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THE IMPORTANCE OF AIR TEMPERATURE AS A KEY PARAMETER TO IDENTIFY CLIMATIC PROCESSES INSIDE CARLSBAD CAVERN, NEW MEXICO, USA

M. Killing-Heinze[1], Andreas Pflitsch[1, C], Wilhelm Furian[2], and Stan Allison[3]

Abstract

The meteorological and climatic conditions in Carlsbad Cavern are very complex. The huge rooms and the large entrance area, in combination with smaller connection tunnels and remote chambers, cause a complexity of different microclimates side by side. As in the case of most others, Carlsbad Cavern is not easy to classify as a barometric or a convective cave system. The objective of this paper is to explain the climate at different positions inside Carlsbad Cavern by evaluating a series of measurements taken during the year 2013. The air temperature will be used as a key parameter for the analysis. We will identify the thermal- or convection-driven influences, as well as some clear barometric effects and underline the importance of air temperature for cave climate research. We will also investigate the influence of the tourist use of the cave, which means the visitors themselves, as well as the elevators, the cafeteria, and the electrical system and lights. Because the analyzed time period includes the time of the government shutdown in 2013, the artificial effects can be identified very easily.

Introduction

Carlsbad Cavern is one of the largest show cave systems of the United States and receives an average of 400,000 visitors a year (National Park Service, 2013). Located in the Guadalupe Mountains of southeastern New Mexico, it is famous for its variety of speleothems and particularly for the Big Room, once the largest known underground chamber in the world and still the largest in the US (National Park Service, 2014). Due to its complexity, some parts of the cave are strongly influenced quickly by the outside weather conditions, while other parts show more long-term signals. Because of the heavy use and the anthropogenic modifications, the cave climate of Carlsbad Cavern is subject to continuous disturbance.

Show caves often are exposed to various human influences: artificial cave lighting can heat up and dry the air and promote lampenflora growth (Parise 2011), enlarged and artificial entrances and access routes may alter the airflow, and the respiration and body heat of a large number of visitors can lead to an increase in air temperature and CO_2 levels (Baker and Genty 1998). The results often lead to an irreversible degradation of the speleothems and the whole ecosystem (Cigna and Forti 1986). Therefore the importance of sustainable use to maintain an undamaged cave environment is stressed (Cigna 2005; de Freitas 2010).

To ensure a balance between visitor experience and sustainable use of the cave, it is of great importance to understand the climatic processes inside Carlsbad Cavern. This work aims at contributing to this issue by concentrating on the following four questions:

What is the recent climatic situation in Carlsbad Cavern? How does the outside weather influence the cave climate in the different parts of Carlsbad Cavern? Which role does the air temperature play in the interaction of the climate parameters? To what extent is the cave climate influenced by anthropogenic modifications and tourists?

To answer these questions, we evaluated the results of a series of measurements that were taken during the year 2013 at different points inside the cave. By employing highly sensitive temperature sensors, we were able to capture very subtle variations in the air temperature of Carlsbad Cavern. In this paper, we describe the air temperature in every monitored part of the cave and discuss its importance for the cave climate. The results of the analysis are placed in the overall context of the Carlsbad Cavern cave system. Finally the influence of the tourist development is clarified by concentrating on two weeks in October 2013 when the whole cave was closed to visitors. In conclusion, there is a detailed description of the current “anthropogenic” cave climate inside Carlsbad Cavern, as well as some information on what the original cave climate might have been before its development into a show cave.

Research Area

The Structure of Carlsbad Cavern

The Natural Entrance of Carlsbad Cavern is located at 1300 m a.s.l. and is the highest point of the cave. Beneath the entrance the cave divides into the Bat Cave, home to one of the largest bat colonies of the US and closed to visitors,

[1] Department of Geography, Ruhr-Universität Bochum, 44780 Bochum, GERMANY
[2] Department of Geography, Humboldt-Universität zu Berlin, 10099 Berlin, GERMANY
[3] Stan Allison, Cave Specialist, 901 N. Thomas Street, Carlsbad, NM 88220, USA
[C] Corresponding Author: andreas.pflitsch@rub.de

and the steep Main Corridor leading to deeper levels of the cave. Following Hill (1987), the cave can be divided into four levels: the Bat Cave Level, the New Section Level, the Big Room Level, and the Lower Cave Level (see Fig. 1).

The dominant Big Room Level comprises, besides the eponymous Big Room, for example the Left Hand Tunnel, the upper section of the Mystery Room, and the New Mexico Room. The Lower Cave Level includes the Lake of the Clouds, located at 316 m below the entrance (McLean, 1971), which forms the deepest known section of Carlsbad Cavern. All chambers and tunnels combined extend to a total length of nearly 50 km (National Park Service, 2015).

Previous Research

The following section contains the chronology of previous research done on the cave climate of the Carlsbad Cavern. (Due to the linguistic skills of the authors, we focus on texts published in English and German, although there might be excellent papers written in other languages.) In the 1950s, the geology and speleogenesis of the Carlsbad Cavern became a subject of increased scientific research; Hill (1987) provides a more detailed bibliography about geological research. But it was not until about 1970 that the cave's climate was intensely studied by the U.S. Geological Survey and the National Park Service.

The first results of this cave climate monitoring program were presented by J.S. McLean in a progress report (McLean, 1970 in Hill, 1987). McLean further analyzed the drying of cave pools in his article "The Microclimate in Carlsbad Caverns, New Mexico" (1971). After a detailed analysis of the cave's climate parameters he ascribed the changes in the cave climate leading to the drying of some cave pools to anthropogenic factors such as cold air circulation through the elevator shaft and increased evaporation due to heat from the installed lighting system. As a result of his work, some alterations, most importantly equipping the bottom of the elevator shafts with revolving doors and installing more efficient light bulbs, were made to minimize the anthropogenic effect on the cave climate.

McLean (1976) came to the conclusion that the microclimate of the cave primarily depends on the variation in the air temperature outside the cave. Also in 1976, Ahlstrand and Fry pointed out the potential risk of the high radon levels

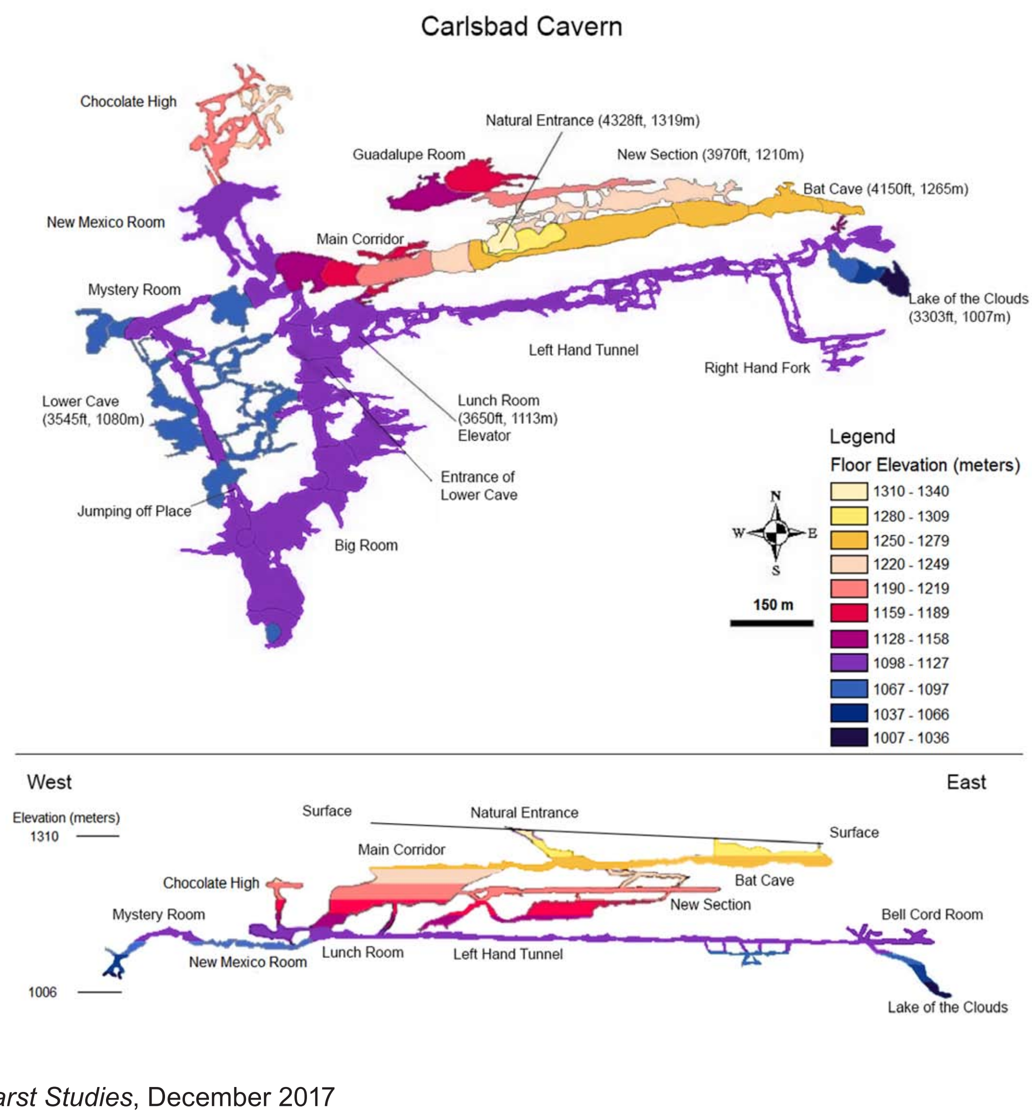

Figure 1. Plan view of Carlsbad Cavern and profile of its northern part, adapted from a figure provided by the Cave Research Foundation.

inside the cave. They presented an overview on the temperature profile of the cave air and conjectured the existence of undiscovered openings at lower levels to explain low radon levels.

