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Front cover: Sandy Glacier, Mt. Hood, Oregon, USA. Photograph by A. Pflitsch

EDITORIAL:
INTRODUCTION TO CAVE CLIMATOLOGY SPECIAL ISSUE

Andreas Pflitsch
Guest Editor

This issue presents a series of articles intended to highlight some recent investigations focusing on cave climatology with the intent of generating or renewing interest in research of this subdiscipline.

Climatological conditions inside caves are immensely important for diverse processes such as the formation of minerals at the cave`s walls, their corrosion, the formation of diverse speleothems, the presence of permanent ice, and for the specific existence of several organisms from bacteria to bats. Nevertheless, the research field of cave climatology still does not attract enough attention.

Both peleometeorology and the speleoclimatology differ from their corresponding counterparts of the free atmosphere significantly. While the weather events and the climatological characteristics of an environment at the earth's surface are strongly influenced by short-term and regional changes, as well as medium-term and global changes, the speleoclimate can be traced back almost solely to the given local conditions affecting the coherent cavities and skylights. So-called constant conditions such as lasting high relative humidity, weak temperature fluctuation, as well as slow or absent air currents are characteristic of numerous cave systems.

At first sight, this might sound monotonous or even boring, which certainly is a reason why speleoclimatological research has lacked interest for several years, and why for many caves, only information about the internal temperature is available. But these special conditions, together with permanent darkness, have led to the development of unique and very sensitive ecosystems. By taking a closer look and considering long term measurements of air temperature, humidity, and air flow in different parts of a cave reveal unimagined and exciting dynamics of the cave climate. This has already been established and described in detail for two barometric caves in South Dakota - Wind Cave and Jewel Cave – by Herb Conn. At the openings of these two cave systems in the Black Hills high air flow velocities appear in a quite spectacular way and have been known for a long time.

One of my numerous field trips with my students brought me especially to the Black Hills in 2000, where I got to know Rod Horrocks and Marc Ohms, who were working at Wind Cave National Park and pretty soon Mike Wiles and Rene Ohms at Jewel Cave National Monument. The following year, I started my first measurements in Wind Cave, which were followed by further measurements in Jewel Cave. Through this work, I received further notice and requests from colleagues, who brought me to numerous fascinating cave systems throughout the US, some of which is already published.

After an invitation of Stan Allison, I also got to the just as interesting Carlsbad Caverns in the Guadalupe Mountains in New Mexico, where I studied the climate conditions in numerous caves of the park. First results will be presented in two articles in this journal.

As a climatologist I was immediately fascinated by the climatological diversity, but also by the lack of research done in this impressive field of study. In some caves, I could start further measurement programs in cooperation with the local National Parks or colleagues that continue until today and are constantly extended. Those measurement series of greater or lesser duration include caves in the pseudokarst of New Hampshire, barometric caves in New Mexico and South Dakota, ice caves in Wyoming, Oregon, Idaho, Hawaii and Alaska, lava tubes in Hawaii and glacier caves in Oregon and Washington.

To finally publish parts of the data and to encourage other scientists in the US to start conducting research in this field of study we will present some topics in this special issue exemplarily. More publications will follow in the upcoming years.

No high wind velocities, like in the barometric cave systems, are needed to discover exciting aspects. Even rather static cave systems without considerable air currents can provide interesting phenomena. Those caves have not only always fascinated people by their unique and fragile ice forms, but also been useful for early settlements. Ice caves containing ice bodies of greater or lesser thickness year round have provided ice for cooling. Today those caves play an interesting role in studies on global warming as the ice inside the cave is continuing to melt. Consequently, many former ice caves do not contain permanent ice any more. In this context, we have first considered the historical development in Europe and the US to build the foundation for detailed investigations.

A completely new discipline, which has only been pursued seriously for three years, is the exploration of the climate of glacier caves. No importance had been attached to those caves before Eduardo Cartaya and Brent McGregor presented first and surprising single measurements on the ice cave conference in Idaho Falls in 2014. Their presentation

was followed by a lively discussion about temperatures far above freezing inside of glacier caves, which led to the beginning of very interesting research with surprising results and to the start of long term measurements on three volcanoes of the Pacific Northwest. The results of a climatology focused expedition to Mt. Hood will first be presented in this Journal.

