transducers were systematically selected because they need a minimum energy transfer from the surrounding medium whilst minimizing the effect of the sensor on the environment. The EDAS technology thus uses resistive, inductive and capacitive (R, L, C) sensors. The signal generated by the sensors is converted into the frequency domain by an oscillating NE555 circuit. Optical sensors, based on on/off detection, are also adaptable to EDAS electronics. The probes are connected to a μDAS board which is a four-channel, stand alone system based on a Z80 microprocessor equipped with static memory. The integration period may be selected by software in a range going from 1 s up to 3,600 s.

Additional information about EDAS is available in the Royal Observatory of Belgium web page (http://www.astro.oma.be/D1/LABO/default.htm).

3.2. Characteristics of the probes used in this study

The drip counting probe is a capacitive sensor in which the drop itself represents one of the electrodes of the capacitor. The other electrode is a copper film glued on a 15 mm diameter PVC tube (Fig. 2(a)). The copper is connected to a NE555 oscillating circuit. It is wrapped in thermally fusable glue, centered in a second 25 mm diameter PVC tube also wrapped in the glue to make the sensor waterproof. The probe is centered near the tip of a dripping stalactite, so that the drops develop and fall inside the inner PVC tube, facing the copper film. As the drop volume increases, the capacitance between the sensor and the drop increases, and the output frequency of the oscillating circuit decreases accordingly. This happens until the moment of the drop fall, when the signal increases nearly instantaneously. The formation of one drop induces a variation in the signal of greater than 1 kHz and the succession of drops gives rise to a jagged signal pattern, illustrated at Fig. 2(b), allowing the measurement of drop growth rate and the accurate determination of the drip events. The relative stability of the temperature in the caves allows us to detect frequency changes with signal to noise ratio of 10^5 and the system is able to accurately detect drip rate as low as 2 drops day^{-1}.

The barometer sensor is also of capacitive type and consists of a standard aneroid barometric cell in which a copper plate replaces the traditional spring driving

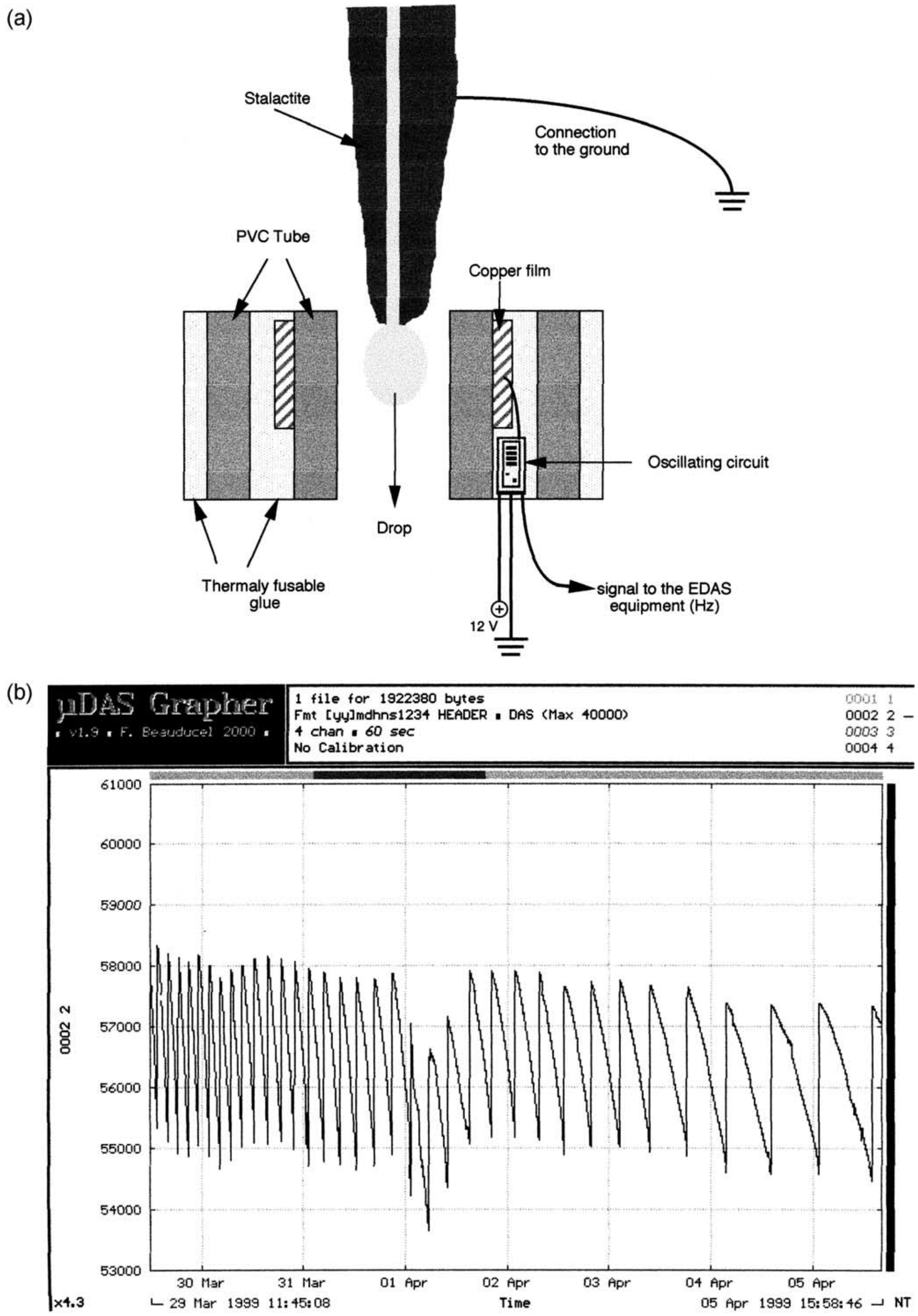

Fig. 2. (a) Schematic section across a drip counting sensor. The total diameter of the sensor is ± 30 mm. (b) Typical output (in hertz) of the sensor as visualized using the μDAS Grapher software package (Beauducel, 1998). Each minimum corresponds to the fall of a drop. One can observe the progressive slowdown of the drip rate from 8 to 2 drops day^{-1} within 5 days.

a needle. The pressure variations induce a displacement of the copper plate with respect to the base of the capsule, thus modifying the capacitance of the system. The barometer is calibrated in a (de)pressurized tank connected to a standard barometer. The dynamic range sensitivity reaches 200 mbar and the precision is around 0.01 mbar.

