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Microclimatic characterization of tourist caves in Parque Nacional Cavernas do Peruaçu, Minas Gerais, Brazil

***Mauro Gomes*[1]**
***Darcy José dos Santos*[2]**
***Úrsula de Azevedo Ruchkys* [3]**
***Luiz Eduardo Panisset Travassos*[4]**

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Abstract
The cave environment has very peculiar atmospheric conditions that directly influence the existence and maintenance of biotic and abiotic, socioeconomic, and historical-cultural elements represented by or associated with caves. In caves where tourist activities occur, the human presence may affect the delicate balance of these conditions. This study was developed to characterize the cave microclimates of seven caves that are part of the tourist itinerary in the Parque Nacional Cavernas do Peruaçu, located in the north of the state of Minas Gerais, Southeast Brazil. Temperature and relative humidity data were collected through 41 automated meters that each accumulated more than 110,300 readings. This research stands out for being one of the only long-term studies (2017 to 2019) developed in the country. The information analysis enabled not only characterization of the cave microclimate, but also observation of the relationship of these attributes with the internal morphology and the position of the caves in relation to the karstic relief of the region. The methodology developed in this study could support the Programa de Monitoramento das Condições Ambientais das Cavernas (Cave Environmental Conditions Surveillance Programme) to be implemented by the administration of the National Park, and identification of more sensitive environments in the interior of the caves will enable reordering of the visitation of these attractions.

[1] Centro Nacional de Pesquisa e Conservação de Cavernas - CECAV, Nova Lima, MG, Brasil. mauro.gomes@icmbio.gov.br
[2] Centro Nacional de Pesquisa e Conservação de Cavernas - CECAV, Nova Lima, MG, Brasil. darcy.santos@icmbio.gov.br
[3] Universidade Federal de Minas Gerais, Belo Horizonte, MG, Brasil. tularuchkys@yahoo.com.br
[4] Pontifícia Universidade Católica de Minas Gerais, Pós-Graduação em Geografia - Tratamento da Informação Espacial, Belo Horizonte, MG, Brasil. luizepanisset@gmail.com

INTRODUCTION

Comparison of the subterranean climate with that observed on the surface may initially transmit the impression of perfectly stable climate conditions, without the occurrence of meteorological fluctuations or seasonal variations over the year, and that the temperature remains constant throughout the entire extension of the cave (BADINO, 2010). However, intrinsic factors to caves, such as spatial confinement, absence of light, low incidence of solar energy, and internal topography and geometry, in addition to the spatial distribution of the entrances (LOBO, 2012; TRAVASSOS, 2016), can promote significant flows of energy and mass between the subterranean environment and the surface (CIGNA, 1993). Therefore, these meteorological conditions, as well as those observed in the external environment, are dynamic, and upon adopting an adequate scale for analysis, distinct variations can be perceived that characterize the cave microclimate (BADINO, 2010).

Climate conditions are very peculiar in subterranean environments and exercise an influence both on biota and the genesis of conduits and their speleothems, and on palaeontological archaeological and cultural records sheltered by the caves. Human interference can directly impact the stability of the environment, causing alterations to temperature or relative humidity (TOOMEY, 2009). Lobo (2012) emphasizes that changes in the cave climate as a result of tourist use may come to compromise the preservation of rupestrian paintings and the constitution of speleothems and rocks, as well as the equilibrium of the subterranean biota. This situation has led specialists to develop specific studies on possible negative impacts, considering caves open to tourism in particular (CALAFORRA et al., 2003; CIGNA, 1993; LOBO et al., 2015; PULIDO-BOSCH et al., 1997; ŠEBELA et al., 2013; ŠEBELA; TURK, 2014). In Europe, studies with the purpose of increasing knowledge on cave microclimate behaviour in relation to tourist use have been carried out since the first half of the 20th century (ŠEBELA et al., 2013). In Brazil, despite the existence of older records (from the 1960s and 1970s), it was at the end of the 1990s that Boggiani et. al (2007) developed one of the first systematized studies addressing cave microclimates. However, it was only at the beginning of the 2000s that research on this theme had access to greatly improved methods, techniques, and equipment, which enabled the attainment of longer, more reliable data series (LOBO, 2010). Thus, some tourist caves in the country started having cave microclimate studies to support the definition of their use and management plan (LOBO, 2011; ROCHA, 2010; ROCHA; GALVANI, 2011; TRAVASSOS, 2010; VERÍSSIMO et al., 2003).

The Parque Nacional Cavernas do Peruaçu (PNCP) is located in Southeast Brazil, in the north of the state of Minas Gerais. It is home to some of the most important tourist caves in the country and, according to information from the team responsible for the management of this Conservation Unit (UC), the number of visitors has been increasing steadily in recent years. The Management Plan of the UC (IBAMA, 2005) determines the development of a Cave Environmental Conditions Surveillance Programme, which has yet to be developed. To meet this demand, Gomes et al. (2019) and Santos et al. (2018) carried out preliminary studies on the theme that serve as a basis for the elaboration of the present study.

This manuscript aims to present the microclimatic characterization of seven caves that make up the tourist itinerary of the PNCP, through the compilation and analysis of data on temperature and relative humidity collected between 2017 and 2019. It is hoped that the analyses conducted in this study can supply the management of the PNCP with more elements to be considered, both in the definition of load capacity, and in the restriction of visitor access to the internal areas of the caves considered more sensitive to microclimatic alterations. Furthermore, considering a broader perspective, it is hoped that this study may offer support to the deepening of knowledge on the climate dynamic of caves in tropical environments, especially those open to tourists.