Wilkening and Watkins (1976) explained the levels of radon concentrations in the cave by concentrating on how natural ventilation affects the concentration of radon. The assumption of a convective circulation system in most parts of Carlsbad Cavern was confirmed. Furthermore, the authors emphasized the importance of the transition months during the fall and the spring to the cave climate and the possible alteration of air currents inside the cave. From measurements of the radon concentration Ahlstrand (1980) ascribed the air currents inside Carlsbad Cavern solely to convective effects.

Shindo (2005) explained some phenomena of the cave climate using computer modeling. This extensive work quantifies many climatic processes and contains detailed models of airflows and temperature gradients throughout the cave system.

Schwabe (2013) discusses the dependence of the thermal dynamic of the cave climate on the outside weather. The result is a nuanced analysis of the thermodynamic conditions that explains the different air temperatures and circulation systems in great detail.

The Climate of Carlsbad Cavern

The climate of the Guadalupe Mountains and the associated Chihuahuan desert is semiarid with mild winters and warm summers. The majority of the average annual precipitation of 360 mm falls during the monsoonal summer months, when thunderstorms lead to short, but fierce, rainfall events that often create flash floods.

The annual average air temperature in Carlsbad Cavern is about 13.3 °C, but with fairly big variations. For example the average temperature at the far end of the Left Hand Tunnel (17 °C) is much higher than at the Devil's Spring, where the annual average is about 11 °C.

The main air exchange between cave air and the free atmosphere takes place through the Natural Entrance, which is 20 m wide and 12 m high and is the largest cave opening (West, 2011). Even though this opening seems very large, there is still a huge discrepancy between its size and the volume of the cave system beyond. Therefore, changes in the atmospheric pressure lead to the development of a (mostly) short-time barometric circulation, as immediate pressure compensation is not possible.

More important for the cave climate is the convective system of airflow. With elevation differences of approximately 300 m, large parts of Carlsbad Cavern, especially the Big Room, can be characterized as an ice cellar type according to Trimmel (1968). Fostered by the slope of the Main Corridor, cold air flows into the Big Room during winter, replacing warmer, moister air. Because of the reduced air exchange between the cave and the outside during the summer months and because of the absence of a lower opening where cold air could flow out of the cave, the Big Room becomes a cold trap.

Figure 2 shows the dominant directions of cold and dry winter air currents as assumed by Hill (1987) after the examination of the orientation of popcorn speleothems. Recent research (Schwabe, 2013) confirms these results.

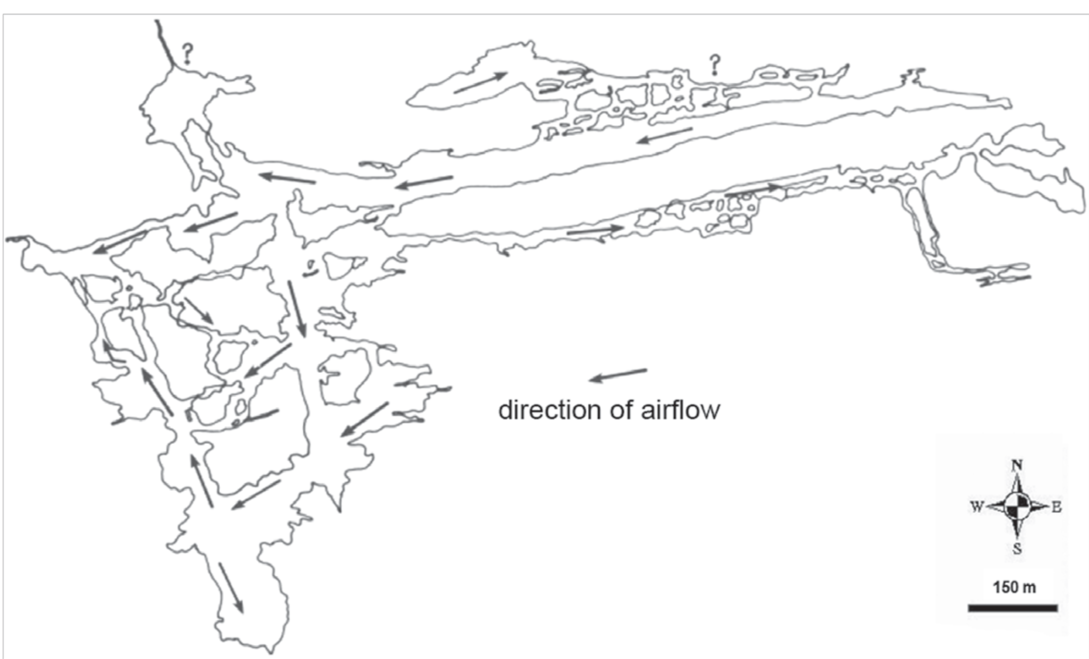

Figure 2. Dominant direction of convective flow of cold air into the cave during winter.

Methods

This paper relies on data from a cave climate monitoring program in Carlsbad Cavern. Since 2009, this program has monitored the temperature and humidity of the air inside the cave by employing wireless data loggers developed by the German company GeoPrecision. Normally, the M-Log5W logger is able to record the air temperature with a resolution of up to 0.01 °C and a precision of ± 0.1 °C. For this program, the M-Log5W loggers were optimized by removing the metal sleeve of the sensor. Without this attenuation, each logger's sensitivity and reaction rate was increased, making it possible to measure even the smallest variations.

To study the climate of Carlsbad Cavern as accurately as possible, seven loggers were placed inside the cave system (Fig. 3). To be able to draw comparisons between the outside weather and possible related alterations of the cave climate, one data logger was positioned on the surface near the Cave & Karst Resource Management offices, 2 m above the ground.

At Devil's Spring, a pool near the Natural Entrance, two data loggers were positioned, the first one at a height of approximately 20 cm, the second one close to the ceiling about 10 m above the ground. Thus, not only could the near ground cold air entering the cave be measured, but also the warm outflow of air near the ceiling.

A part of Carlsbad Cavern that is only visited once a day by a ranger-guided tour is the long, straight, and partially very narrow Left Hand Tunnel. Because of its shape, the air temperature in this area was monitored by two data loggers. The first (LHT-F) was placed near the ground at the junction of the Underground Lunchroom and Left Hand Tunnel, while the second (LHT-B) was positioned at the narrowest passage of the Left Hand Tunnel at some distance beyond the end of the tour route so that a part of the cave that is not subject to tourist use could be involved in the analysis.

The air temperature in the Papoose Room, a part of Carlsbad Cavern only open to five ranger-guided King's Palace tours a day, was measured by a data logger placed above an excavated tunnel between two smaller chambers. Previous studies have shown a frequent increase in wind velocity at this point (Furian and Weigel, 2013). The data logger in the Big Room was placed near the floor at a height of 20 cm at a very central spot in the large chamber.

The seventh data logger was installed in the Lower Cave to evaluate air movement in a deeper part of the cave system. During data collection, it was observed that the measurements of this data logger were faulty and could not be adjusted manually. So the analysis of the cave climate inside Carlsbad Cavern draws on the data collected by the remaining six data loggers.

Every data logger was programmed to create a very detailed record of the air temperature at its respective position from February 2013 to January 2014. The data loggers were set to measure the air temperature every five minutes. These are the first high-precision temperature data in Carlsbad Cavern.

Results

Outside Weather and Devil's Spring

The following paragraphs give an overview of the weather in Carlsbad Caverns National Park during the year 2013 and its impact on the cave climate. It relies on data provided by the data logger outside of the cave and the ones near Devil's Spring.

Figure 4 illustrates how the air near ground level at Devil's Spring is influenced by the variations of the outside weather. During the winter months, when cold air flows near the ground into the cave, the similarity of the two curves shows the influence of the outside weather, at least at this point of the cave. However during the summer, when rising temperature leads to reduced air exchange between the cave and the surface atmosphere, the climate at Devil's Spring is independent of variations of the outside weather. Daily fluctuations have hardly any impact on the air temperature because a temperature inversion around the cave entrance blocks any exchanges; only a slight upwards trend can be seen over the summer months. Even the short cold period in mid-July and the cooling in September with outside temperatures below the cave temperature had no impact on the cave. Only outside temperatures below 10 °C find their way deeper into the cave and reach the Devil's Spring area. So it can be seen that the cave climate can be divided into a stable summer phase and a more fluctuating winter period.

In Figure 5, the air temperature at the Devil's Spring is shown as a comparison between the ground and the ceiling. The fact that the air at the ground is colder than the air at the ceiling and that the winter cold air events are much more conspicuous near the floor make possible some conclusions about the direction of the airflow: colder air at the ground flows into the cave, replacing warmer air that then forms a convective compensation flow along the ceiling and out of the cave.