The air temperature sensor consists of a thermistor sealed in a 15 mm diameter PVC tube and connected to a NE555 oscillating circuit to convert the resistance variations into frequencies. The sensor is calibrated against an electronic thermometer and presents a resolution better than 0.001 °C in the range +10 to +35 °C.

The rain gauge is a commercial model (Rain-0-Matic®, Pronamic-Denmark). It consists of a spoon rocking when filled up by a fixed amount of rain water. Each oscillation gives rise to a 1 Hz signal recorded by the μDAS device. It is calibrated using known amounts of water.

3.3. Monitoring installation and conditions

The μDAS equipment has a 512 Kb SRAM and a four-channel data entry. The electric supply is provided by a 12 V-65 Ah battery connected to a 30 × 30 cm solar electric module (model SM10, Siemens Solar PowerPro™) through a 12 V regulator with temperature compensation. This solar module has a rated 10 W output, easily exceeding the 600 mW total consumption of the station and sensors. The solar module, regulator and battery are installed near the entrance of the cave on a metallic support connected to the ground; the electric parts are fitted in a waterproof plastic box to avoid damage by rain or animals. Using an electric cable section of 2.5 mm^2, the voltage drop between battery and μDAS equipment is low (0.2 V), even with 200 m of cable.

The monitoring began in July 1998 in Paineira; it was conducted until August 1999 when damage was caused to the installation and part of the material was stolen. In the João Arruda cave, monitoring began in May 1999. Some periods of interruption occured due to electrical failures and to damage caused to the cables inside the cave by rodents.

μDAS devices were installed near the far end of each cave, i.e. 100 m from the entrance for the Paineira cave and 90 m into the João Arruda cave, nearby active stalactites. The probes connected to the equipment were a barometric cell, an air temperature sensor and two drip counting sensors. Using an acquisition period of 3 min, the capacity of the 512 Kb memory was around 3.5 months. Another device was installed in March 1999 inside the Paineira cave to monitor dripping of three active stalactites in a very wet section situated 45 m from the entrance. This recorded data until its withdrawal five months later.

One additional μDAS device was installed at the surface near the Paineira cave to measure local meteorological parameters (atmospheric pressure, air temperature, and rainfall). These measurements in the vicinity of the cave, using the same acquisition period, ensured that the meteorological data used for further interpretation were consistent with the data acquired inside the cave. The temperature sensor and the barometer were isolated from solar insolation in a ventilated shelter. For the Bonito area, we used surface temperature data recorded by a thermometer installed near the entrance of the Lago Azul cave, a cave located some 25 km SSW from the João Arruda cave; rain data were obtained from a rain gauge located in the agricultural cooperative of Bonito.

Whenever necessary, datasets were downloaded via the RS-232 interface to a laptop computer using the MDASNet software package (van Ruymbeke et al., 2001) and dedicated software (μDAS Grapher software package available at http://www.ipgp.jussieu.fr/~beaudu) was used to visualize and process the signals (Beauducel, 1998). The software also allowed the transformation of the output of the sensors (in the frequency domain) into absolute value by using the calibration curves obtained from the calibration procedure of each sensor.

4. Results and discussion

4.1. Drip flow rate

At the beginning of the monitoring, in July, 1998, the flow rate at the tip of one of the stalactites monitored near the end of the Paineira cave was regular (Fig. 3) with 7–9 drops day^{-1}. The rainy season starts in October, but the flow rate did not change until the second week of December, when the drip frequency increased to more than 30 drops day^{-1}. The drip rate culminated at