I would like to give special thanks to my numerous wonderful colleagues in the United States, without whose support and strong commitment I could have never conducted this research. Their company in the field, the construction of mounts for measuring devices, accommodation of myself, my students as well as my equipment, the organization of my stays, teaching of several techniques, the transportation of batteries in the heat, snow and ice and much more were a huge help for me. Especially I would like to thank alphabetically:

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Photograph by A. Pflitsch

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REPORTS ON ICE CAVES IN LITERATURE FROM THE TWELFTH TO THE MIDDLE OF THE TWENTIETH CENTURY

Christiane Meyer[1, C], Andreas Pflitsch[1], Julia Ringeis[1], and Valter Maggi[2]

Abstract

The main goal of this paper is to summarize the history and the progress of ice cave research in the northern hemisphere as an introduction to the following papers about modern research in the U.S. We focus on the earliest descriptions of ice caves starting from the twelfth century, a cave with ice in India, as well as the beginning of modern ice cave research in the nineteenth and twentieth centuries. Moreover, we give a short overview of the different theories about ice caves over the course of time. The article is an introduction to the much younger ice cave research in the U.S., which will be the topic of a second paper in this journal.

Ice Cave Research Over the Course of Time

Ice cave research plays only a minor role in the research of ice and snow. Less visible and much smaller than the vast ice masses above ground, the more concealed subsurface ice has been of little interest to many researchers. However, beneath the surface are numerous ice formations with a great variety of forms ranging from ice monoliths several meters thick, to ice lakes, to delicate ice crystals millimeters in size. These icy features store a vast record of climate history.

Over the centuries, clergymen, amateurs, natural scientists, and locals have visited the subsurface world of ice to see this phenomenon themselves and to find an explanation for its existence. Over time, many theories about the development of ice caves have evolved, but as of today, the fundamental research has not been completed. Later in this paper, we will give a basic overview of the best-known ice cave theories.

As research often focuses on cost-benefit considerations, basic research without a clearly defined impact increasingly loses prominence. This questions the benefit of ice cave research in general. But just as the exploration of the most distant regions of the universe or the abyssal depths of the sea, ice cave research has the potential to create new knowledge. For example, one can learn about the regional and local climate history outside the mountainous regions that are covered by glaciers on the surface.

In a series of three papers in this journal, the historical, as well as the current research on ice caves, will be presented to review lost or forgotten knowledge and to attempt to revive and support ice cave research, which is stagnant in some countries. After an overview of the first records of underground ice in Europe and Asia, the second article covers the records and research in the United States. The third article is about our own research in gulch, talus, and slope ice in New England.

It is well known from the analysis of ice cores and pollen that the ice in some caves is several thousand years old, has outlasted several climatic temperature maxima, and is not a remnant of the Little Ice Age as was supposed in former times (Silvestru, 1999). Historic documents, for example, describe the complete extinction of ice from the Chaux-lès-Passavant (France), which was followed by a new ice accumulation (Fugger, 1893).

When were ice caves first studied scientifically? What can we learn about the geographic distribution of ice caves from historical sources? Here we must take into account that research developed differently in different parts of the world, and we may learn more about the development of research than about the occurrence of ice caves. In general, we can state that the increase in knowledge was slowed due to the difficult accessibility of ice caves in mostly high mountain regions and the inconsistency of reports about the investigations. In addition, ice caves in more remote mountain ranges remained undiscovered for a long time. Therefore many ice caves have probably never been written about, or accounts of them are not accessible to us because of language barriers.

For the first part of this series, documents covering the occurrence of ice caves were evaluated. Works in German, English, French, and other European languages dating from the twelfth century until today were reviewed. Due to their age, it was not possible to view all of the known original sources. In cases where original documents were not accessible, multiple citations in secondary sources were used. Access to original sources is also complicated by the many different languages in which they are written. To date, there is no complete evaluation of the publications on ice caves. The surveys of Turri et al. (2009) or Mavlyudov (2008) are important studies and will be further complemented by this article.