MATERIAL AND METHODS

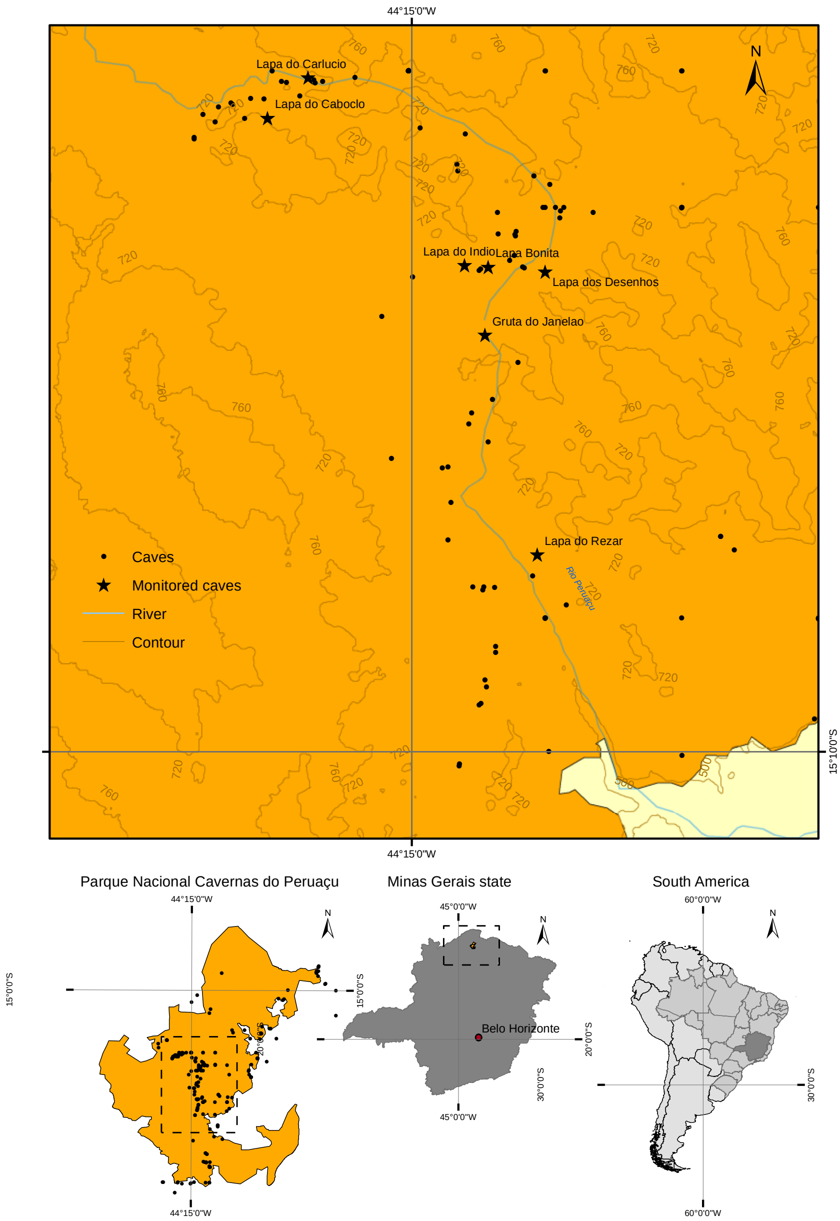
Study area

The PNCP is a conservation unit of integral protection created with the objective of protecting natural ecosystems in the Karstic Valley of the Peruaçu River (BRAZIL, 1999). It has an estimated area of 56,800 ha and is located in the north of the state of Minas Gerais. (Figure 1). The park is in the basin of the São Francisco River, between the municipalities of Januária, Itacarambi, and São João das Missões, 653 km from the state capital, Belo Horizonte (IBAMA, 2005). The natural ensemble of the Peruaçu River valley, the canyon (karstic valley), the caves, and the archaeological sites are nationally and internationally recognized as being one of the few places on the planet to assemble all these characteristics in one place and in such splendid fashion. In addition, the PNCP also encompasses other extremely relevant attributes, both from the scientific and the natural point of view, which have led the park to be recommended for recognition of Human Heritage by the United Nations (IBAMA, 2005).

The unit is found in a transition area between the Cerrado and Caatinga biomes and important fragments of Seasonal Deciduous Forest (*Mata Seca*), Seasonal Semi-deciduous Forest, Riparian Evergreen Forest, Rupestrian Formation, Savanna Formations, Savanna-Steppe Formation, and Alluvial Communities (IBAMA, 2005) are protected in its interior. In the geological context, the carbonate outcrops of the Bambuí Group

(Neoproterozoic) stand out, which, in certain parts of the park, are partially covered by siliciclastic rocks of the Upper Mesozoic, belonging to the Urucuia Formation (SCHOBBENHAUS; NEVES, 2003). During the Paleogene, the region passed through tectonic uplift and, in parallel, a broad network of subterranean conduits developed as a result of the circulation of water from the karstic aquifer. In the Quaternary, karstic relief evolution led to the collapse of various segments of the cave roofs, culminating in the opening of the Karstic Valley of the Peruaçu River (KOHLER et al., 1989; MOURA, 1997; PILÓ, 1989).

Figure 1 - Location of the Parque Nacional Cavernas do Peruaçu and the monitored caves.



Source: By the authors.

Four morphological units have been defined in the park (IBAMA, 2005), distributed between altitudes of 830 m to 440 m: (a) Planalto das Gerais (Gerais Plateau); (b) Zona de Transição (Transition Zone); (c) Compartimento Carstificado (Karstified Compartment); and (d) Depressão do São Francisco (São Francisco Depression). The Planalto das Gerais compartment includes a unit situated above 760 m, developed on rocks of the Urucuia Formation. It has planate relief with smooth undulations, ample interfluves, and low-density drainage. The Zona de Transição compartment is situated between 760 m and 720 m. It has planate relief, with the presence of karstic features such as residual tabular hills and slow subsidence dolines, characterizing the transition between the Planalto das Gerais and the underlying carbonate sequence. The Compartimento Carstificado, situated between 720 m and 500 m, developed on carbonates of the Bambuí Group. The relief is rugged and marked by discontinuity in the drainage network. This compartment exhibits a large quantity and variety of karstic features such as caves, collapse dolines, karstic valleys, fissured massif, ruiniform towers, gulleys, resurgences, walls, scarps, and *karren* of various dimensions. The Depressão do São Francisco compartment is found between 500 m and 440 m; it has planate relief with smooth undulations and the presence of subsidence dolines and hills with evidence of carbonate rocks of the Bambuí Group.

Most of the caves in the Peruaçu region are found between 750 m and 500 m on the Planalto Cárstico do São Francisco (São Francisco Karstic Plateau), where there are supracrustal carbonate sequences (dolomites and limestones) of the Neoproterozoic belonging to the Bambuí Group. The Peruaçu River has been modifying the landscape over time, constructing an important canyon on its way towards the São Francisco River. As a result of this process, the subsequent roof and wall abatements of the karstic aquifer conduits promoted the appearance of ample dissolution and abatement caves (PILÓ; RUBBIOLI, 2002).

Up to 2020, the UC had a little over 150 caves registered on the official database of the Brazilian government (CECAV, 2021). Of this total, eleven were selected for public visitation and integrated into six tourist itineraries, as per the management plan of the unit (IBAMA, 2005). It is important to highlight that despite the incipient records, the activity of visiting the park caves has been growing each year. According to information from the UC administration, an average of 330 visitors/month was recorded in 2016, and in 2018 this number had already increased to 682 visitors/month.

This research refers to the monitoring of the temperature and relative humidity inside seven caves that are part of the itineraries that receive the highest annual number of tourists (Table 1). Both caves that receive tourists in their interiors, such as Gruta do Janelão, Lapa Bonita, Lapa do Carlúcio, and Lapa do Rezar, and caves in which visitors only access the external areas close to the entrances, such as Lapa dos Desenhos, Lapa do Índio, and Lapa do Caboclo were selected.

Gruta do Janelão is among the group of caves drained by the Peruaçu River. Its main characteristics are the ample galleries that reach heights of up to 100 m and others that are 100 m wide at certain points. The conduits have rectangular sections, which are generally singular and with a sinuous planimetric pattern. The large skylights are also noteworthy as they promote the installation of plant formations inside the cave. The other caves cited in this study are part of a group of dry caves, disconnected from the karstic aquifer. Lapa dos Desenhos, Lapa do Rezar, Lapa do Caboclo, Lapa Bonita, Lapa do Índio, and Lapa do Carlúcio are positioned above the current base level represented by the Peruaçu River and are inserted in the walls of the main canyon or in secondary dry valleys. These caves have a rectilinear and angular development pattern, with predominantly rectangular sections (IBAMA, 2005).

Table 1 - Caves currently monitored on the tourist itineraries of the PNCP with the respective quantities of automated measuring stations.

Caves	Elevation (m)	Horizontal projection (m)	Station
Lapa do Caboclo	698	100	4
Gruta do Janelão	686	4,740	5
Lapa do Índio	678	150	5
Lapa do Carlúcio	677	160	6
Lapa do Rezar	639	380	5
Lapa Bonita	638	420	10
Lapa dos Desenhos	619	140	6

Source: Adapted from IBAMA (2005)

A characteristic common to all the caves in this study is the presence of *Mata Seca* (Seasonal Deciduous Forest) close to the entrances, with deciduous arboreal-shrubby species. The plant coverage found around the caves can be observed in two distinct ways as a result of the pedological coverage and the greater humidity, presenting floristic composition similar to Atlantic Forest, or presenting certain elements of Mesophilic Forest, Atlantic Forest, and Caatinga (IBAMA, 2005).