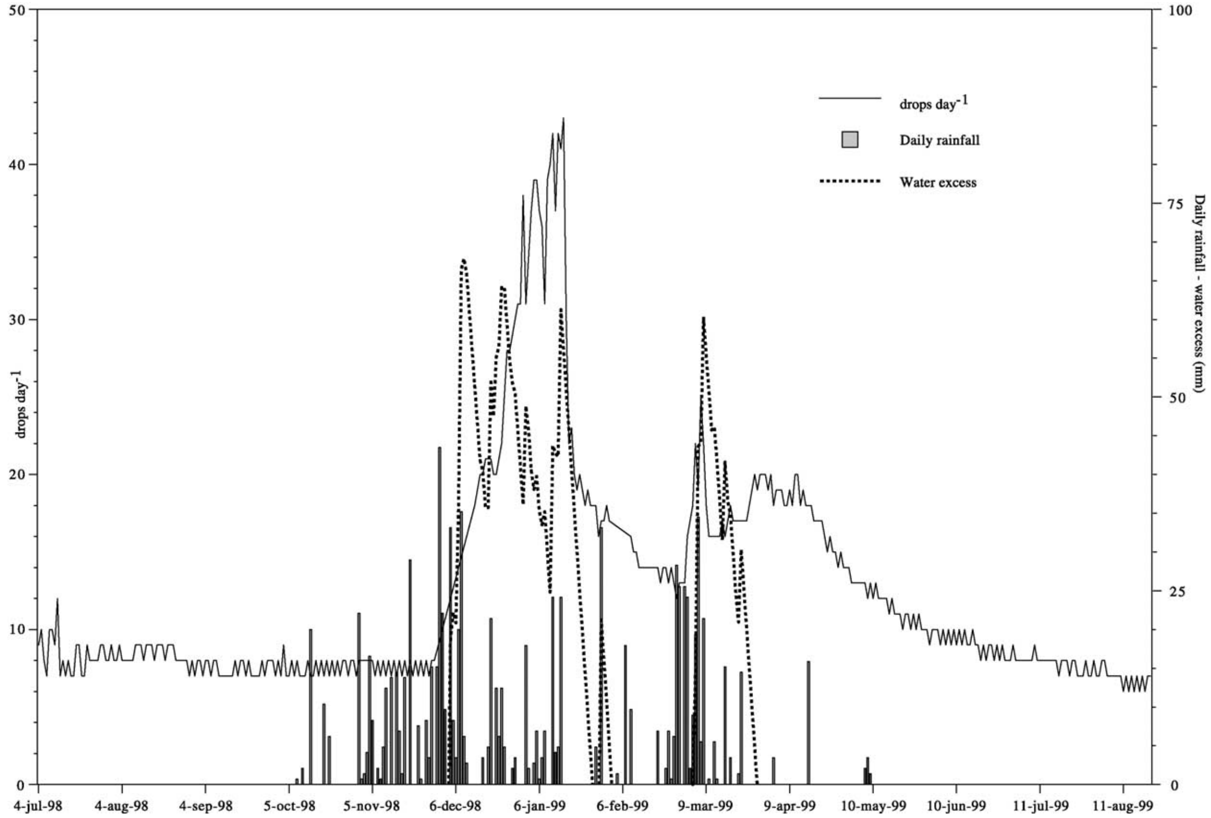

Fig. 3. Variation of the drip rate (continuous line) for one stalactite near the end of Paineira cave and daily rainfall (bar). The dashed line represents the calculated water excess (for explanation see text).

the beginning of January with 40–45 drops day^{-1} one month after rainfall maximum (30 November–10 December). A second maximum occurred in the first days of March, a few days after major rainfall events from 26 February to 8 March. From mid April on, the drip rate slowed down progressively to reach the value of 7–9 drops day^{-1} in June; this value remained stable until the end of the monitoring in September 1999 and was equal to that measured one year before. It should also be noted that the stalactite did not record the 16 mm rain event of 16 April.

Difficulties were experienced with data from the second sensors installed near the end of the cave as it gave very erratic signals. The replacement of the sensor by another one did not resolve the problem, so monitoring of this stalactite was discontinued.

The data of two of the three stalactites monitored since March 1999 near the entrance are shown at Fig. 4. It can be observed that at the beginning of the monitoring period there was nearly no time lag between rainfall events and the increase in the drip rate of these stalactites. From the beginning of April on, the drip rate slowed quickly and nearly stopped even when some rain occurred again later in April or in May. The dripping of the third monitored stalactite stopped two weeks after the beginning of the monitoring and is not presented in Fig. 4.

In the João Arruda cave, measurements of drip rate began in May 1999, at the beginning of the dry season (Fig. 5). At this time, the drip rate was 7–8 drops day^{-1}. The frequency decreased then to 3–4 drops day^{-1} in July. From August to mid-October an instrumental failure occurred due to the cutting of the cable by rodents. In October, the drip rate was around 2–4 drops day^{-1} and remained at these values until March 2000. It increased suddenly above 10 drops day^{-1} in the first days of March 2000 and

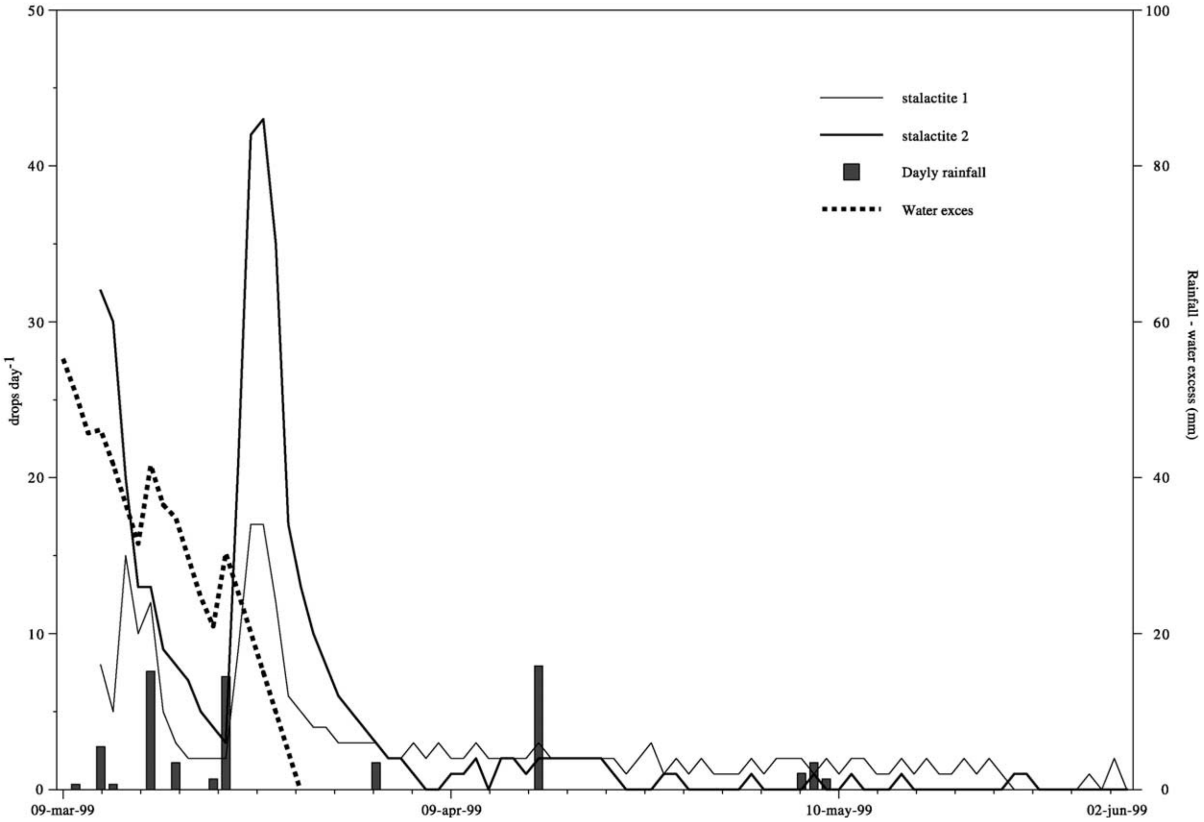

Fig. 4. Variation of the drip rate (continuous lines) for two stalactites monitored near the entrance of the Paineira cave and daily rainfall (bar). The dashed line represents the calculated water excess (for explanation see text).

culminated at 17 drops day^{-1} on March, 9. This happened nearly three months after the beginning of significant rainfall in December 1999 (which was later than usual that year) and perhaps is linked to the particularly high rainfall (122 mm) which occurred on December, 11. This high drip rate was of relatively short duration and it returned to values below 10 drops day^{-1} from the end of April on. The measured values in July 2000 (3–5 drops day^{-1}) were very close to those observed in July 1999.