One particular phenomenon best seen in the summer is depicted in Figure 6. During midday the air temperatures at the ground and at the ceiling tend to converge. At the same time, there is an increase in the fluctuations of the air temperatures. This probably is a result of turbulent mixing moving cold air to the ceiling and warm air to the ground. This mixing develops during the summer months especially at noon, when high solar radiation leads to a turbulence in the

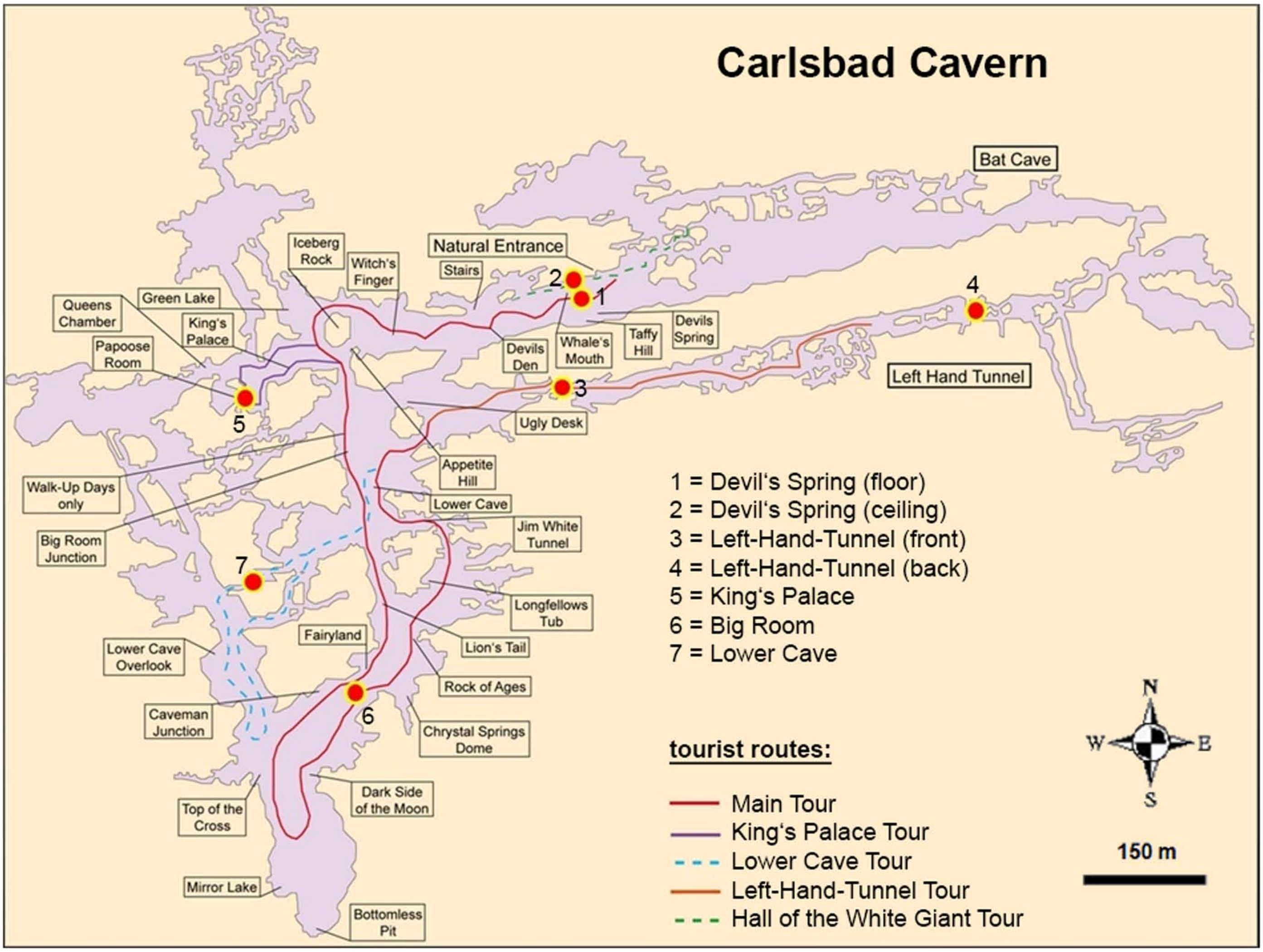

Figure 3. Positions of the data loggers used during the climate measurements inside Carlsbad Cavern and the various tourist routes through the cave system, adapted from a figure from the National Park Service.

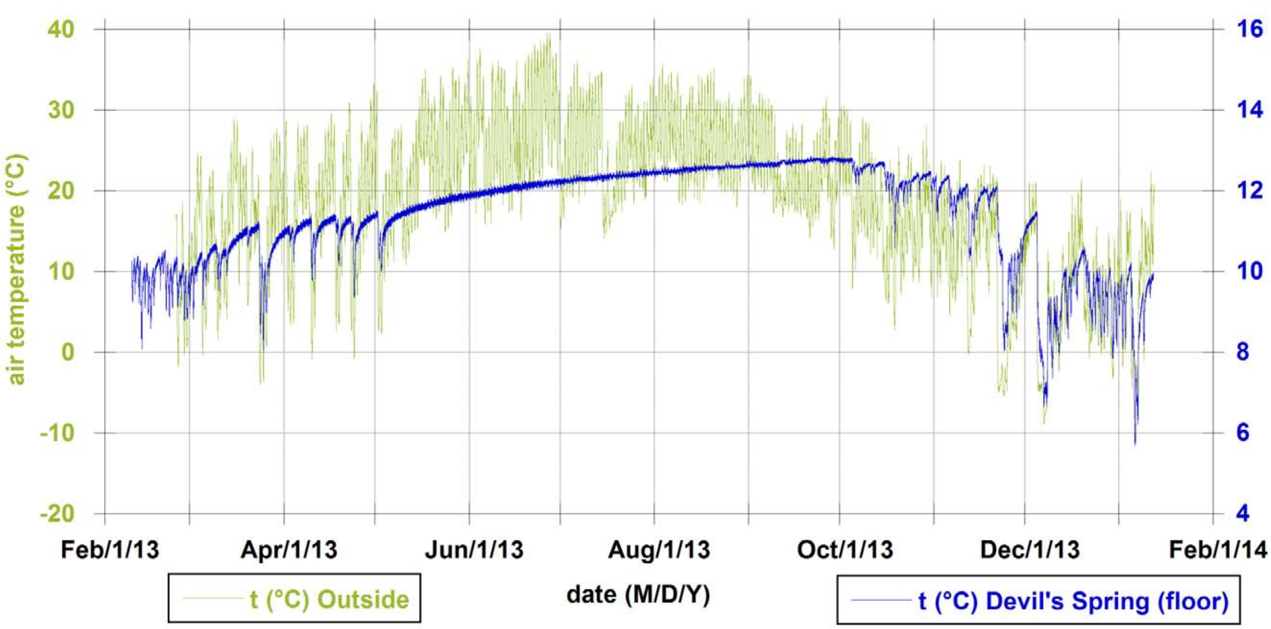

Figure 4. Records of the near-ground air temperature on the surface and near Devil’s Spring inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes.

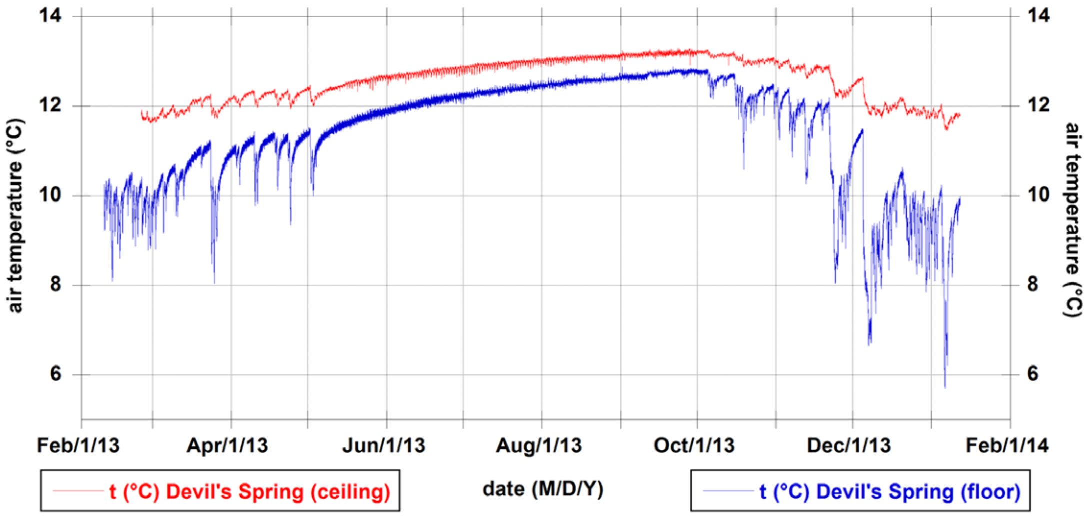

Figure 5. Records of the air temperature at the ground and the ceiling near Devil's Spring inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes.

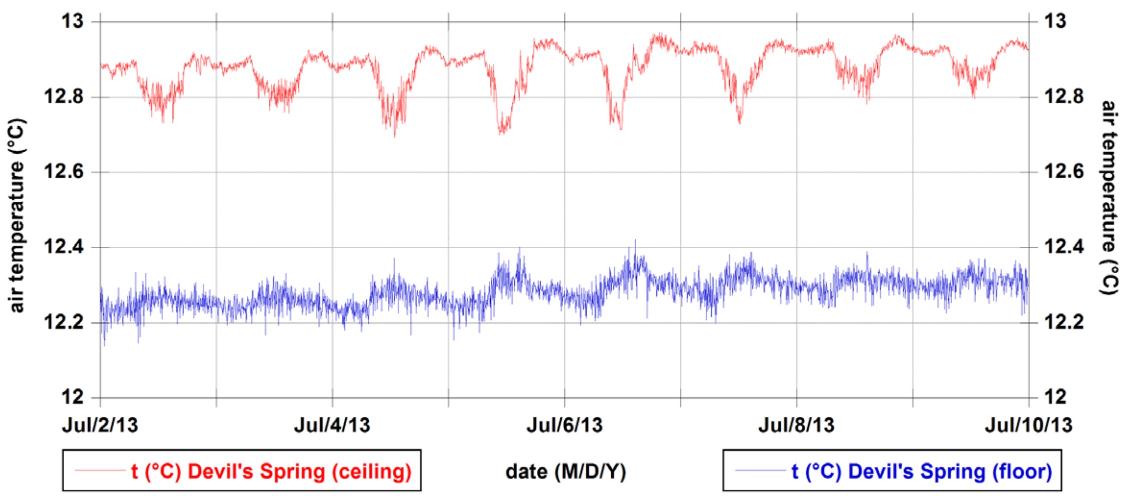

Figure 6. Records of the air temperature at the ground and the ceiling near Devil's Spring inside Carlsbad Cavern on an expanded scale from July 2 through July 9, 2013, recorded every 5 minutes.