Equipment installation and configuration

Automated measuring stations were used to record the temperature and humidity data, using a Testo 175-H2 model (resolution: 0.1 °C for temperature and 0.1 % for relative humidity; accuracy: 0.1 °C for temperature and 0.3 % for relative humidity) set to record data every 10 minutes. All the equipment was positioned at a mean height of 1.5 meters from the floor in the caves that receive visitors inside, preferably at locations close to those used for the passage of tourists.

Based on the topographic map of each cave (IBAMA, 2005), a network of points was defined, and three sessions of temperature and humidity data collection were carried out at these points on distinct dates, using an ITMP 600 multifunction meter. Subsequently, these data were interpolated through Inverse Distance Weighting (IDW) on the Geographic Information System (GIS), which made it possible to elaborate maps that enabled the identification of the different climate zones of the caves. Based on the reading of these maps, distinct environments were defined within the caves, also considering the morphology of the conduits and the position and distribution of the entrances. The spatial distribution of the equipment considered the existence of internal walkways to be used by visitors and prioritized data collection in heterothermic zones (close to the entrance), homeothermic zones (deeper zones), and in unsaturated transaction zones (LOBO, 2012).

The definition of places for equipment installation considered the use of minimum impact practices, seeking to position the stations without needing to make holes in the cave structures. Steel cables and attachment clips were used, making it possible to accommodate the meters on speleothems, in fractures, or on rock ledges (Figure 2a). For the caves receiving tourist visitation inside, the positioning of the meters at points close to the place of tourist passage was observed (Figure 2b). The same type of equipment was also installed in the external part of Gruta do Janelão and Lapa Bonita (Figure 2c) at places close to the entrances, in order to obtain more specific references of the external climate conditions. For this situation, small meteorological shelters were constructed to protect the meters (Figure 2d).

Figure 2 - Installation of the measuring stations in Lapa Bonita. a) Attachment of the equipment on a speleothem, b) Meter installed close to the place of tourist passage, c) Attachment of the equipment on a tree close to the cave entrance, d) Meteorological shelter installed for the external meter.

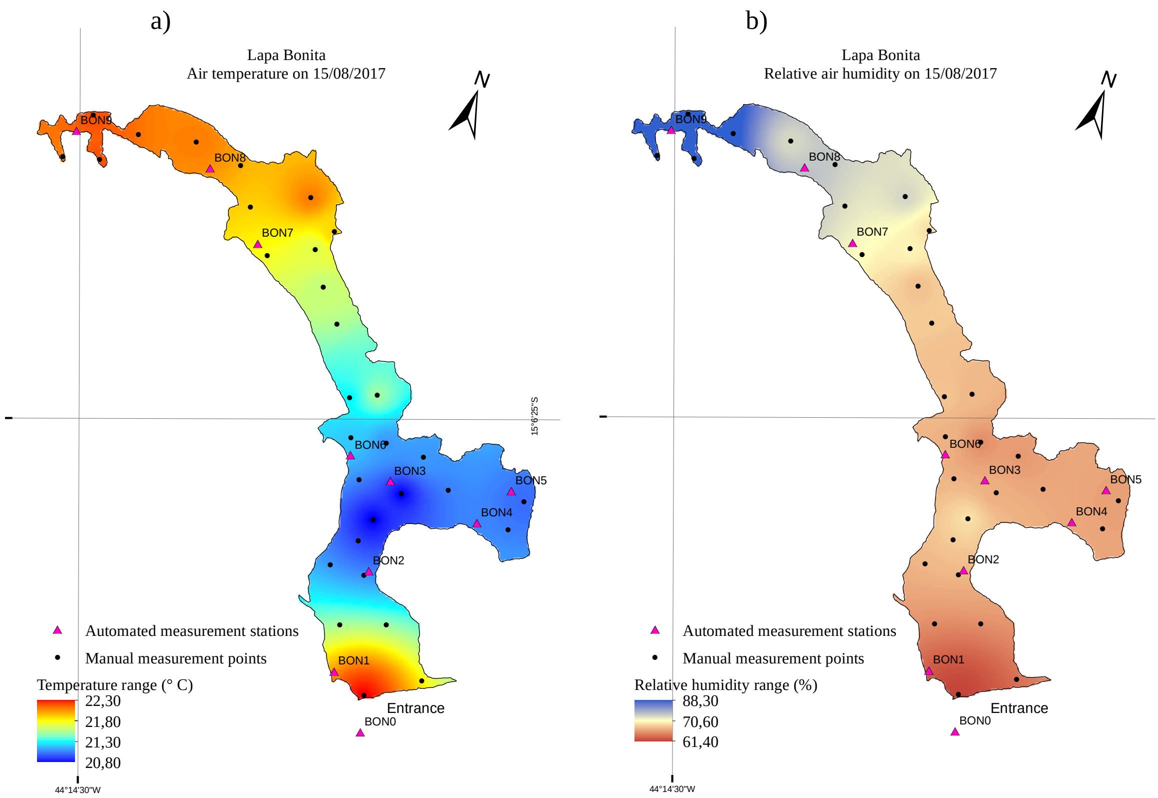
Source: By the authors.

Each station received a tag identifying not only the cave in which it was installed, but also referring to the spatial disposition of its location in relation to the cave entrance. Thus, the suffix 1 indicates the station positioned immediately after the entrance to the cave, and suffixes 6, or 9 for example, are stations installed in the last hall, at the opposite extremity to the entrance. Therefore, the identification CAR1, indicates the equipment installed soon after the entrance to Lapa do Carlúcio, and BON9, is the meter installed in the last hall of Lapa Bonita. The suffix "zero" refers to the two external meters, installed close to the entrances of Lapa Bonita (BON0) and Gruta do Janelão (JAN0).

RESULTS AND DISCUSSION

The maps produced through the interpolation of internal climate data, together with the morphological information and information on tourist use of each cave were used in the definition of the places that would receive the automated measuring stations. These maps enabled identification of temperature (Figure 3a) and relative humidity (Figure 3b) conditions in the different environments of the caves in the three field campaigns that occurred at the beginning of the project in 2017.

Figure 3 - Maps presenting the result of data interpolation that supports the choice of places for the installation of automated stations in Lapa Bonita. a) Temperature and b) Relative humidity.



Source: By the authors.

In the data collection carried out at Lapa Bonita on 15/08/2017, the highest temperatures were recorded at the extremes of the cave, close to the entrance (22.3°C) and in the last hall (22.1°C) (Figure 3a). It was also observed that the hall located immediately after the entrance hall was the coldest area of the cave, where the lowest temperature was recorded (20.8°C). Regarding relative humidity, it was observed that the entrance area had the lowest value (57.1%) and the last hall had the highest value (88.3%) (Figure 3b). This information was a determining factor in identifying the places where it would be possible to record climate variations associated with different environments, as well as the influence that the external conditions exert on the cave microclimate.

The monitored caves are in the Compartimento Carstificado, more specifically in the Karstic Valley formed by the canyon of the Peruaçu River. According to IBAMA (2005), the climate in this region is influenced by the process of geomorphological sculpting that favours the channelling of winds loaded with humidity arising from the São Francisco River, among other places. This factor, associated with the arboreal vegetation present in the region favours a climate with mild temperatures, around 24°C, higher relative humidity, 80% on average, and low amplitudes.