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First Historical Sources

The first mention of an ice cave is found in a document from the twelfth century. In his chronicle of the kings of Kashmir, Kalhaṇa describes the Armanath Cave (Stein, 1961). This cave, located in today's India, is still visited by pilgrims who worship an ice formation in the cave as the manifestation of a deity: "[…] the famous cave of Amarnath […] In it S'iva Amarésvara is believed to have manifested himself […] The god is worshipped in a lingashaped ice-block" (Stein, 1961, p. 41).

In the late fifteenth century, a report on an ice cave in the Carpathian region appeared, according to Schönviszky (1968). Petrus Ranzanus writes on an ice cave in the Hungarian kingdom: "[…] near Scepusium there are cliffs, where […] water […] in summer is frozen" (Ranzanus, 1977, p. 71, own translation, see original text I). From this time period we also have an account by Leonardo Da Vinci of Moncodeno ice cave in the Italian Alps: "These excursions are to be made in the month of May. And the largest bare rocks that are to be found in this part of the country are the mountains of Mandello near to those of Lecco, and of Gravidona towards Bellinzona, 30 miles from Lecco, and those of the valley of Chiavenna; but the greatest of all is that of Mandello, which has at its base an opening towards the lake, which goes down 200 steps, and there at all times is ice and wind"i (Richter, 1883, p. 238f [see text II], Balch 1900, p.211).

The best-known descriptions of a European ice cave date from the sixteenth century, when Poissenot (Poissenot, 1586, p. 436–453) and Gollut (Gollut, 1592, p. 88) write about the Chaux-les-Passavant and also give explanations of this phenomenon. Poissenot writes in a letter: "[…] having come to the cave, which we found of the length and width of a large hall, all surfaced with ice in the lower part […] After having searched in my mind the cause for this antiperistase, I did not find another but this: namely it is that as the heat dominates in summer, the cold retreats to places low and subterranean like this to which the rays of the sun cannot reach" (Poissenot, 1586, p.265 [see text III], own translation).

Gollut notes: "[…] since at the bottom of a mountain of Leugne ice is found in summer, for the pleasure of those who wish to drink cool. Nevertheless at this time, this is disappearing, for no other reason (as I think) except, that they have despoiled the top of the mountain, of a thick and high mass of woods, which did not permit that the rays of the sun came to warm the earth, and dry up the distillations, which slipped down to the lowest and coldest part of the mountain where (by antiperistase) the cold got thicker, and contracted itself against the heats surrounding and in the neighborhood during the whole summer, all the external circumference of the mountain" (Gollut, 1592, p. 88 [see text IV] [translated by Balch, 1900, p. 202]). That Chaux-les-Passavant (also known as Baume or Grâce de Dieu) in the Jura Mountains is the cave discussed by those authors is confirmed by Schwalbe (1886, p. 7). Over the following centuries, there were several other publications on Chaux-les-Passavant. In 1885, Giradot and Trouillet published a monograph on it.

In the seventeenth century, there are the important descriptions by Valvasor of ice caves of the former archduchy Carniola dating from 1689, which became known as the earliest descriptions of ice caves in this region. By then, only individual sites were known and an ice cave was assumed to be a unique phenomenon. In the eighteenth and nineteenth centuries, this opinion changed, and descriptions of ice caves became more numerous.

Before the Twentieth Century

In the latest comprehensive literature research, Turri et al. (2009) evaluate sources, including Italian and Russian literature, and compile descriptions of ice caves in Europe and Asia and their geographical distribution. Mavlyudov (2008) and Turri et al. (2009) agree that the first mention of ice caves in Russia were from the Volga River valley in the year 1690, and both also list several publications on Russian caves from the eighteenth century, including the Kungur Ice Cave, from 1730. They also show that starting with the records of the ice caves in the French and Swiss Jura Mountains and in Slovenia, more and more descriptions of ice caves in Europe and east of the Ural were published. Another recent study with a focus on the Alps and Slovenia was published by Kranjc (2004).