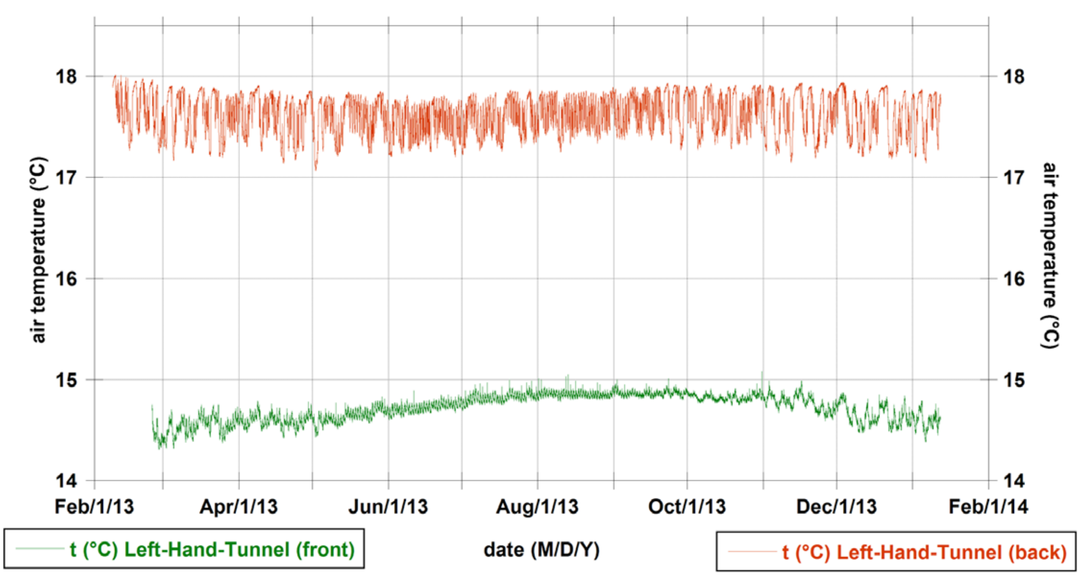

Figure 7. Records of the air temperature in the exterior (front, logger LHT-F) and the interior (back, logger LTH-B) parts of the Left Hand Tunnel inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes.

outside air that affects the air inside the cave, too. This assumption is supported by the fact that the maximum changes of the air temperature are reached shortly after noon when the solar radiation is greatest.

The Left Hand Tunnel

While the climate at Devil's Spring is highly influenced by changes of the outside weather because of its proximity to the Natural Entrance, this does not apply in a similar way to the rest of the cave system. In some areas in the very compartmentalized topography of Carlsbad Cavern far from the openings, the influence of the outside weather is much less distinct and the structure of the cave climate is far more complex. The Left Hand Tunnel is regarded as an example for these conditions.

The Left Hand Tunnel is not completely open to visitors, so data logger LHT-B could be positioned 200 m beyond the end of the tour route. The passage is not illuminated by any electrical lighting. The ranger guided tour that visits the tunnel once a day carries candle lanterns to create an impression of the cave exploration during the early 1900s.

Figure 7 shows that the Left Hand Tunnel is distinguished by a relatively large variety of climatic conditions. For example, the air temperature in the entrance part of the tunnel is approximately 3 °Celsius lower than in the interior part. On top of that, the amplitudes of the air temperature at the position of data logger LHT-B are remarkably high for a part of the cave that is so distant from the cave opening and is known as a cold air trap and also beyond an even colder spot. Another peculiarity of the cave climate in this part of Carlsbad Cavern can also be seen in Figure 7: the annual curve of the air temperature in the distant eastern end of the tunnel is shifted several months in comparison to the western end. Also unexpected is the greater amplitude of short-term fluctuations in the temperature deeper into the tunnel that are apparent in Figure 7, which is paradoxical. All this points out the special climatic conditions of the Left Hand Tunnel as explained here.

The very strong rise of the air temperature between LHT-F and LHT-B can be traced to its position inside a very narrow tunnel. While the sensor in the beginning of the Left Hand Tunnel near the ground and below the popcorn line is most affected by the cold air moving into the cave, the sensor deeper in the tunnel is influenced by the mixture of the near ground cold airflow and the warm air of the ceiling squeezed together in the small passage. This explains at least part of the strong increase of the mean annual air temperature, which is 14.7° C at LHT-F and 17.6 °C at LHT-B. Perhaps the high air temperature at the Lake of the Clouds—Hill (1987) quantified it as around 20 °C—beyond the Left Hand Tunnel plays a role in this, too.

The shifted annual curve with the lowest minima in May and the lowest maxima in June is probably caused by the particular structure of the Left Hand Tunnel, as well as by the course of the convective airflows between late fall and early spring. In the winter season, cold air entering the cave accumulates in so called cold air traps. The cooling of the cave during the winter does not happen in a few weeks. It starts in late fall with the cooling of just the entrance area. While the cold air warms up on the way into the cave, it does not reach the deeper regions instantly. With each cold air event, the cooling of the cave advances forward over the whole winter deeper into the cave. It lowers the air and rock temperature more and more in the entrance area and a cooling front invades the cave deeper and deeper. In spring, when the cold air events are less strong, but still present, they have no visible effect on the now cooled entrance area. Cooler air is still invading the deeper parts of the cave, however. Even when the warm air in spring affects the cold entrance area and warms it up slowly, the relatively cold front is moving in the relatively warm cave and cools it down until the summer season. Figure 8 shows this process.

While the air in the upper parts of the cave such as Devil's Spring is already warming up in spring, the air in the rear parts of the Left Hand Tunnel still cools down because colder air from the cold air traps is flowing into this part of the cave. It is not until summer that warmer air enters this area and leads to rising air temperatures.

The third point that has to be investigated is the high amplitudes measured by the sensor at LHT-B. Figure 7 shows a strong fluctuation of the air temperature that cannot be explained by a gravimetric inflow because it is well-marked throughout the year. To analyze this effect, it is necessary to take a look at the daily profile of the air temperature. In Figure 9, a double wave with two peaks per day attracts attention, visible in the data collected by both loggers LHT-F and LHT-B. This indicates a ventilation system that differs from the convective one described at Devil's Spring. If it is not convective, it can only be caused by barometric effects.

Long-lasting barometric ventilation systems develop mainly in parts of a cave where the large ratio between their volume and the diameter of their entrances inhibits a fast pressure equalization. The Left Hand Tunnel is an example of this phenomenon; a relatively large cave volume, including the Bell Cord Room, the Right Hand Fork, the Lake of the Clouds, and maybe other yet unknown passages beyond the Left Hand Tunnel, is separated by the small tunnel entrance from the rest of the Carlsbad Cavern.

It is known that besides its irregular variations caused by crossing cyclones and anticyclones the atmospheric pressure exhibits a nearly steady double wave with an amplitude of about one hectopascal (Sellick, 1947). Different authors agree that the highest pressures are reached at about 10 a.m. and 10 p.m. local time, while the lowest air pressures

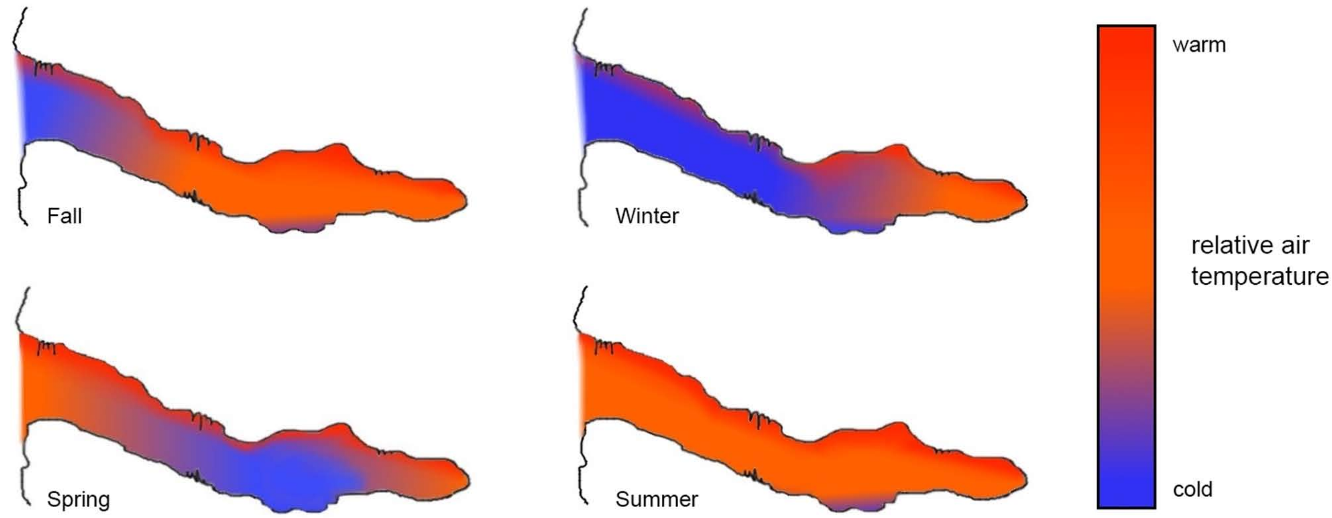

Figure 8. Schematic profile of the air temperature in a cold-trap cave influenced by the outside weather.