As suggested by Genty and Deflandre (1998), the gap between the start of rainfall and the change in the drip flow rate may partly result from the time required for water to fill soil porosity after a long dry period and to infiltrate rock fissures before reaching the cave. This explains why the response of drip rate to rainfall is lagged at the beginning of the rain season while it is more immediate later. At the end of the rain season, the soils are saturated in water and the rain water runs off, what explains that the rain events in April do not alter the drip rate.

Evapotranspiration, which is maximum at the end of the dry season, has also probably a major influence on seepage water quantity. We tried to evaluate the water excess at Paineira using data of potential evapotranspiration (ETP) rates obtained at the EMBRAPA-CPAC meteorological station in Planaltina (50 km to the west of the cave). These rates were calculated using the Penman formula (Penman, 1948). This rather complex formula depends on the mean daily temperature, the partial pressure of water vapor at this temperature, the evaporative power of the air (a function of windspeed and of saturation deficit of the air), the latitude and number of hours of solar insolation. Using the daily data from 1974 to 1998, we computed a mean daily ETP value for each day of our observation period; this value was then substracted from the cumulative rainfall to obtain the water excess.

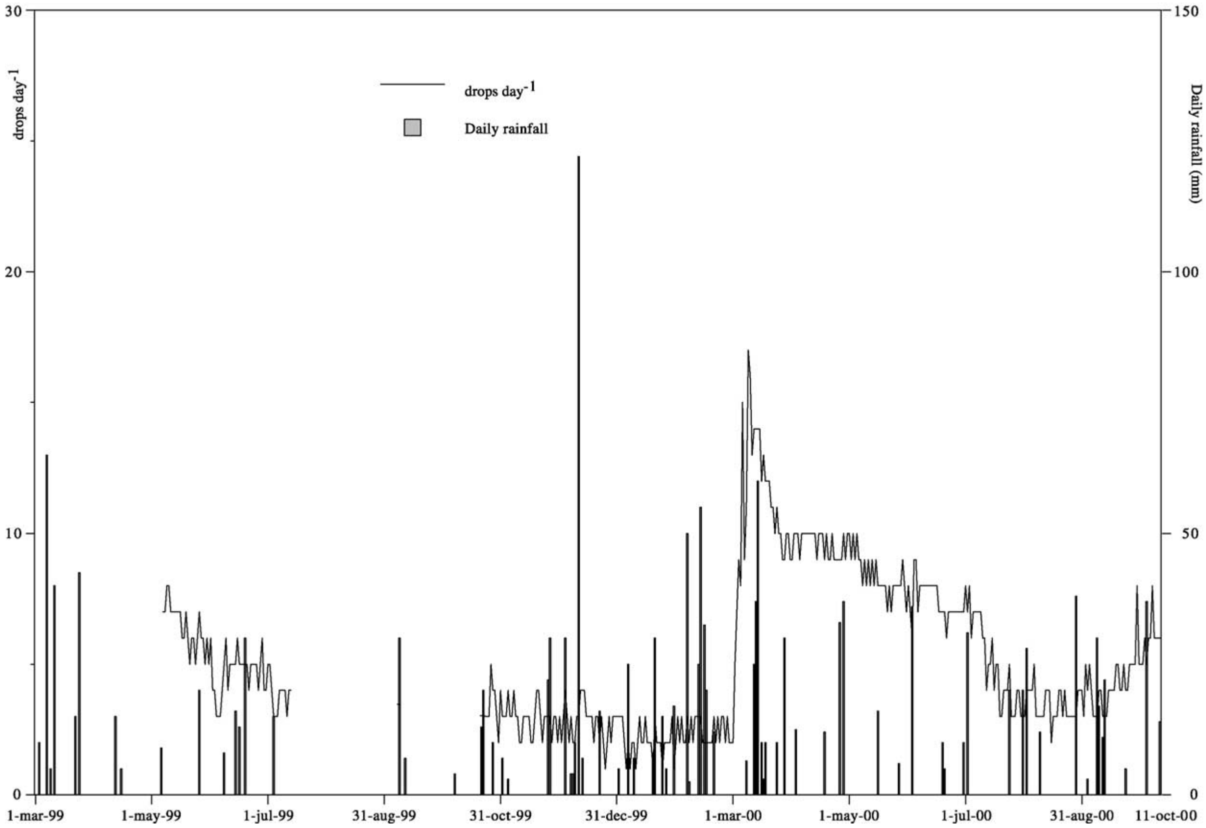

Fig. 5. Variation of the drip rate (continuous line) for one stalactite monitored in the João Arruda cave and daily rainfall (bar).

As indicated by the dashed line on Figs. 3 and 4, the water balance was positive only from December 04 to February 01 and from March 04 to 27. These periods fit very well with the observed maxima of the drip rates, which confirms that water excess is an important parameter for drip rate acceleration or decrease.

The stable slow-drip rate found during the dry season may result from the infiltration of ‘seepage water that remains in the upper vadose zone for up to several decades’ as stated by Ayalon et al. (1998) in their work on rainfall–recharge relationships in karstic terrains in the Eastern Mediterranean region, a semi-arid area characterized by well defined dry (summer) and rain (winter) seasons. On the other hand, fast-drip waters may ‘represent vadose flow with a short residence time of less than 1 year’ and which ‘start only after several massive…rainstorms’ (Ayalon et al., 1998). As these waters are related to infiltration through the soil and the fracture system of the overburden, the time lag between rainfall and fast-drip start depends also on the thickness of the pedological and rock cover. This explains that the stalactites located nearer the entrance, where the soil is very thin, presented a more immediate response to rainfall events, at least when the water balance was positive and soil under-saturated.