As observed by Lobo (2013) and Travassos (2016), the subterranean microclimate is dependent on intrinsic characteristics, such as topography, geometry, and the distribution and quantity of entrances, but is also heavily influenced by the external environment. According to IBAMA (2005), the northern limit of the Karstic Valley where the caves are located is with the geomorphological compartment of the Planalto dos Gerais, where there is a fresher and slightly more humid environment, and the southern limit is with the Depressão do São Francisco compartment, with a warmer environment with lower relative humidity (Serafini-Júnior, 2005).

The results of the data collection carried out between 2017 and 2019 are shown in Table 2, which also presents the descriptive statistics of the temperature values recorded at each of the 41 stations installed in the caves of the PNCP. According to Badino (2010), the cave environment is more stable from the point of view of climate conditions due to relatively low amplitudes for internal temperature and humidity when compared to the external environment. This affirmation can be seen when observing the amplitude data in Table 2. The BON0 and JAN0 stations installed in the external area of the caves are those that present the highest amplitude values with 31.2 °C and 29.8 °C, respectively. When these values are compared with those recorded by the equipment located close to the entrances, albeit in the internal part of these caves, it can be verified that the amplitude values are significantly lower, with 14.9 °C for BON1 and 17.5 °C for JAN1.

Table 2 - Descriptive statistics for temperature in the stations of the monitored caves.

	Stations	**Average**	**Standard deviation**	**Variance**	**Minimum**	**Maximum**	**Amplitude**
Carlúcio	CAR1	20.7	2.57	6.59	9.5	29.5	20.0
	CAR2	21.1	2.09	4.35	11.3	26.0	14.7
	CAR3	20.9	2.13	4.53	11.0	25.0	14.0
	CAR4	21.3	2.39	5.69	9.9	27.0	17.1
	CAR5	21.3	1.66	2.75	15.0	24.4	9.4
	CAR6	21.1	1.55	2.4	14.0	24.9	10.9
Caboclo	CAB1	22.9	1.86	3.46	13.6	26.8	13.2
	CAB2	23.0	1.53	2.34	14.6	26.0	11.4
	CAB3	24.0	0.96	0.91	20.1	27.5	7.4
	CAB4	24.4	0.7	0.5	22.4	28.3	5.9
Desenhos	DES1	23.0	2.2	4.85	13.8	28.0	14.2
	DES2	23.7	1.13	1.28	19.1	26.6	7.5
	DES3	24.3	1.64	2.69	18.0	29.5	11.5
	DES4	24.2	1.08	1.16	20.2	27.5	7.3
	DES5	24.6	0.82	0.68	22.2	28.4	6.2
	DES6	24.3	0.8	0.63	21.8	28.6	6.8
Bonita	BON0	23.6	4.54	20.56	9.2	40.4	31.2
	BON1	21.5	1.92	3.69	13.2	28.1	14.9
	BON2	20.0	1.39	1.94	12.8	22.1	9.3
	BON3	20.7	0.31	0.1	19.7	27.4	7.7
	BON4	20.7	0.26	0.07	20.1	23.7	3.6
	BON5	20.5	0.34	0.11	19.7	22.3	2.6
	BON6	20.4	0.36	0.13	19.3	25.7	6.4
	BON7	21.1	0.12	0.02	20.8	22.7	1.9
	BON8	21.2	0.08	0.01	21.1	27.4	6.3
	BON9	20.6	0.07	0.01	20.4	24.8	4.4
Índio	IND1	23.7	3.31	10.94	12.3	33.7	21.4
	IND2	22.6	0.42	0.17	21.7	25.3	3.6
	IND3	21.9	0.08	0.01	21.7	25.1	3.4
	IND4	21.7	0.11	0.01	21.5	23.3	1.8
	IND5	21.4	0.12	0.01	21.2	24.5	3.3
Janelão	JAN0	23.2	4.64	21.51	7.9	37.7	29.8
	JAN1	22.1	2.39	5.71	11.5	29.0	17.5
	JAN2	22.4	2.75	7.58	13.0	39.0	26.0
	JAN3	22.0	1.79	3.22	14.3	28.1	13.8
	JAN4	22.1	1.66	2.75	15.2	26.7	11.5
Rezar	REZ1	24.3	3.38	11.45	13.9	35.4	21.5
	REZ2	23.7	1.26	1.59	17.9	26.3	8.4
	REZ3	24.0	0.74	0.54	20.9	27.8	6.9
	REZ4	23.8	0.58	0.34	21.1	25.4	4.3
	REZ5	24.1	0.42	0.18	22.8	27.2	4.4

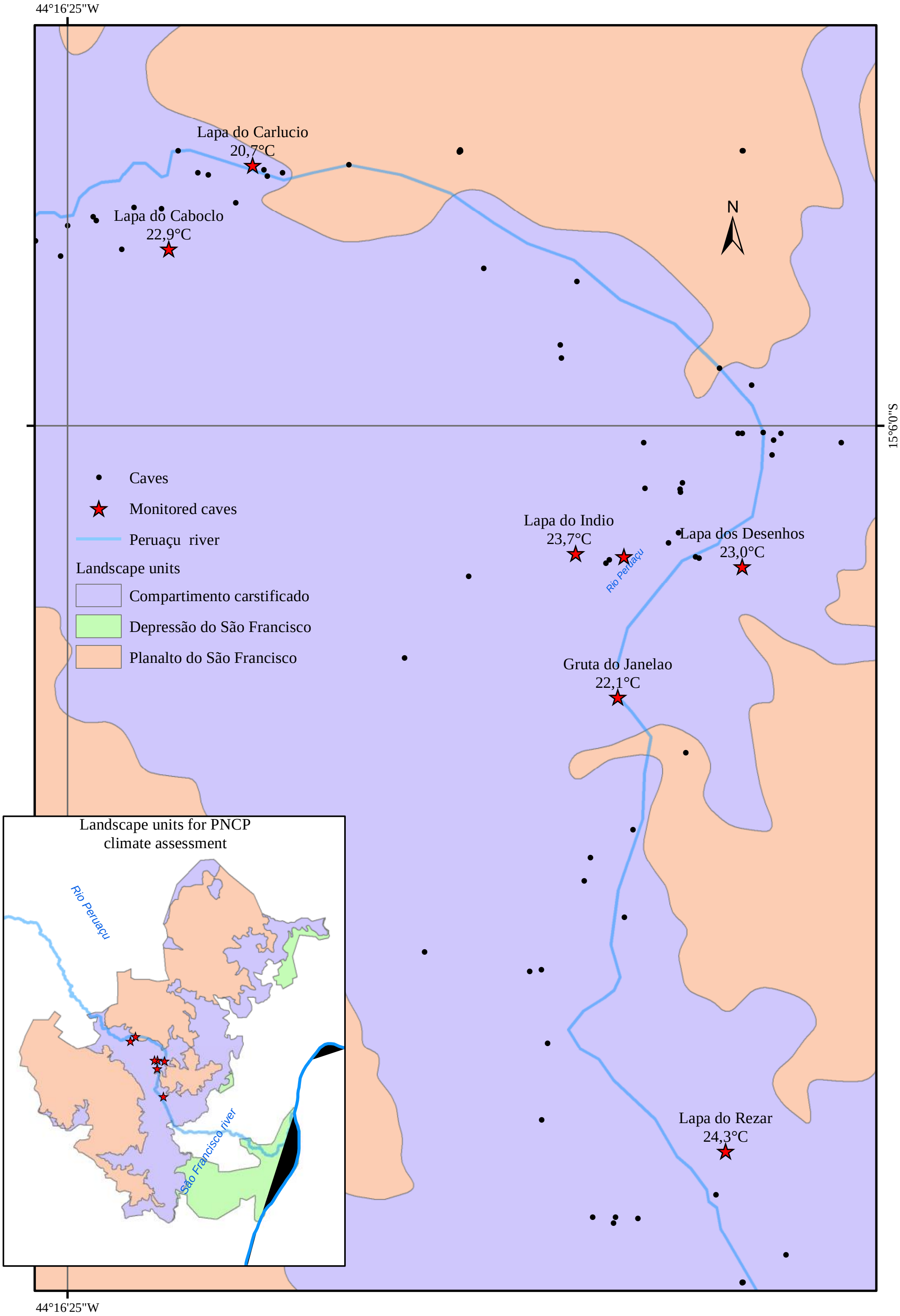
Source: By the authors.