occur at 4 a.m. and 4 p.m. (e.g. Sellick, 1948; Carlson and Hastenrath, 1970; Nishina and Mikami, 2009). It can be seen in Figure 9 that the daily minima of the air temperature coincide with the daily peak of the atmospheric pressure and that the daily maxima of the air temperature occur during the times of the lowest air pressure. This conformity can only be explained by a barometric ventilation system. Once rising atmospheric pressure pushes air into the Carlsbad Cavern, colder air from the cold air trap is pressed into the Left Hand Tunnel and leads to falling air temperatures. In the reverse case, with low atmospheric pressure drawing air out of the cave, warmer air flows from the Lake of the Clouds or the Bell Cord Room into the Left Hand Tunnel, resulting in rising air temperatures. This, in comparison to the effects in the well-known barometric caves like Wind Cave and Jewel Cave in South Dakota (Pflitsch et al., 2010), seems to be relatively insignificant, but it explains a few climatic effects inside the Left Hand Tunnel and also for the whole cave.

Apparently the narrower parts of the Left Hand Tunnel are mainly ventilated by barometric airflows. However, this influence is vastly more distinct in the back end of the tunnel, because the anterior is affected by the convective ventilation from the entrance. As soon as the tunnel widens and there is enough room for a distinct airflow, as shown by the popcorn line, we can find the denser, cool airflow well-developed near the ground, where logger LHT-F was placed, and a more barometrically driven airflow near the ceiling. As shown in Figures 5 and 10a and 10b, this effect is very visible up to the Devil's Spring area. In Figure 5, the well-developed gravitational influence of the cold air stands in a strong contrast to the warm ceiling pattern. However, when compared with LHT-B the temperature data from the ceiling near the Devil's Spring shows a similar pattern (Fig. 10a).

By comparing the data from LHT-B and both temperature graphs of Devil's Spring (Fig. 10b), it becomes clear that the temperature near the ground is driven by the barometric pressure waves as well. This means that the warm air flowing out of the cave is not just pushed out by the cold air flowing in gravitationally in winter, but also influenced by barometric effects that pump warm humid air out of the deeper and remote areas beyond the Left Hand Tunnel. To summarize, the barometric airflows bring a second dynamic component to the climate in Carlsbad Cavern.

The graphs in Figure 10b show us some correlations. During high pressure and inflow situations the temperature is decreasing at the Left Hand Tunnel while the colder air from the main cave is flowing to the deeper parts. Close to the ceiling at Devil's Spring it is warming up because some air from the hot outside atmosphere is mixed in to the higher parts of the cave from the nearby entrance. At the floor, we see a weak cooling trend caused by the cooler temperatures at the floor level due to flow toward the entrance even in August. The barometric flows are not strong enough to mix warm air from the entrance through the strong temperature inversion to the floor level. In contrast, during outflow conditions the warmer air from deep in the cave warms up the deep part of the Left Hand Tunnel. At Devil's Spring, the outflow blocks the warm air from the entrance area, which has a slight cooling effect. At the floor level, the air deeper in the cave is warmer than in the cold entrance area.

King's Palace

The King's Palace tour consists of several smaller chambers connected by short, narrow tunnels. Figure 11 shows the record of the air temperature at a height of approximately 3 m, relatively close to the ceiling. The structure of the

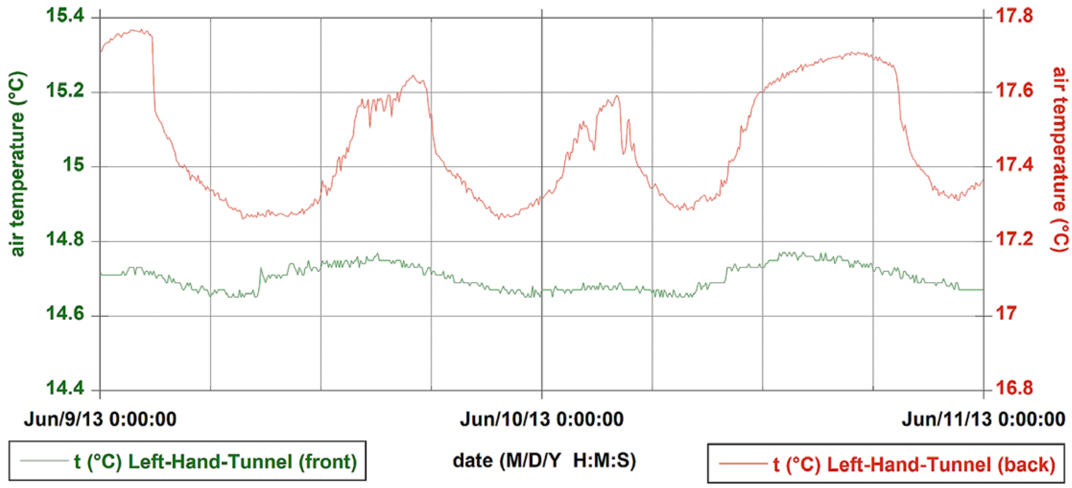

Figure 9. Records of the air temperature in the exterior (front, logger LHT-F) and the interior (back, logger LTH-B) part of the Left Hand Tunnel inside Carlsbad Cavern, on an expanded scale for June 9 and 10, 2013, recorded every 5 minutes.

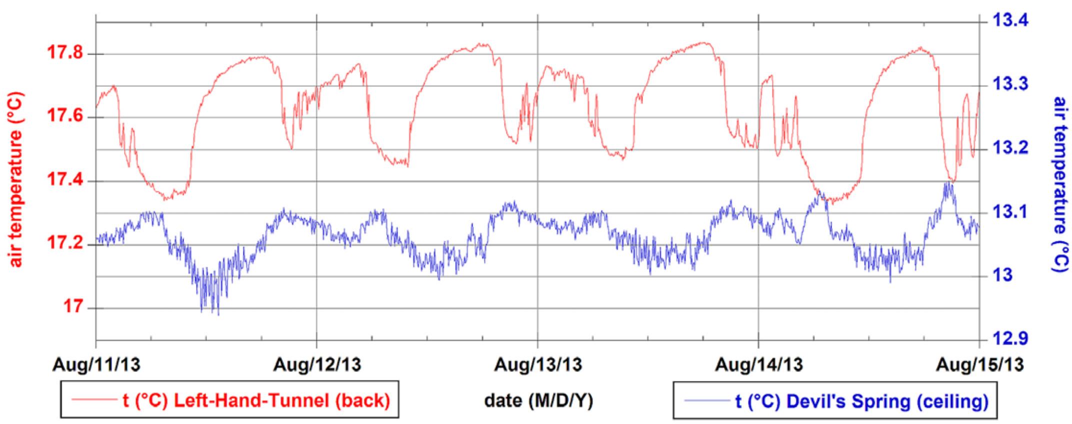

Figure 10a. Records of the air temperature in the exterior (front, logger LHT-F) part of the Left Hand Tunnel and the ceiling near Devil's Spring inside Carlsbad Cavern, on an expanded scale from August 11 through August 14, 2013, recorded every 5 minutes.

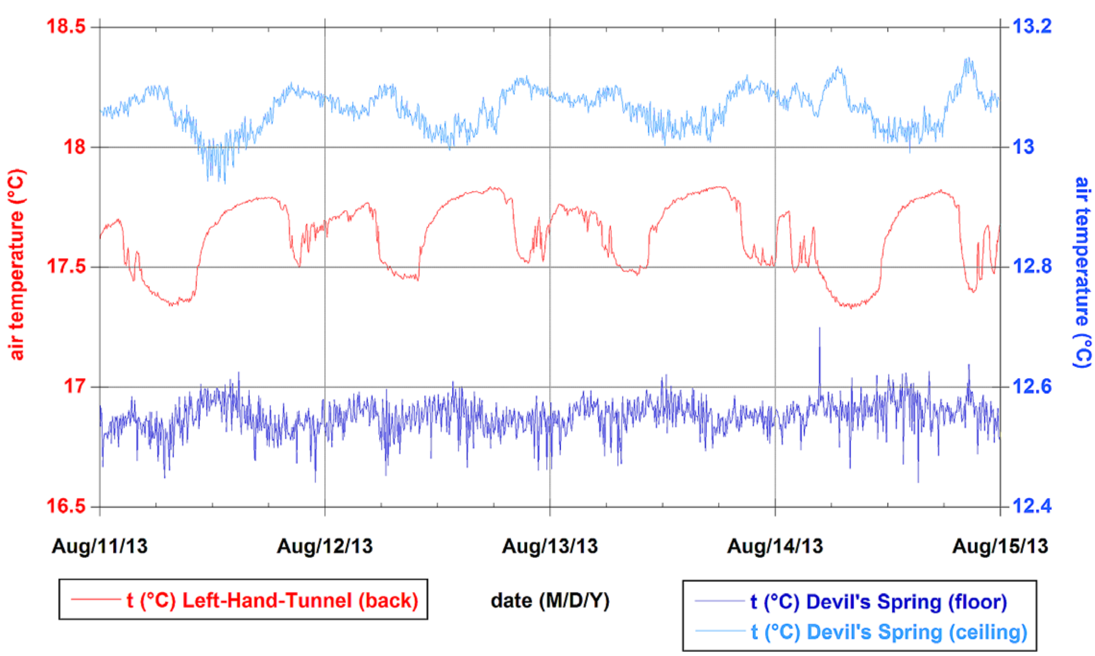

Figure 10b. Records of the air temperature in the interior (back, logger LTH-B) part of the Left Hand Tunnel and the floor and ceiling near Devil's Spring inside Carlsbad Cavern, on an expanded scale from August 11 through August 14, 2013, recorded every 5 minutes.