In the nineteenth century, a number of review articles were published. The works of Schwalbe (1887), Fugger (1891 and 1893), and Balch (1900) contain extensive evaluations of original sources and compilations of ice cave locations known at that time. These publications also contain theoretical discussions concerning definitions of terms and theories of ice cave formation and processes. In 1865, Browne published a monograph in which he reports on several ice caves he had visited. He also included a literature review and an overview of ice cave theories. These publications extend the known source material considerably. For Eastern Europe, Fugger (1893) names the previously mentioned publication by Valvasor as the first document about this region. The documentation by Schwalbe (1887) is characterized by its geographical diversity. Schwalbe (1886, p. 13) emphasizes the importance of this aspect for the understanding of the existence of ice caves: "The geographic distribution is very important for the explanation of the phenomenon". At the same time he judges, "After all the phenomenon is rare and not widely spread" (see original text V).

In his final remarks Schwalbe (1887, p. 38) writes that most of the works he evaluated mainly consisted of simple descriptions of ice cave locations. Some reports included observations or measurements of the physical properties, but only a few described systematic research. Nevertheless, he thought that every record added some information helpful for the understanding of the phenomenon.

The compilation of Balch (1900) includes about 300 locations worldwide in sedimentary and magmatic rock, including sites in different parts of Europe, Asia, and America.

The evaluation of source material shows that before the nineteenth century the knowledge on ice caves was still limited in the number of known locations. In addition to this, it was also geographically limited. Beyond Central Europe, and later Russia, locations of ice caves in other parts of the world became known much later.

In the nineteenth century, a large number of primary descriptions and other ice cave publications appeared, along with some of the first broad theoretical analyses about their formation. There was also great interest in understanding the distribution of ice caves. Figure 1 shows geographic regions in which ice caves were known to exist prior to the twentieth century. The compilation derived from the cited sources includes different types of natural caves, such as caves in soluble rock, caves in magmatic rock, and ice in artificial underground spaces such as mines. For many of the locations, it is not known whether they still have ice today.

The Twentieth Century

In the twentieth century, the assessment of ice caves changed. "Ice caves are […] a very common phenomenon. Apart from the European limestone high mountain regions […] they are found in the Jura Mountains, the Alpine foothills […] Several hundred ice caves are known in the United States and in Canada […] a very large number of ice caves can also be expected to exist on other continents of the northern and southern hemisphere. Provided that karstic rock is present, their occurrence above the 35th degree of latitude north or south seems to be ensured, with their height above sea level decreasing with increasing latitude" (Saar, 1956, p. 58 [see text VI]). For the United States, Merriam (1950) and Halliday (1954) compiled ice cave locations in several different states.

The Early Twenty-First Century

Today there is greater interest in the geographical distribution of ice caves as shown by Mavlyudov (2008) in the paper "Geography of caves glaciations" and also by "Cave glaciation in the past" (Mavlyudov, 2010), based on historical data. New first descriptions of ice caves are still being published today, often in combination with results from research in the caves as in "First data from a Pyrenean ice cave (A294 cave, Cotiella massif, Spain)" by Ribas and Marcén (2010). The publications of caving organizations in many parts of the world have not been evaluated. These publications probably hold information about ice-cave locations.

General Overview about the History of Ice-Cave Theories

Since the discovery of ice caves, different theories have been developed, each of which aimed to find a single universal explanation for the origin of subterranean ice. Some of these often contradictory concepts were only discussed for a relatively short period of time, while others are still viable today. Figure 2 shows the chronology of ice cave theories and their development over time based on evaluation of the literature.