For Lapa Bonita, it is important to highlight that the distance between the internal and external meters is no more than 15 metres. In the case of Gruta do Janelão, the high amplitude (26.0 °C) recorded by the JAN2 sensor is noteworthy. This equipment is installed in the median portion of the cave, at the base of a skylight of large dimensions, formed by the debasement of the cave roof, known as Dolina dos Macacos. This opening, considered another entrance, makes this sector of the cave more susceptible to variations in the external climate.

According to Serafini-Júnior (2005), the characteristics of the geomorphological compartments act as agents supporting the physiographic manifestations involving the plant and human communities of the PNCP. From this premise, the author proposes three landscape units considered homogeneous for study of the climate (Figure 4). The Planalto do São Francisco, a unit that approximately covers the geomorphological limits of the Planalto das Gerais and the Zona de Transição, is that which has the lowest temperature values and the highest humidity values, on average. The Compartimento Carstificado, which is the region where the caves in this study are found, had intermediate temperature and humidity values. The Depressão do São Francisco unit corresponds to the region with the highest temperatures and the lowest relative humidity.

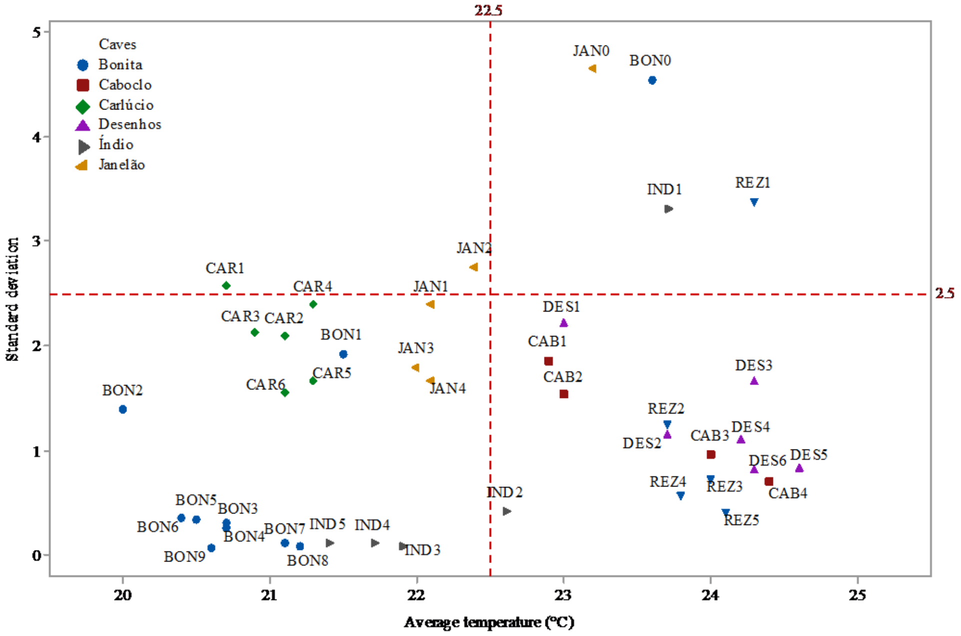
Lobo (2012) uses the term “Heterothermic Zone” to designate the region of the cave where the effects of external atmospheric influence on the cave microclimate are most perceptible. The positioning of the measuring stations near the entrances of the caves aimed to contribute to characterising climate conditions in this sector of the cave. In Table 2, the CAR1 equipment recorded the lowest average temperature (20.7 °C) among all the entrances to the monitored caves. It is emphasized that, taking the canyon of the Peruaçu River as reference, Lapa do Carlúcio is the cave closest to the Planalto do São Francisco compartment, which is the region with the mildest temperature. On the other hand, the highest average temperature (24.3 °C) was found at REZ1, and Lapa do Rezar is that which is closest to the warmer climate of the Depressão do São Francisco, situated at the entrance to the Peruaçu Canyon. Figure 4 highlights the insertion of the caves on the relief and enables comparison between the average temperature values recorded on the internal sensors installed closest to the cave entrances. The differences in temperature as a result of alterations in the relief, perceived by Serafini-Júnior (2005) when studying the external environment in the PNCP, can also be observed in relation to the entrance halls. The values recorded in this section of the caves, show a discrete tendency (R^2=0.3763) of increase in average temperatures as we move from the Planalto dos Gerais compartment to the Depressão do São Francisco compartment, descending the course of the Peruaçu River.

Figure 4 - Landscape units used for the study of the climate in the PNCP (Serafini-Júnior, 2005), with emphasis on the disposition of the monitored caves along the Peruaçu River Canyon and the respective average temperatures measured at each entrance.



Source: By the authors.

Figure 5 – Analysis of the standard deviation according to average temperatures for the data collected in the monitored caves.



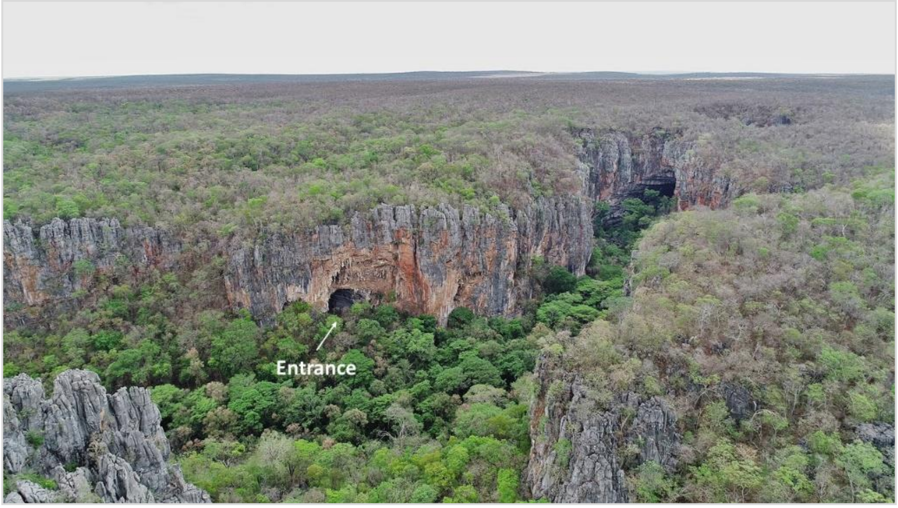
Source: By the authors.