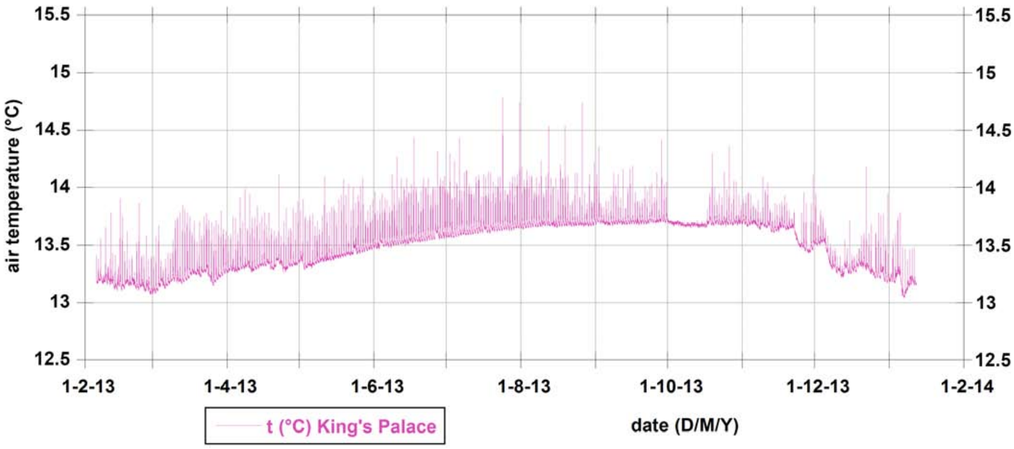

Figure 11. Record of the air temperature at a height of 3 m in the Papoose Room on the King's Palace tour inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes.

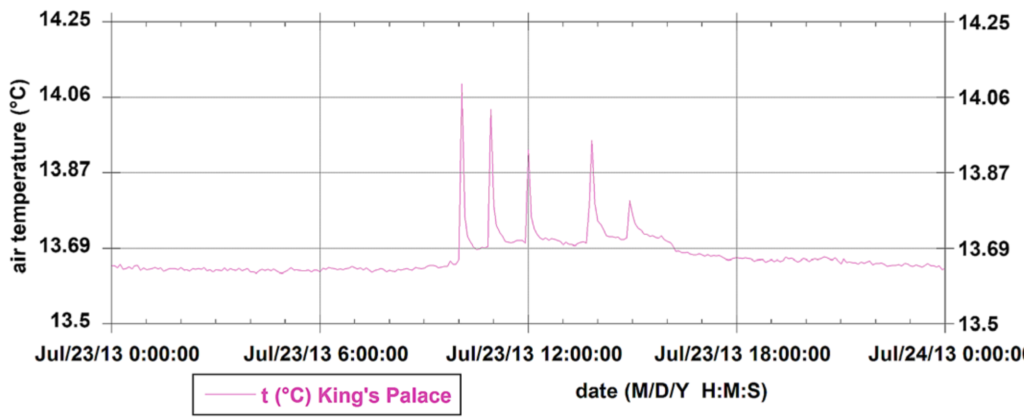

Figure 12. Record of the air temperature at a height of 3 m in the Papoose Room on the King's Palace tour inside Carlsbad Cavern on an expanded scale during July 23, 2013, recorded every 5 minutes.

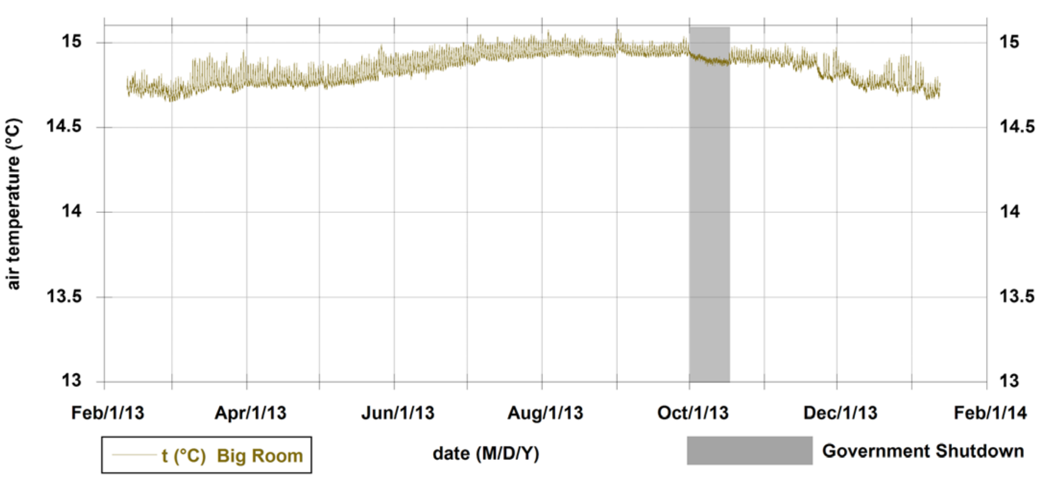

Figure 13. Profile of the air temperature in the Big Room inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes. The period when the cave was closed to tourists is highlighted.

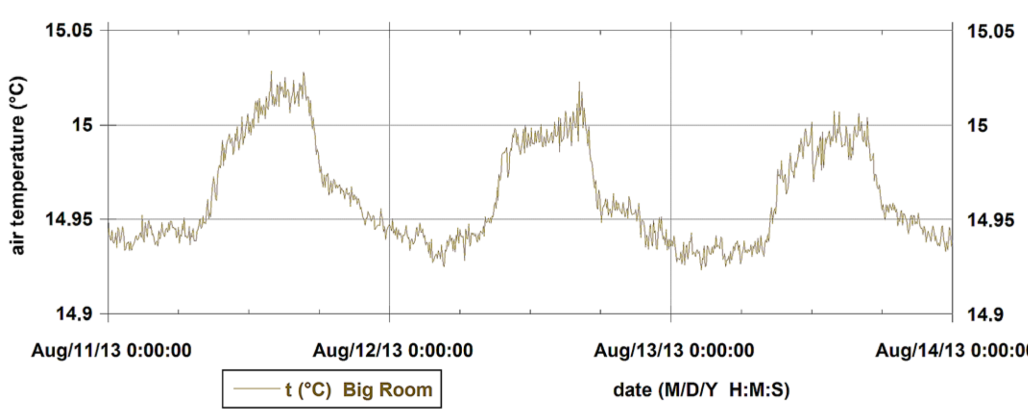

Figure 14. Record of the air temperature in the Big Room inside Carlsbad Cavern on an expanded scale from August 11 through August 13, 2013, recorded every 5 minutes.

graph, with its nearly stable minima and its highly variable maxima, differs from the previous ones. This can be explained by the horizontal layering of the air in parts of a cave with only minor air movement. With cold air sinking and warm air rising, unimpeded by airflows, horizontal isotherms develop; the positioning of the data logger close to the ceiling shows this relationship.

In Figure 12, an example day of the peak tourist season is depicted. Five peaks in the air temperature are distinctly visible. They occur exactly when the five ranger guided tours pass the data logger at 10 a.m., 11 a.m., noon, 2 p.m., and 3 p.m. Whether this impact on the air temperature is only temporary or it has long-lasting ramifications on the cave climate will be discussed later in this work.

Big Room

The cave climate in the Big Room (Fig. 13) hardly reacts to the daily variations of the outside weather; only extreme cold spells can lead to a very minor decrease of the air temperature. Unless there is an exceptionally high inflow of cold air, inside the Big Room the daily curve of air temperature is hardly influenced by the outside weather on a day-to-day basis. The gray area in this and some of the following figures shows the duration of the government shutdown of October 2013 which is discussed in more detail in the next section.

In Figure 14, this daily temperature profile is shown for three typical summer days. In this figure the plateau-like peak of the air temperature is obviously related to the tourist use of the cave, as is the temperature in the Papoose Room on the King's Palace Tour and in the Left Hand Tunnel. The Big Room is open for visitors from 8.30 a.m. to 5 p.m., exactly the time during which the temperature of the Big Room increases. The fact that this increase is very small, only approximately 0.07 °C, should not lead to the assumption that it is of small significance. The data logger inside the Big Room could only measure the effect of the tourists some distance from the visitor path at a height of 20 cm. Therefore, most of the ascending warmer air was not measured, so the influence of the tourists in reality is greater by an unknown factor. What we see in the data is just a result of a slight turbulence caused by the cave lights and moving and heat-emitting visitors that brings warmer air even to the ground. The proof that these effects are caused by the tourist use of the cave is given in the following section.

The Government Shutdown and its Effect on the Cave Climate

A shutdown of the federal government in 2013 led to a temporary closure of all units of the National Park Service during the first two weeks of October. Carlsbad Caverns National Park was closed from 1 to 16 October, and for more than two weeks the cave climate was unaffected by moving elevators, electric lights, and by the presence of nearly one thousand visitors a day. Unfortunately, the long-term effects of the tourist use have affected the unspoiled situation of the cave. However, the analysis of the climatic situation during these two weeks allows an insight into a more undisturbed state of the cave, and therefore, helps to quantify the long-lasting anthropogenic influence on today's cave climate.