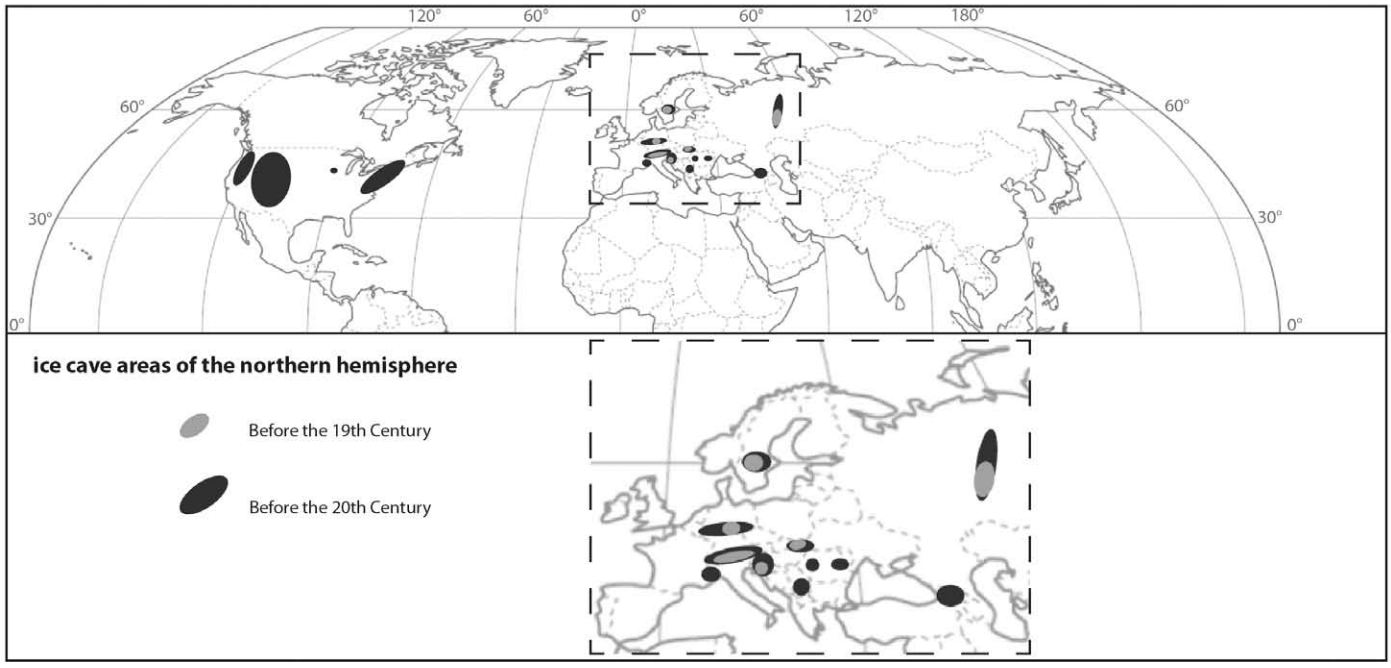


Figure 1. The distributions of known ice cave areas worldwide before the nineteenth and before the twentieth century.