4.2. Air temperature and pressure measurement

4.2.1. Long term variations

Table 1 presents a summary of mean, maximum, minimum and amplitude of atmospheric pressure and temperature in both caves and at the surface. It can be observed that the pressure is more stable in the João Arruda cave (amplitude = 5.3 mbar) than in the Paineira cave (amplitude = 17.7 mbar). Conversely, air temperature in Paineira cave is very stable with an annual amplitude of 0.6 °C compared to 13.0 °C in the João Arruda cave. The river flowing beneath the Paineira cave has probably a damping effect on the variations of temperature in this cave

Table 1
Characteristic values of air pressure and temperature at both studied sites

	João Arruda			Paineira			
	Cave		Surface	Cave		Surface	
	P (mbar)	*T* (°C)	*T* (°C)	*P* (mbar)	*T* (°C)	*P* (mbar)	*T* (°C)
Mean	1010.0	25.1	24.3	1009.4	23.0	1012.4	24.4
Maximum	1012.4	28.4	40.5	1015.8	23.2	1040.2	43.6
Minimum	1007.1	15.4	2.3	997.2	22.6	985.3	4.4
Amplitude	5.3	13.0	38.2	17.7	0.6	54.9	39.2

while the temperature amplitude observed inside the João Arruda cave reflects the larger external temperature variations of the Bonito area. The minimum of 15.4 °C in the João Arruda cave was observed at the end of the austral winter (August and September) when frosty days occurred.

Fig. 6 illustrates the evolution of outside and inside pressures at Paineira. The outside pressure presents three distinct periods: from December to mid-March, the values were lower than 995 mbar; then a jump, corresponding to the end of the rainy season, occurred and pressure values fluctuated around 998 mbar; the third period began in July and was characterized by high (> 1005 mbar) pressure conditions prevailing during the dry season. The inside pressure showed weaker amplitude variations than outside pressure. A general increase of pressure values was also observed inside the cave during the monitoring period, but it was more gradual than outside. It should be noted that the difference in absolute value of ~10 mbar between inside and outside pressure values encountered during the rainy season diminished progressively and was annulled at the dry season. An instrumental bias, due either to a bad thermal isolation of the external barometer or to sensor calibration difference for

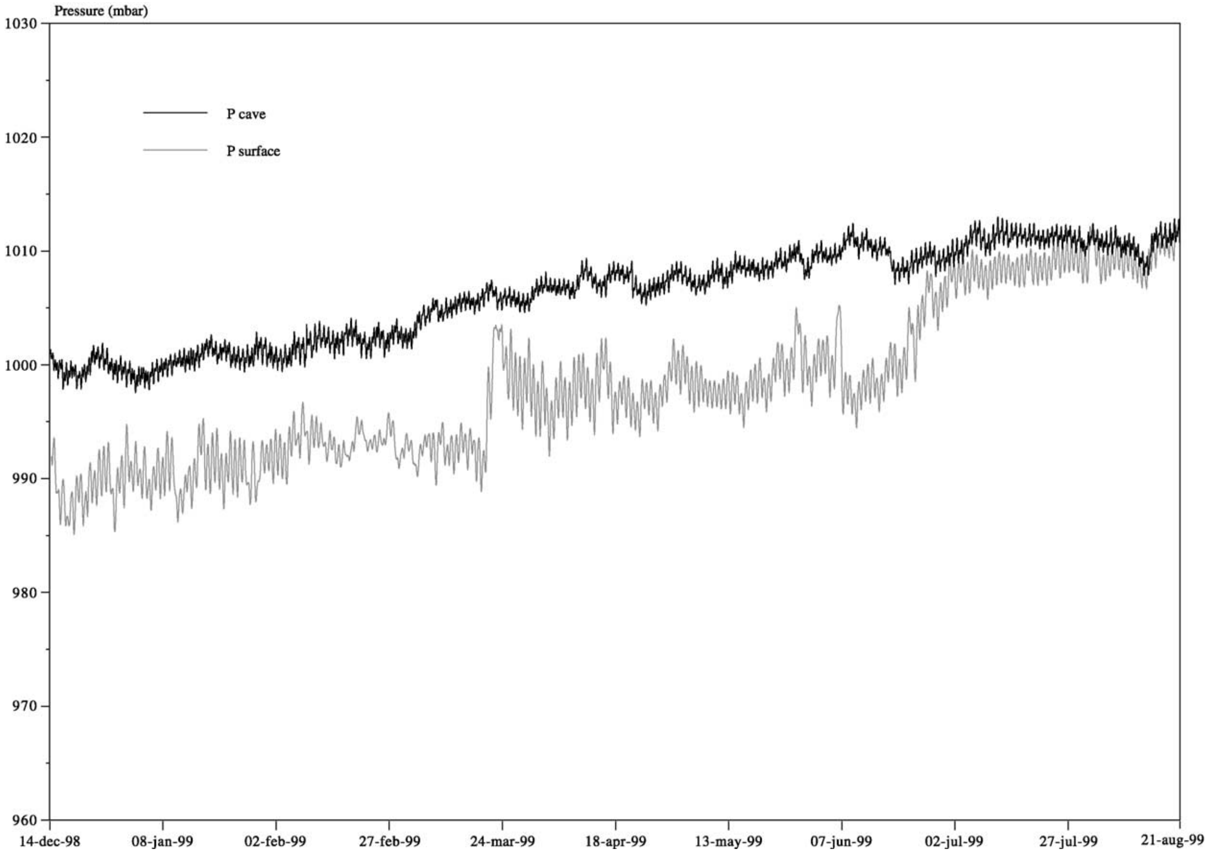

Fig. 6. Comparison between air pressure measured inside the Paineira cave and at the surface.

instance, could explain the differences between the internal and external pressure value and amplitude. It may also be related to the lower level of the river flowing beneath the cave during the dry season which might cause an opening of the siphons allowing an equilibration of the inner pressure with the outside pressure.