The sudden absence of the tourists mostly affected the King's Palace tour and the Big Room (Figs. 11 and 13), as they are the most visited areas and are located far from the entrance and its strong climatic influence. So the analysis of the cave climate during the government shutdown concentrates on changes in the atmosphere of these two areas. At Devil's Spring (Fig. 5) the influence of the large opening dominates everything, and in the Left Hand Tunnel (Fig. 7) the influence of the visitors is too small.

In Figure 15, the record of the air temperature in the Papoose Room of the King's Palace tour over the time of the government shutdown is shown at a larger scale. The difference is clearly visible. The daily variations caused by the five ranger guided tours disappear completely. No longer disturbed by the body heat of the visitors, the temperature measured at a height of three meters hardly fluctuated. Instead, a slight decrease in the air temperature can be perceived during these two weeks, which strongly decelerated when the National Park opened again on 16 October. Thus, the long-ranging anthropogenic alteration of the cave climate in the King's Palace tour is proven. The air temperature is not only heated up several times a day during the guided tours, but also is constantly held at a higher level year-round.

Similarly to the King's Palace tour, the air temperature of the Big Room shows a decrease during the two weeks of the government shutdown (see Fig. 16). The plateau-like fluctuations vanished and were replaced by a completely different daily curve which will be discussed later. The downward trend of the air temperature continued until the reopening of the National Park, but even then was still only temporarily reversed. This makes it clear that the air inside the Big Room and King's Palace tour is consistently warmer than it would have been without the development of Carlsbad Cavern into a show cave.

As can be seen in Figure 17, the daily record of the air temperature is quite different from the rest of the year (compare Figs. 12 and 14). The daily increases during the opening hours are replaced by a small scale pattern that is nearly congruent in both parts of the cave system; despite the different mean levels of the air temperature, its variations are almost the same. During the government shutdown, a daily double wave develops with an air temperature minima at 2 a.m. and 2 p.m. and maxima at 8 a.m. and 8 p.m. The temperature profile resembles the one in the Left Hand Tunnel caused by a barometric ventilation system. But relative to that part of the cave, the minima and maxima in the Big

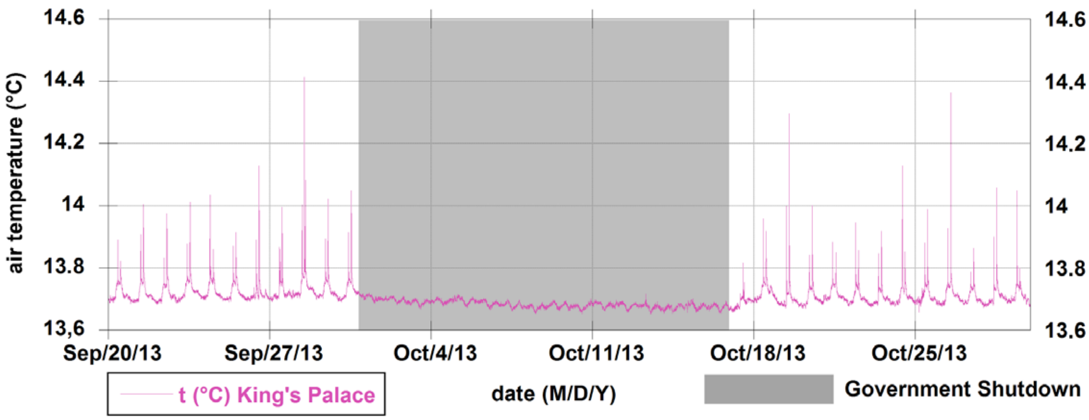

Figure 15. Record of the air temperature in the Papoose Room on the King's Palace tour inside Carlsbad Cavern on an expanded scale from September 20 to October 30, 2013, recorded every 5 minutes. The period when the cave was closed to visitors is highlighted.

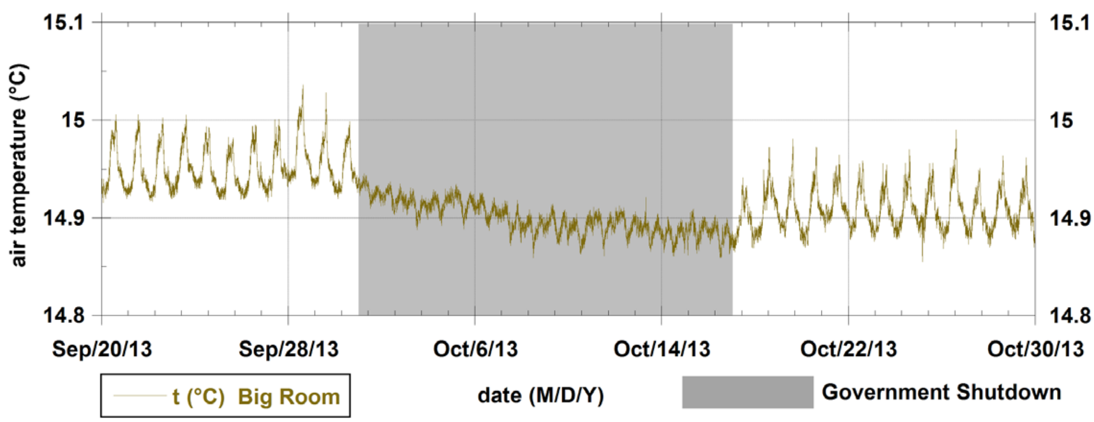

Figure 16. Record of the air temperature in the Big Room inside Carlsbad Cavern on an expanded scale from September 20 to October 30, 2013, recorded every 5 minutes. The period when the cave was closed to visitors is highlighted.

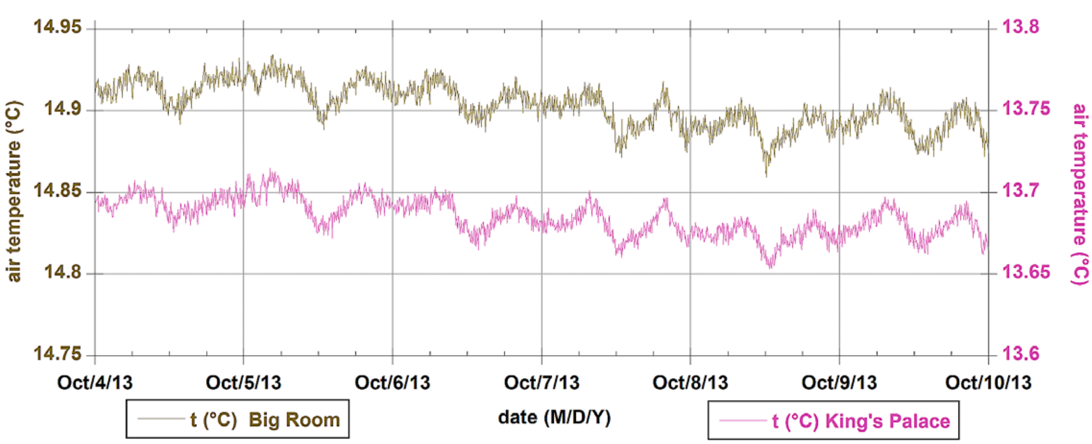

Figure 17. Records of the air temperature in the Big Room and the Papoose Room on the King's Palace tour inside Carlsbad Cavern on an expanded scale from October 4 through October 9, 2013, recorded every 5 minutes. The cave was closed to visitors during this time.

Room and the King's Palace are shifted. While the air temperature in the Left Hand Tunnel reaches its minima at about 10 a.m. and 10 p.m., the highest temperatures in the King's Palace and Big Room occurred at about 8 a.m. and 8 p.m. Both profiles, however, are caused by a barometric ventilation system.

To explain the cave climate developing in the Big Room, it is necessary to rely on research done by McLean (1971), as our data logger placed in Lower Cave was malfunctioning. McLean's results show that the Lower Cave is slightly colder than the Big Room. During phases of low atmospheric pressure at approximately 2 a.m. and 2 p.m. air is drawn out of Lower Cave and into the Big Room, so it causes the air temperatures to drop in this area. The rising air temperatures during phases of high atmospheric pressure at approximately 8 a.m. and 8 p.m. seem to be contrary to the results of our own and previous research (McLean, 1971; Hill, 1987), as there are no known areas between the Natural Entrance and the Big Room from which warmer air could be pushed into the Big Room. However, there are some possible explanations for these data.

During phases of high atmospheric pressure warmer air may be pushed out of the New Mexico Room/Chocolate High area and into the Big Room, as they are about at the same elevation. Previous research done by NPS rangers

(Allison, 2014) seem to indicate a slight barometric effect in the mentioned area, which would support this hypothesis.

If we keep in mind that Lower Cave and the entrance to the Left Hand Tunnel are colder than the Big Room, and if we look more at the cooling while the cave exhales barometrically, it appears that the colder air flows out of the cooler parts of the cave, invading the Big Room at least at the floor level. During high-pressure periods the cold air is pushed back.

Another explanation would assume that a local circulation inside the very high Big Room, which is almost 1220 m long, 191 m wide, and 78 m high at its highest point, could bring warm air from the ceiling closer to the floor during high pressure periods that is seen in the slight increase of the air temperature. The source of this warm air could be airflow that has been observed in tall, narrow fissures in the ceiling of the Big Room above the Jumping Off Place where the Big Room connects to Lower Cave, by NPS rangers (Allison, 2014).