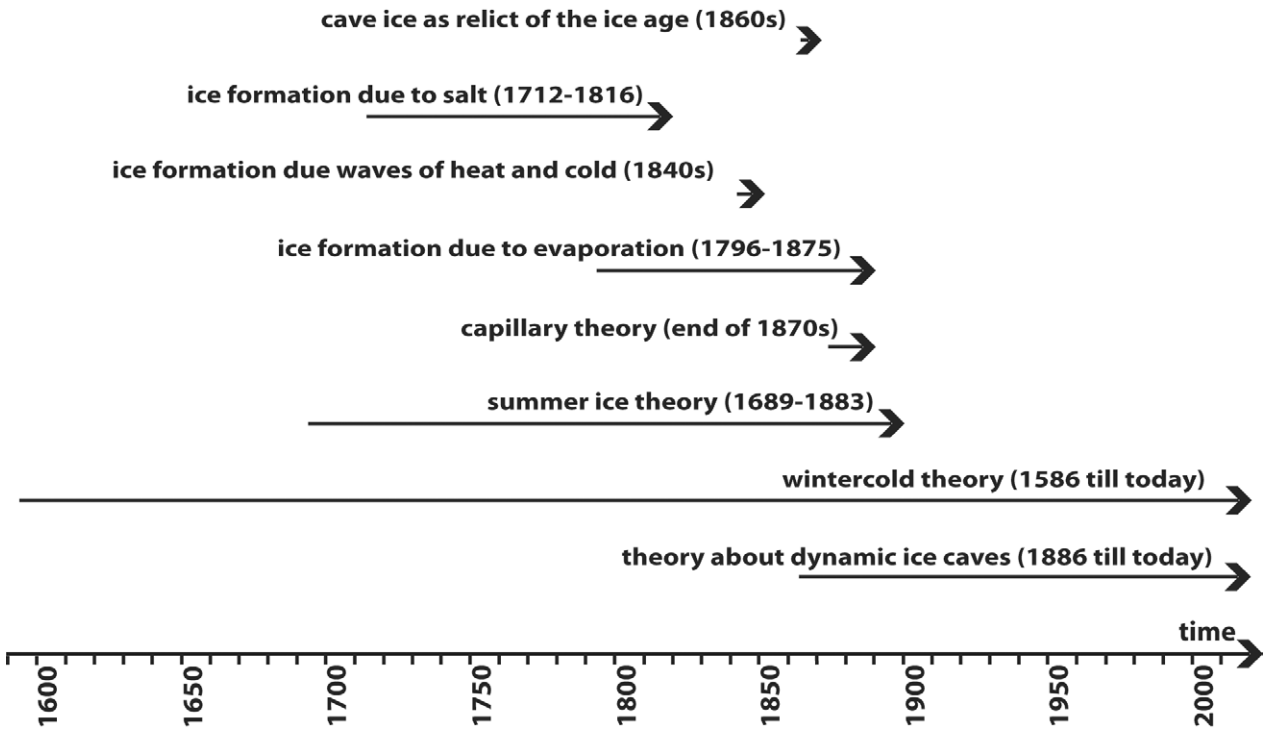


Figure 2. Chronology of ice cave theories over the centuries (Grebe, 2012).

From 1689 to 1883, many authors including Valvasor, Billerez, Behrens, and Scope agreed that ice in caves only formed during the summer months (Fugger 1893). However, they gave different explanations for this phenomenon. The most famous summer ice theory was developed by Pictet in 1822 (reported by Fugger, 1893), who stated that ice only formed due to evaporation driven by air currents, which were stronger in the summer than in the winter. Several measurements and observations, however, disproved the summer ice theory.

Another theory, developed by Billerez and discussed from 1712 to 1816, held that subterranean ice formed by salt (Fugger 1893). The soil above the cave contained saltpeter and other salts, which dissolved in water and flowed into the cave, where they produced cold through solution. Consequently, the water inside the cave froze. According to Fugger (1893), a chemical analysis by Cossigny in 1743, did not find saltpeter or any other salts needed for such cooling. According to Schwalbe (1886), this theory is only of historic interest, but not scientifically tenable due to the absence of salts in soils.

In 1796, de Saussure published his observations of cold-current caves in the Alps, in which the temperature was reduced by air currents flowing along the wet walls of the cave (cited by Balch 1900). In 1815, Parrot stated that dry and sufficiently deep caves showed steady temperatures of 10 to 12 °C, according to Fugger (1893). Evaporative cooling, however, could lower the temperature until the air was saturated. A steady inflow of warm and dry air led to maximum cooling on hot days. After observations in Saint-Georges and Grand Cave de Matarquis, Thury (1861) disproved the theory that evaporation caused the formation of ice in caves (Balch 1900).

The theory of ice formation through waves of heat and cold was only discussed in the 1840s, when Hope and Herschel explained that ice in caves formed during the summer months when cavern water froze due to the penetration of cold winter waves. In contrast, an advancing warm summer wave led to warmer temperatures, and therefore, melting in winter (Schwalbe 1886). This concept, however, is contradictory to the distribution of soil temperature.

Fugger (1893 and Turri et al. (2009) report that Hitchcock in 1861 and Dawkins in 1876 explained ice in caves as a relic from the Pleistocene. The ice formed during the ice ages and persisted under the surface. According to Schwalbe (1886), the ice age theory has only a minor significance, as most caves have been intermittently ice free and show a steady formation of new ice.

Lowe first formulated the theory that subterranean ice formed by capillary forces. Bubbles of air in water, which flows down through fissures in rocks, are liberated at the bottom of the cave. The air has lost its heat due to its compression, and therefore, absorbs the heat from the air and water in the cave, leading to a decrease in temperature (Balch 1900). However, almost all caves contain dripping water, but not all caves contain ice, which contradicts the theory. In addition, no ice caves are found in hot climates.