Analysis of the averages and standard deviations highlighted the variations in temperature in the external stations (BON0 and JAN0) and in the entrance areas in relation to the other sections of the caves (Figure 5). In this Figure it is possible to observe three distinct patterns in relation to internal temperature behaviour. Lapa do Carlúcio and Gruta do Janelão have the highest standard deviation in each measuring station and average temperatures below 22.5 °C.

Lapa do Carlúcio (Figure 6) is located on the mid-slope of the Peruaçu River Canyon, in the midst of riparian forest present on the fluvial channel, where there is a predominance of evergreen vegetation due to the presence of the river (IBAMA, 2005). This factor, along with its proximity to the Planalto dos Gerais compartment, influenced the occurrence of milder temperatures, as identified by Serafini-Júnior (2005). The temperature records at its entrance (CAR1) have one of the highest standard deviations (12.40), although its average temperature (20.7 °C) is the lowest when compared to the other cave entrances. This cave, with its entrance of approximately 20 m high and 40 m wide, is formed from an ample conduit with 160 m horizontal projection. Its initial stretch has an approximate height of 30 m and extends for 100 m. After an inflection, this conduit is directed to the east for another 60 m. These dimensions and the absence of significant physical barriers in its interior favour large temperature variations at its entrance.

As with Lapa do Carlúcio, Gruta do Janelão also has a large variation in average temperature, indicating a strong influence of the external climate along the entire length of the cave. This cave has sectors with more than 100 m in height, reaching widths of 150 m at some points, and with skylights of expressive dimensions. These attributes, in addition to the presence of the Peruaçu River, contribute to explaining the internal temperature variation. In Gruta do Janelão, the large variations observed at station JAN2 deserve mention. Among all the monitored caves, this is the only one with multiple entrances as a result of the presence of various skylights. The equipment in question was installed at the bottom of the Dolina dos Macacos, close to the left bank of the river. As a result of the expressive dimensions of the skylight, this place receives direct solar radiation for many hours a day, which explains the large variations in temperature and the recording of the highest temperature (39.0 °C) among the measuring stations.

Figure 6 - Aerial view of the entrance to Lapa do Carlúcio highlighting the riparian forest of the Peruaçu River at the bottom of the canyon.



Source: By the authors.

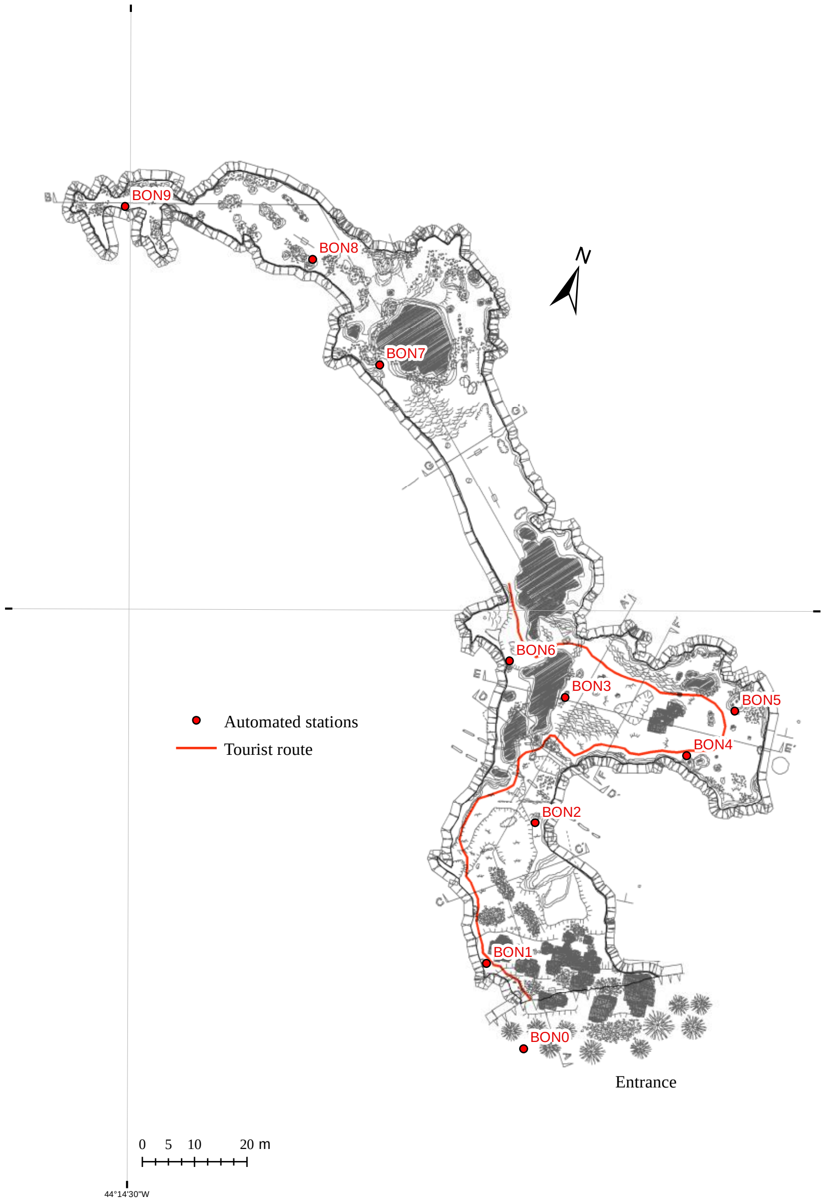
Also, in relation to Figure 5, another pattern of behaviour can be observed, represented by Lapa Bonita and Lapa do Índio, characterized by presenting the lowest average temperatures and the lowest standard deviations. The behaviour of the climate conditions observed in these two caves is that which most approximates to the climate zoning model proposed by Lobo (2012). The two caves are located in the Fazenda Terra Brava depression, at the base of a limestone escarpment, where there is a noteworthy area of extensive pasture and a straight line of *Mata Seca*, which marks the transition from the pasture to the wall (Figure 7). Lapa Bonita has 420 m horizontal projection and a rectilinear pattern. The entrance hall occupies the first 45 m of its development and is where the BON1 and BON2 stations are installed (Figure 8). The two stations have standard deviation values of 1.92 and 1.39, respectively, which indicates that this section of the cave is still reasonably influenced by the external environment and could be classified as a Heterothermic Zone.

Figure 7 - Aerial view of the entrance to Lapa Bonita located in the karstic depression of Fazenda Terra Brava.

Source: By the authors.

After the place where BON2 is installed, the cave has a large deposit of chemical sedimentation causing a significant narrowing of the conduit. After, it is possible to access large halls where BON3, BON4, BON5, and BON6 are located, where lower average temperatures were recorded (20.7 °C, 20.7 °C, 20.5 °C and 20.4 °C, respectively) and the standard deviations were lower than those observed in the entrance hall (0.31, 0.26, 0.34, and 0.36, respectively), characterizing what could be considered an Unsaturated Transaction Zone described by Lobo (2012). In the final third of the cave, after the place known as Salão Vermelho (The Red Hall), is the sector with the lowest temperature variations and where BON7, BON8, and BON9 are installed. This last segment of the cave has slightly higher average temperatures than those observed in the intermediate section (21.1 °C, 21.2 °C, and 20.6°C, respectively), though the values remained practically constant throughout the investigated period. The low standard deviation values observed at BON7 (0.12), BON8 (0.08), and BON9 (0.07), contribute to what can be considered the Homeothermic Zone of Lapa Bonita.

Figure 8 - Spatial distribution of the automated stations in Lapa Bonita.