4.2.2. Daily variations

Fig. 7 shows a typical diagram of pressure and temperature variations in the Paineira cave in January (austral summer), when the daily thermal amplitude may reach 17 °C at the surface (from 20 to 37 °C). Inside the cave, the pressure peaks twice a day with amplitudes ranging from 1 to 2 mbar. One maximum occurs in the morning around 11:00–12:00 h (local time) and a second one, lower than the first one, occurs around 00:00–01:00 h. These oscillations thus have a periodicity of nearly 12 h and are more or less synchronous with pressure oscillations observed at the surface (Fig. 7). For air temperature inside the cave, one also observes a twice-daily peak pattern with maxima occurring around 10:30–11:30 h and 22:30–23:30 h, very synchronous with the surface pattern. The amplitude of these oscillations varies from 0.02 to 0.05 °C (± 0.001 °C), the peak in the morning being generally higher than that in the night.

The spectral analysis of the cave data using a Fourier transform is illustrated in Figs. 8(a) and (b) as the spectral power of pressure or temperature vs frequency. Beside low frequency (i.e. long period) peaks corresponding to seasonal variations, significant energy appears centered on the frequencies of 1.0

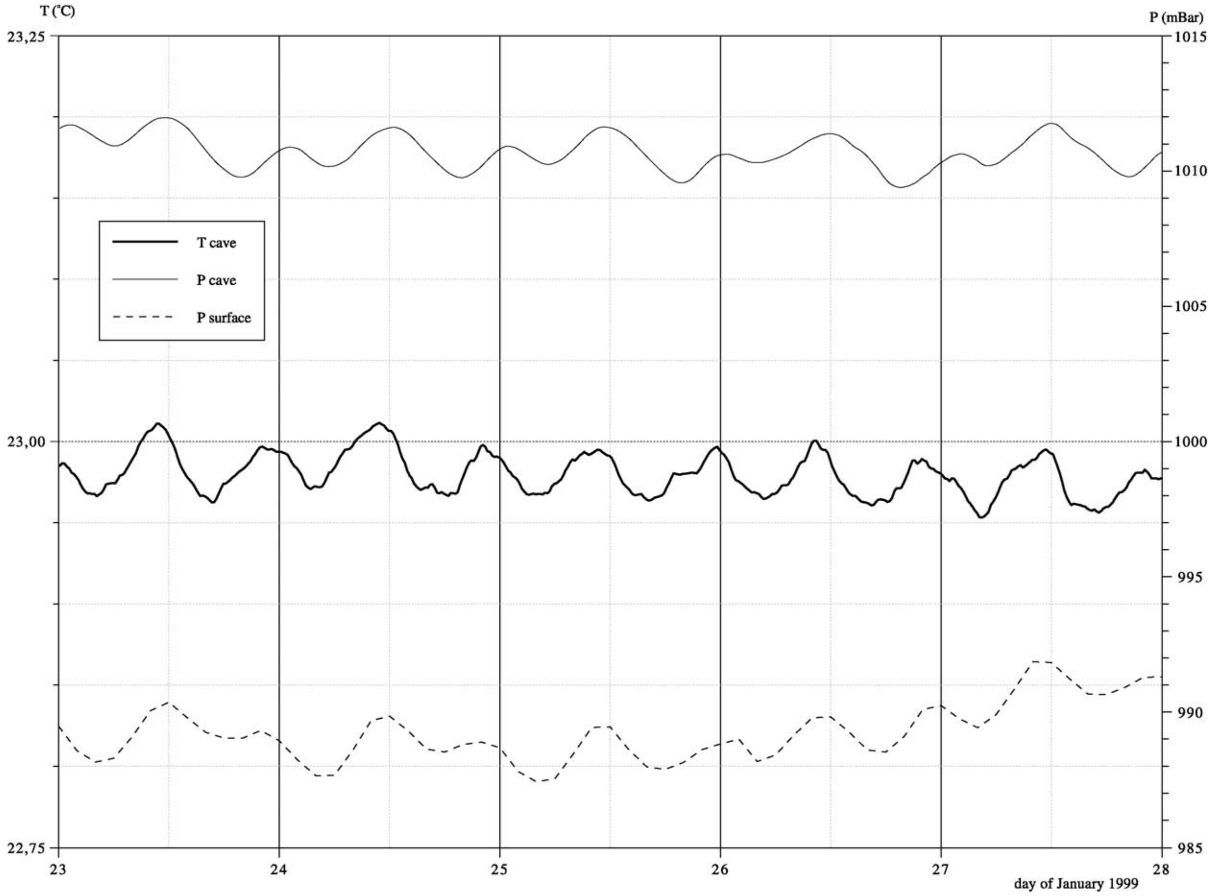

Fig. 7. Variation of temperature and pressure inside the Paineira cave from January 23 1999 to January 27 1999.

and 2.0 cycles day^{-1}, corresponding to the oscillation periods of the S1 diurnal (24 h) and S2 semi-diurnal (12 h) components of the atmospheric solar tides (Melchior, 1978; Wallace and Hobbs, 1977). It should also be noted that the semi-diurnal signal has a higher power than the diurnal one, which corresponds with the respective amplitude of these tides (Lindzen, 1971). As one can assume that the damping of thermal effects increases with the depth of the cave and that the volume of the rock surrounding the cavity has an