Unlike all the theories about the formation of subterranean ice mentioned above, the winter cold theory, as well

as the theory of the dynamic ice cave, are still viable today. The former was first mentioned by Poissenot (1586), and therefore, is considered the oldest ice cave theory (Fugger 1893). Fugger (1893) cites Prévost as writing in 1789 that caves serve as reservoirs for ice that forms during the winter and does not completely melt during the summer. Also Balch (1900) describes caves as "iceboxes" preserving ice and snow from the winter months, because in the summer warm air cannot enter the cave.

After Thury (1861) made a distinction between static and dynamic ice caves, the latter were not accepted as an independent type until the end of the nineteenth century. Bock (1913) explained the formation of subterranean ice by a temperature decrease resulting from uneven air currents during the summer and winter months. This theory was supported by long-term measurements in ice caves in Austria (Saar 1954).

Summary

A review of the scientific literature from the twelfth century onward shows that in the beginning only few ice caves, mainly in Europe, were known and described. The knowledge about ice caves was limited, and they were assumed to be a very rare natural phenomenon. In the eighteenth and especially the nineteenth centuries, more and more new and first descriptions as well as review articles were published. By the twentieth century, it had become clear that ice caves are not a rare phenomenon, and the knowledge on ice caves increased. Yet there is more work to do. Today descriptions of new ice caves are often made by caving groups who discover ice caves in remote alpine karst regions. From historic reports, ice cave locations can be reconstructed even if the caves no longer contain ice. All these records can help to understand the geographical distribution of ice caves, as well as the factors determining the formation of ice in caves. The literature described in this paper provides the background for understanding the formation and distribution of ice caves through the world as a basis for the following articles.

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ICE CAVE RESEARCH OF THE UNITED STATES

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Abstract

Natural and anthropogenic ice caves are spread out on the North American continent, especially in the United States. Many of these climate archives are already forgotten, no longer contain ice due to climatic changes, or are expected to lose their ice soon. However, sources from the nineteenth and twentieth centuries suggest the former density of ice caves in this nation. A synopsis of the American ice cave research from its beginnings in the early nineteenth century to the present is the focus of this article. A priori, basic terms and problems of ice cave research are addressed and elucidated. Subsequently, climatic conditions that facilitate or counteract the buildup of cave ice over the course of a year are presented. On the basis of an ice cave classification, different ice cave types are outlined and analyzed in their distribution in the United States. The accompanying map illustrating the geographic locations of caves in the mainland United States represents the first version of an American ice cave distribution.

Introduction

Ice caves have always drawn the attention of mankind. Native Americans, like the Zuni in Arizona, regarded ice caves as religious places (Balch, 1900). During the colonization of the country by European settlers, ice caves were used to cool and store perishable goods, extending their shelf life. At a later time, cave ice was chipped off and transported into the basements of townspeople to enable in-house cooling of groceries. With the invention of the electric refrigerator, ice caves lost their importance, and over decades, vital knowledge about them from previous generations was lost (Balch, 1900).

Today, information about many ice caves is only available from older literature. Still, ice caves represent hidden archives that provide information about the climate decades to centuries past. Ice caves can help to assess current climate shifts, giving important information about regional changes. The changes in ice mass over the course of a year during the phases of ice formation and melting are meaningful climate indicators for short- and long-term changes of regional climate (Saar, 1956). For this reason, scientific ice cave research in northern America has great untapped potential.

American and European literature from the nineteenth and twentieth centuries (e.g. Balch, 1900; Halliday, 1954) was reviewed, and oral evidence from local cavers was gathered and combined with findings and results from our own cave visits and research beginning in 2007. In addition to this information, measurements undertaken since 2007 were compiled to establish an ice cave distribution for North America.

This first overview includes information about the spatial distribution and changes in American ice caves in the last 110 years, as well as the variability of ice thickness of individual ice caves. A main goal of the ice cave distribution data is a future expansion to a method of climate monitoring that may provide usable information of past and present climate changes.