Source: Adapted from IBAMA (2005).

The observations referring to the microclimate behaviour of this cave corroborate the results of Gomes et. al. (2019) in respect to the tendency of diminishing external climate influence with distance from the entrance. With more consistent data, the results of the present study also confirm that the temperature and relative humidity values have much lower variations than those observed in the external environment.

Despite being located very close to Lapa Bonita (308 m), Lapa do Índio is inserted at a higher point of the limestone outcrop, a little above the tree canopy, its entrance being more exposed to insolation and wind circulation. These factors combined with the presence of a low roof at the entrance (less than 4 m), contribute to explaining the higher standard deviation at IND1 (3.31), when compared to that observed at BON1 (1.92).

As with Lapa Bonita, Lapa do Índio has a significant narrowing of the conduit after the place where the IND1 station is installed. The records obtained on this equipment enable the observation of a much higher standard deviation that that observed on IND2 (0.42). After this site and the transposition of another stretch with a low roof, are the other sensors, IND3, IND4, and IND5, which recorded even lower standard deviation values (0.08, 0.11, and 0,12, respectively).

The third temperature behaviour pattern can be observed in Lapa do Caboclo, Lapa dos Desenhos, and Lapa do Rezar (Figure 5). These caves have intermediate standard deviation values when compared to the other caves, demonstrating that the external influence is not as accentuated as that observed at Lapa do Carlúcio and Gruta do Janelão, and not as discrete as that observed at Lapa Bonita and Lapa do Índio.

Regarding relative humidity, Serafini-Júnior (2005) highlights that two distinct scenarios can be observed in the PNCP. The summer includes the months from December to March and is also the rainy season. Winter begins in June and finishes in September and is also the dry season. Table 3 shows the data collected in the caves, grouped considering these two periods. When comparing the mean values of relative humidity in the two periods, significant differences between the rainy period and the dry period are evident for almost all the sampled points.

The only exception is the last hall of Lapa Bonita, where the relative humidity value remained practically constant during the entire evaluation period. The confined environment, with an area of approximately 30 m² and less than 1,60 m in height, only connects to the rest of the cave through a centimetric space existing between a set of columns, stalactites, and stalagmites. This may be the main reason for having observed such low standard deviation values (0.94 in the rainy season and 0.90 in the dry season) and very high relative humidity values, close to 100 %, at point BON9 during the entire research period.

Even considering the peculiarities of each cave, it can be observed that in the rainy period (Figure 9a) practically all the sampled points have relatively high humidity values (above 70 %). However, in the dry period (Figure 9b), except for certain points in Lapa Bonita and Lapa do Índio that remained above 70%, the other stations recorded low relative humidity values, reaching close to 45% at Lapa dos Desenhos and Lapa do Caboclo.

Table 3 - Relative humidity records discriminated by season into dry and rainy periods.

Stations		Rainy period		Dry period	
		Average humidity (%)	Standard deviation	Average humidity (%)	Standard deviation
Carlúcio	CAR1	83.5	10.65	66.7	9.23
	CAR2	82.5	10.08	64.6	8.33
	CAR3	82.6	10.10	65.4	8.56
	CAR4	81.9	12.14	64.7	10.38
	CAR5	80.6	10.17	62.2	8.42
	CAR6	82.4	10.44	63.0	7.96
Caboclo	CAB1	78.8	12.19	54.6	9.08
	CAB2	76.4	10.20	55.0	7.45
	CAB3	71.2	11.10	48.7	7.55
	CAB4	70.4	10.33	47.7	6.80
Desenhos	DES1	78.9	11.28	53.8	9.64
	DES2	72.7	10.72	48.4	7.82
	DES3	72.3	11.72	49.0	8.66
	DES4	71.7	10.56	48.2	7.61
	DES5	69.9	10.41	45.7	7.41
	DES6	71.9	10.68	47.4	7.34
Bonita	BON0	75.8	21.42	53.2	16.96
	BON1	83.1	11.02	60.0	9.83
	BON2	91.5	5.63	72.7	7.16
	BON3	91.7	1.39	68.7	5.99
	BON4	93.4	2.25	69.0	6.27
	BON5	96.2	2.08	74.1	6.23
	BON6	94.7	2.42	71.8	7.04
	BON7	91.8	1.43	71.0	5.39
	BON8	94.2	0.65	75.8	4.87
	BON9	98.9	0.94	98.7	0.90
Índio	IND1	74.9	15.57	53.2	12.93
	IND2	80.4	9.35	60.0	8.59
	IND3	88.3	7.15	70.9	6.44
	IND4	87.2	8.26	70.7	7.75
	IND5	88.7	8.19	73.0	7.26
Janelão	JAN0	79.7	19.55	57.0	17.41
	JAN1	82.7	11.76	64.1	10.70
	JAN2	80.7	10.67	66.5	9.73
	JAN3	83.2	9.34	63.8	9.14
	JAN4	82.7	9.17	63.1	8.31
Rezar	REZ1	73.6	18.26	53.6	14.03
	REZ2	72.3	10.92	51.5	8.48
	REZ3	70.3	9.75	52.1	7.76
	REZ4	69.3	9.19	48.8	6.86
	REZ5	71.0	10.37	48.2	6.87

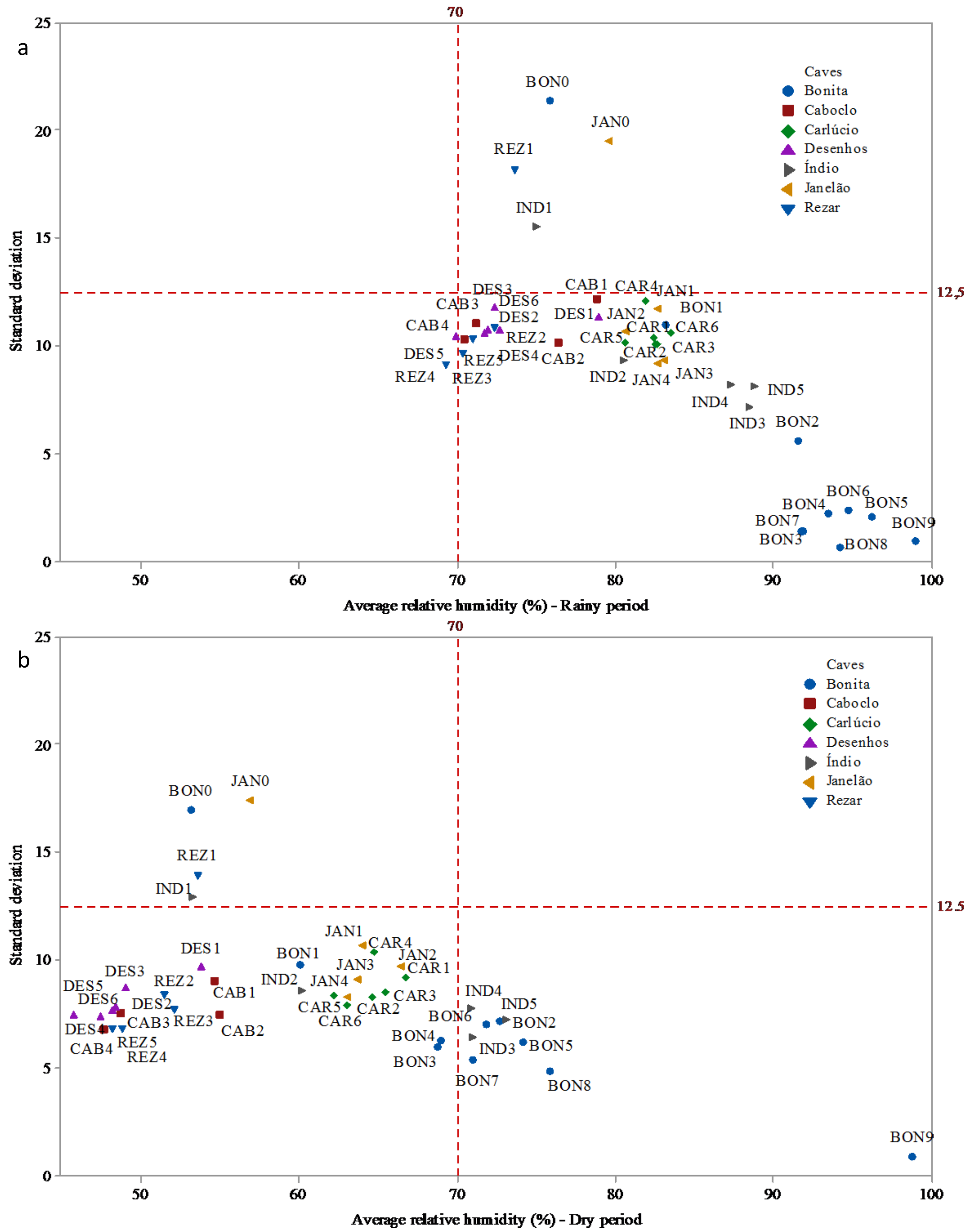
Source: By the authors.