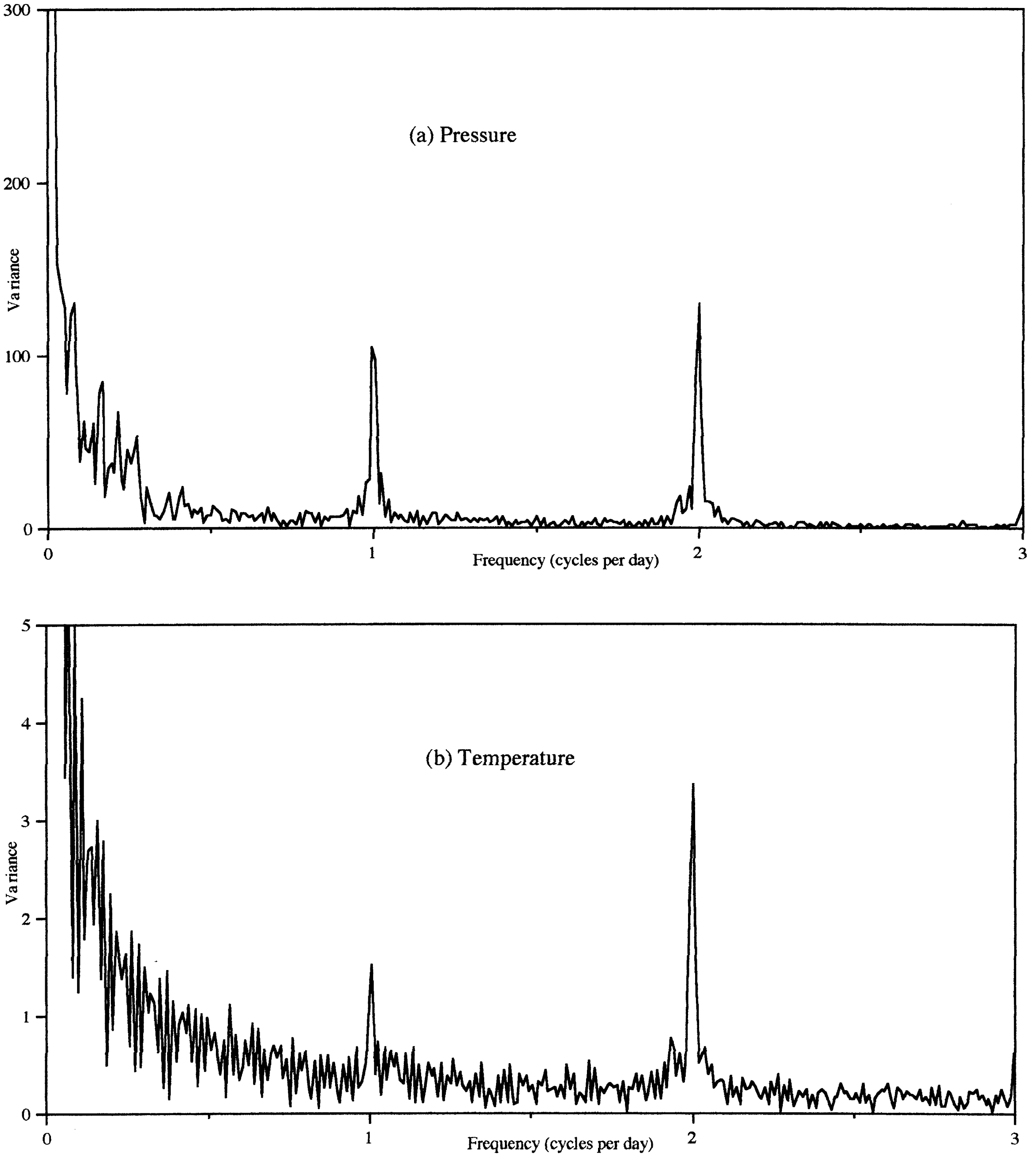

Fig. 8. Spectrum analysis (Fourier transform) of pressure (a) and temperature (b) data from the monitoring station inside the Paineira cave.