The peak air temperature in the Papoose Room of the King's Palace tour also is linked to the peak outside air pressure. Because the King's Palace and the Queen's Chamber are somewhat separate from the main part of the cave and behave more like a cold air pocket, the warm external air is pushed into the area from higher areas and causes rising temperatures. Adjacent chambers like the Mystery Room and the New Mexico Room are warmer than the King's Palace (McLean, 1971). Air drawn from these parts of the cave should lead to rising air temperatures in the King's Palace. However, the drop in temperature occurring parallel to decreasing atmospheric pressure is related to the backflow of the cold air. Whether the cooling is caused by other reasons could not be ascertained, but further measurements, especially airflow measurements inside these areas of the cave, should give us exact explanations.

Summary

The cave climate of Carlsbad Cavern, New Mexico, USA, is a system of complex microclimates connected through various air currents and heat flows. This study evaluated a series of measurements taken during the year 2013 to investigate this complex situation. The climate in the cave is determined by two main causes. The Main Corridor, the King's Palace, and the Big Room are influenced by a relatively stable convective air circulation where cold air flows in near the ground and warmer air flows out of the cave at the ceiling. A barometric ventilation system has developed inside the Left Hand Tunnel due to its large volume and its small entrance. This issue is made visible in Figure 18 by comparing the course of the air temperature in four probed areas of the cave. Nevertheless, the effects of the barometric ventilation are also measurable at the entrance of Carlsbad Cavern.

In every part of the cave open for public visitation, the body heat of the tourists and the heat from artificial lighting and other heat-producing electrical devices leads to permanently increased air temperatures. In the King's Palace and the Big Room, the two most visited sections, the convective ventilation, as well as the influence of the barometric ventilation, are nearly completely overwhelmed by the anthropogenic influence.

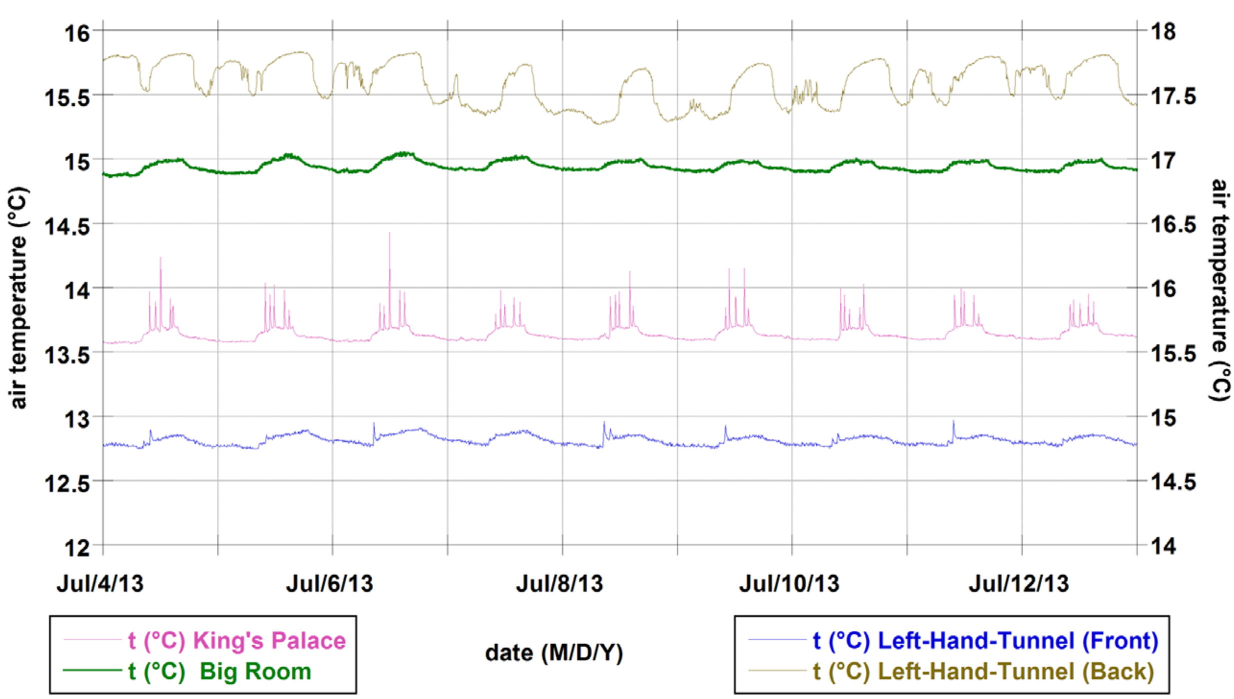

Figure 18. Records of the air temperature in four different parts of the Carlsbad Cavern on an expanded scale from July 4 through July 12, 2013, recorded every 5 minutes.

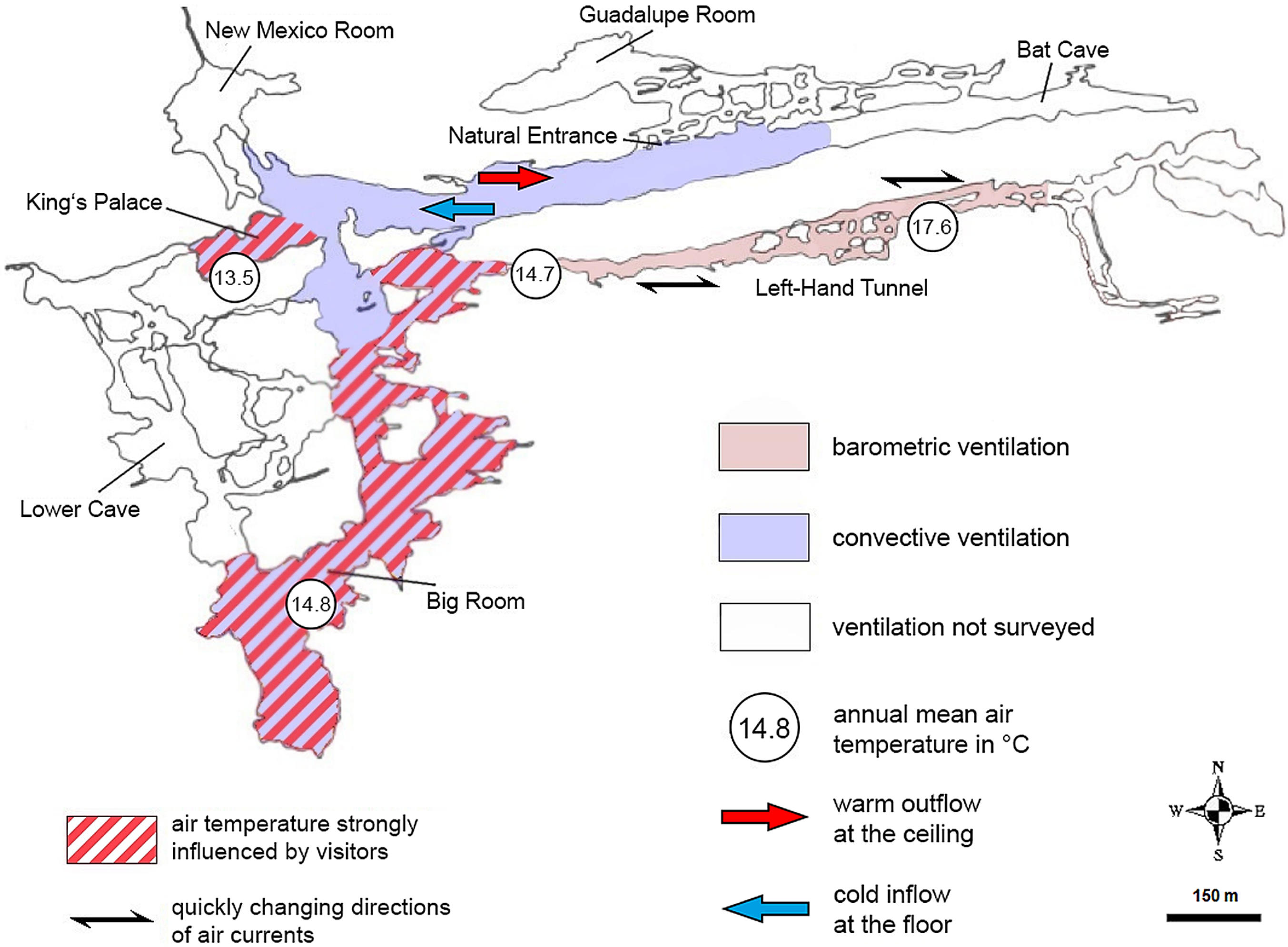

Figure 19. Spatial distribution of the predominant effects on the climate in Carlsbad Cavern studied in this paper. The underlying map of the system is based on Hill (1987).

Figure 19 summarizes the main results of this study. Especially noticeable is the difference between the quickly changing barometric air currents inside the Left Hand Tunnel and the relatively stable convective air stream within the Main Corridor, the King's Palace, and the Big Room. The striped areas indicate parts of the cave where a permanently increased air temperature can be ascribed to intense tourist use. There, the natural convective air circulation is altered because of the visitors.

With this work, the results of previous studies were partly confirmed and partly extended by new knowledge. Due to the exceptional high data resolution, already known features of the cave climate could be confirmed in the course of a whole year. During the government shutdown, the cave climate returned to a more undisturbed condition, allowing us to determine the extent of the tourist impact. How the described anthropogenic modifications of the cave climate affect the flora and fauna and the speleothems remains unsolved. Further studies should concentrate on this subject to be able to combine actions protecting the ecosystem with a sustainable use of Carlsbad Cavern.

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