Cave groupings can also be perceived when analysing the data on relative humidity. Influenced mainly by external conditions, the sensors positioned at the entrances to Lapa do Índio (IND1) and Lapa Bonita (BON1) have the highest standard deviations when compared to the other meters installed in these caves, be it in the rainy period (IND1=15.57 and BON1=11.02), or in the dry period (IND1 = 12.93 and BON1=9.83). However, as distance in relation to the entrances increases, the variations become smaller and smaller. This condition makes it possible to join the two caves in a group characterised by lower standard deviation values and higher relative humidity values, both in the rainy period (Figure 9a), and in the dry period (Figure 9b). In this group, the behaviour observed at station IND2 is noteworthy (standard deviation of 9.35 in the summer and 8.59 in the winter), as despite being located after the narrowing of the conduit between the entrance hall and the second hall, it is still subject to great external influence. Lobo (2013) highlights the influence that spatial confinement exerts on the variability of cave climate parameters, and as such, it is possible to emphasise the behaviour observed in Lapa Bonita, where an existing obstruction between the entrance hall and the rest of the cave is largely responsible for hampering the process of energy exchange with the external environment. This characteristic is the most responsible for maintaining humidity above 90 % during the rainy season and with an average above 68 % in the dry season. Figures 9a and 9b also demonstrate the high relative humidity values and very discrete variations in standard deviation of the parameter observed in the final section of the cave (BON9) during the research period. Therefore, this hall can be considered the environment that has the most homogenous conditions of temperature and relative humidity among all those evaluated in this study.

Upon verifying the average relative humidity of the other caves, it is possible to identify two more groupings, in addition to that represented by Lapa Bonita and Lapa do Índio. One of the groups contains Gruta do Janelão and Lapa do Carlúcio with records of humidity between 83.5 % and 80.6 % in the rainy period (Figure 9a) and 66.7 % and 62.2 % in the dry period (Figure 9b), constituting the group with intermediate average relative humidity values. In this group, it is noteworthy that the values are very similar for both caves in both seasons, demonstrating the little influence that the Peruaçu River exerts on the relative humidity of Gruta do Janelão, which has an environment with high energy exchange with the external environment as a result of its multiple entrances (skylights), in addition to the presence of the river.

The third group of caves is composed of records obtained from Lapa dos Desenhos, Lapa do Rezar, and Lapa do Caboclo, which are characterized as the caves with the lowest relative humidity values among the studied caves. In this group, values varying between 78.9 % and 69.3 % in the rainy period (Figure 9a) and 55.0 % and 45.7 % in the dry period (Figure 9b) were observed. It is worth emphasising that among all the studied caves, Lapa do Rezar is that which is found closest to the Depressão do São Francisco (Serafini-Júnior, 2005) and would be, therefore, more susceptible to the influence of the drier climate of this landscape unit than the other caves. Thus, it was found that the lowest relative humidity averages among the three cave entrances were observed on the meter installed at the entrance to this cave (REZ1), with 73.6 % in the rainy period and 53.6 % in the dry period. However, Lapa dos Desenhos and Lapa do Caboclo also had values as low as Lapa do Rezar and are not as close to the Depressão do São Francisco unit. In this case, the explanation may be associated with the morphology of the caves, as both are characterized by a single, rectilinear conduit with a length of less than 140 metres, being the smallest of the investigated caves. The absence of large obstacles favours the circulation of wind and the exchange of energy with the external environment.

Figure 9 – Analysis of standard deviation according to relative humidity measurements for the data collected from the monitored caves. a) Rainy period; and b) Dry period.



Source: By the authors.

FINAL CONSIDERATIONS

The Karstic Valley of the Peruaçu River and its diverse associated attributes (speleological, landscape, cultural, archaeological, and palaeontological) compose one of the most representative natural conjunctions in the country. The singularity and relevance of these characteristics highlight the importance of implanting surveillance measures with the aim of compatibilization between touristic use of the resources and their conservation.

Minas Gerais is currently the state with the highest number of known caves in Brazil and this study is pioneering in the state, not only for gathering data collected over a little less than three years, but also for considering many caves monitored simultaneously. When observing the spatial distribution of research related to cave microclimates in Brazil, this study also stands out for being one of the only studies in the country on microclimate behaviour in caves situated in a more arid climate.

Therefore, when characterizing the microclimate of seven of the eleven caves that are part of the tourist itinerary in the PNCP, the present study provides support for the improvement of visitation guidelines for these attractions, as well as rescaling the internal visitation routes. In addition to this contribution, it is important to highlight that the methodological proposal of cave microclimate monitoring may serve as reference for the elaboration of the Programa de Monitoramento das Condições Ambientais das Cavernas (Cave Environmental Conditions Surveillance Programme) foreseen in the UC management plan. By the end of 2019, this investigation had already generated more than 4 million records on temperature and relative humidity. The project is scheduled to finish at the end of 2022, which will enable the formation of a robust database and the development of various products to support the public use of the attractions in the PNCP, such as the microclimatic zoning of the caves.

The results of the present study confirm the external influence on the behaviour of the cave microclimate already shown in caves in countries with a temperate climate and in other regions of Brazil with a milder climate. It was also observed that there was a tendency towards microclimatic stability in the more distal halls of the caves. Despite the increase in the number of tourists in the caves of the PNCP, collection of data on visitation is still very incipient. Information related to the entrance and exit times, as well as the quantity of people that effectively enter the caves still need to be better ascertained. Thus, actions are being developed with the administration team of the UC and the guides that operate in the unit so that this process is improved. Therefore, by the end of the project in 2022, it will be possible to obtain reliable data, which will enable the development of deeper studies to verify the influence of human presence on the behaviour of temperature and relative humidity in the caves of the PNCP.

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AUTHORS' CONTRIBUTION

MG Study design, data collection and analysis and text writing. D.J.S. Data collection and analysis and text writing. U.R.A. and L.E.P.T. Data collection and text writing.