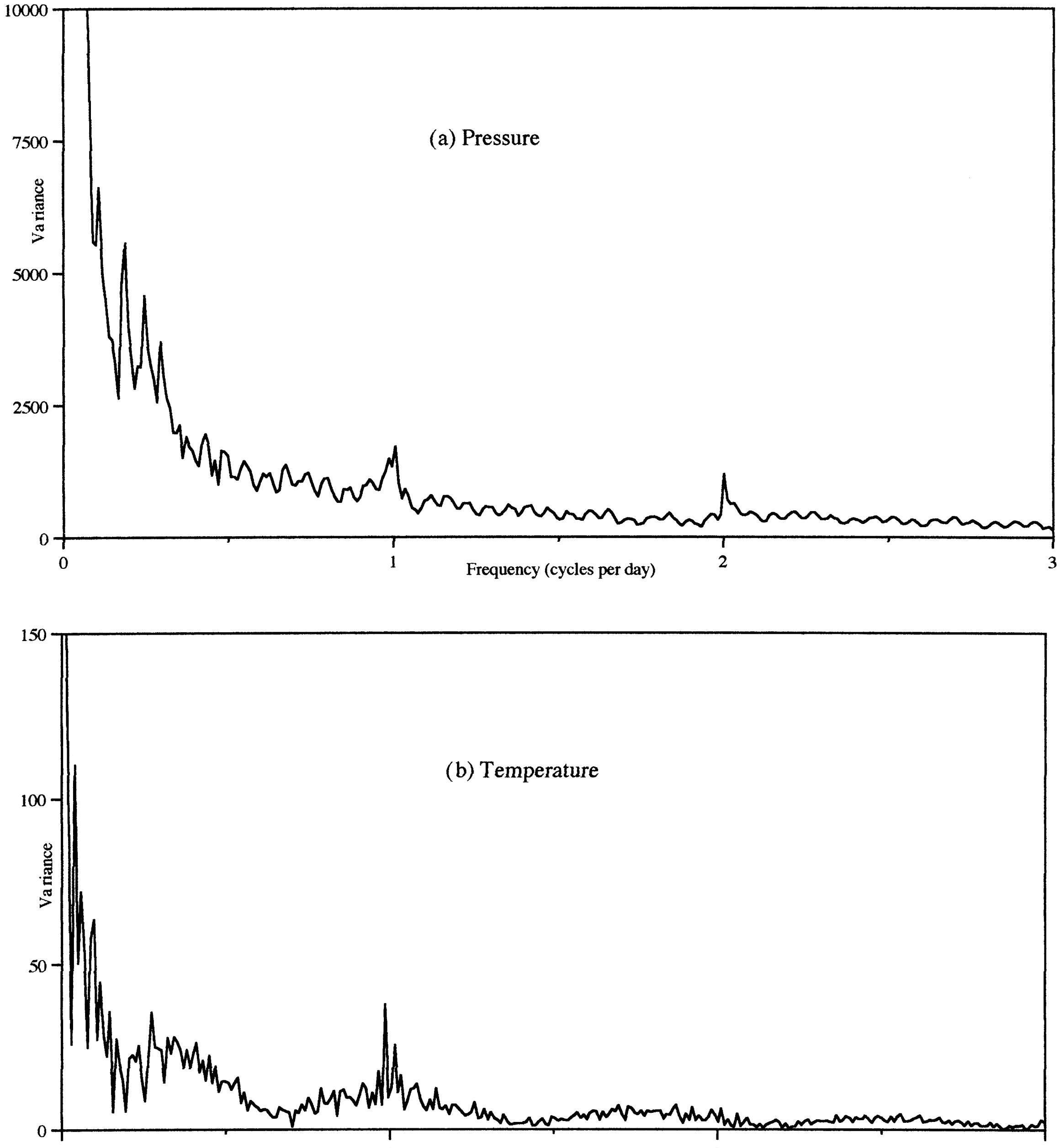

Fig. 9. Spectrum analysis (Fourier transform) of pressure (a) and temperature (b) data from the monitoring station inside the João Arruda cave.

infinite heat capacity, thermal exchanges between the air and the rock may occur and may stabilize the air temperature. Concerning the S2 thermal effect, the modulation of temperature at the surface is not significant and the peaks shown in the spectra suggest another process. Inversely to the thermal convections, the air pressure inside the cave varies with some attenuation from the outside one for periodicity of twelve hours; the thermal signature found at the S2 period should thus be a side effect of air pressure changes. Assuming that all gradients of temperature in the cave are in equilibrium, the air motion will be limited. The low thermal conductivity of air excludes any other thermal modulations than an adiabatic expansion/compression process of the air under the influence of atmospheric pressure variations. If one calculates the difference of temperature induced by the observed pressure modulations, assuming that (i) the atmosphere of the cave behaves like a perfect gas, (ii) the volume of the cave is constant and (iii) the number of molecules inside the cave do not vary significantly, the results are in very good agreement with the observed values. Indeed at 23.0 °C and 1000 mbar, a rise of pressure of 1 mbar induces an increase of temperature of 0.023 °C and a rise of 2 mbar corresponds to an increase of 0.046 °C. From these observations one can conclude that the process generating the thermal components on the S1 and S2 frequencies inside the cave is a mixture of thermal convection produced by the surface meteorological variations and of an adiabatic induction of S2 atmospheric pressure modulation. This was also observed in French caves by Mangin and D'Hulst (1996) who stated that the weak 'trace signal' of the S2 component is of fundamental importance to understand the exchange mechanisms between the surface and cave atmosphere.

In the spectral analysis of pressure data from the João Arruda Cave (Fig. 9(a)), the diurnal and semi-diurnal peaks are also detected, although with very weak energy. A 4 to 5 days cyclicity appears that could be related to incursions of midlatitude air toward tropical latitudes, at the east of the Andes, as documented by Ronchail (1989) and Garreaud and Wallace (1998), among others. These air incursions are associated with drops in temperature and increase in atmospheric pressure and, as they are generally preceded by a southward flow of moist air from central Amazon, the front at the leading edge of the cold advection often produces rainfall. It is a year-round phenomena, that maintains its identity over intervals of about 5 days (Garreaud and Wallace, 1998). This periodicity is detected in the Bonito area because it lies nearer from the Andes than the Paineira cave, and is situated on the usual pathway of the Antarctic cold waves. For temperature (Fig. 9(b)), most of variance is also detected in long period signals. A slight diurnal peak exists but the semi-diurnal one is absent. This confirms that the temperature of the João Arruda cave is more directly influenced by the external temperature; a better ventilation than in Paineira thus exists in this cave, probably because it developed in dolomitic rocks which are more fissurated than the limestones surrounding the Paineira cave.

5. Conclusions

The use of automatic equipment to monitor climatic conditions in caves allows a better understanding of some factors controlling the growth of speleothems with minor disturbance of the environment.

The specially designed sensors, adapted to monitor the water drop growth and dripping processes, improve the observation methods of stalagmite development, particularly in the tropical environment where drip rates may be very slow during the dry season. The low noise level of this passive sensor allows detection of drip rate as low as two drops day^{-1}.

The results of more than one year of measurements indicates that the monitored stalactites have drip rate variations related to rainfall with a lag in the temporal response, linked to the conditions of the water circulation in the overburden and to the effective rainfall (water excess). In both caves, the drip rate remains very stable during the rainy season. It seems to be reproductible from one year to the other, at least for what concerns the dripping related to the state of the aquifer during the dry season. This is of particular importance for the understanding of the formation of laminated speleothems in a tropical environment; indeed this implies that the laminae thickness and chemical composition is indirectly controlled by climatic parameters through rainfall and induced variations of drip water amount and chemistry.

The monitored caves present different patterns of long term variation for temperature and pressure, one being more stable than the other with respect to pressure but less stable with respect to temperature. The diurnal and semi-diurnal solar tides control slight diurnal pressure oscillations, especially in the pressure-stable cave.

The use of a high sensitivity (0.001 °C) thermometer permits observation of small temperature variations. This allows the detection of the low fluctuations (0.02–0.05 °C) generated by thermal exchange with the surface and also by the adiabatic expansion/compression of the cave atmosphere induced by the semi-diurnal component of the solar tides. The range of these fluctuations is however too low to influence the mean temperature value of the cave on a longer time scale.

The large thermal amplitude (13 °C) observed in the João Arruda cave is a great incitement to study the stable isotope geochemistry of the speleothems of this cavity because they should have registered with great resolution past temperature fluctuations linked to paleoclimate variations in this part of south-western Brazil.

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