Definition of Terms Relating to Ice Cave

The term *ice cave* and its distinction from *glacial caves* have been discussed in the literature for centuries. The problem and the historical development of a clear nomenclature are summarized in the master's thesis by Grebe (2010), which deals with the global ice cave research since the sixteenth century. There have been different attempts to define the term *ice cave* since the eighteenth century. The first definitions solely related to a particular characteristic of ice caves. Such a characteristic could be air currents (Thury, 1861), the shape of the cave (Schwalbe, 1886), the presence of ice, the location and morphology of the cave, the air temperature inside the cave in comparison to the air temperature outside of the cave, or the formation and position in the rock (Balch, 1897). Nearly sixty years later, Saar (1956) was the first to summarize more than one characteristic element in his definition, defining the cave type by combining the influence of the outdoor climate with the specific soil temperature. Despite these efforts, a much-needed international, globally uniform definition of the term *ice cave* is still missing.

The authors of this paper define ice caves as chambers that contain or are composed of ice. The specific rock, its structure, or the position of the cave are not relevant. Any underground cavities where ice is present for more than six months a year are considered as ice caves, while short, seasonal snow and ice are not considered. As Halliday (1954)

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stated, the ice itself is the curiosity and not the cave. Cave ice is defined as moisture that freezes in the inside of the cave. Snow masses that are blown into the cave during winter and subsequently accumulated in the cave are not considered cave ice (Halliday, 1954).

Factors for the Formation of Cave Ice

Percolating water from the surface and temperatures below the freezing point are the two elementary factors that are mandatory for the formation of cave ice. Without these low temperatures and a simultaneous supply of moisture, ice cannot form in caves (Balch, 1897; Fugger, 1888; Fugger, 1893). In addition to these two elementary factors, each cave has features that impact the climate of the cave. These factors can be the morphology of the cave or the orientation and size of the entrances, which impact the formation of ice in caves in various ways. As these factors often favor the formation of ice in caves, ice caves are much more common than generally believed and even occur in regions with hot summer climates, such as New Mexico or Hawai'i (Balch, 1900; Fugger, 1888; Fugger, 1893; Kraus, 1894; Schwalbe, 1886).

Factors that vary with season like regional snowfall during winter also impact the occurrence of ice in a cave. Strong snowfalls in late winter have a particularly positive impact on the growth of ice. Snow masses that block openings can preserve cave ice from direct solar radiation or prevent warm air masses from entering the cave, so that the melting of cave ice may be delayed until late spring or summer by limiting the time that defrosting processes affect the ice. In contrast, the penetration of cold and dry air masses during winter can lead to degradation of ice masses by sublimation, while dripping water during snow melt supplies the necessary moisture for ice formation (e.g., Fugger, 1888; Fugger, 1893; Kraus, 1894). A comparative consideration of the various impact factors is given in Table 1.

Table 1. Climatological impact factors for the formation and degradation of cave ice.

Positive Impact	Negative Impact
Early-onset and/or prolonged winter	Early-onset and/or prolonged summer
Autochthonous radiation weather conditions	Long-lasting summer heat waves
Long-lasting cold periods, especially with extreme cold winter storms (air temperature ≤ 0°C)	Warm and/or short winter Storms with air temperatures > 0 °C
Snow fall that blocks cave openings during late winter or early spring	Early snow fall that blocks cave opening
Entering humidity in spring facilitate ice formation (e.g. snow melting, precipitation)	Large amounts of precipitation and prolonged rainfall in the months with air temperatures > 0 °C
Summer months with low amounts of precipitation	
Early onset of winter in autumn	

Classification of Ice Caves by Halliday

Based on the classification of ice caves by Halliday (1954), different ice cave types are listed below. Halliday classified ice caves by their cave type and not by the properties of the ice. We expand Halliday's classification by the category of the glacier caves. Additionally, the term *glacières* is replaced by the term *ice caves* to prevent misunderstandings because most cave ice has nothing to do with glaciers. Figure 1a shows the location of all ice caves in mainland US that have been reported in the literature.

Limestone Solution Ice Caves

The group limestone solution ice cave includes a large number of ice caves. This type comprises ice caves that have formed by dissolution of limestone. While this type of cave is spread all over the country, the special climatic conditions in mountain areas favor this type of ice cave, leading to a cluster of limestone solution ice caves in the Rocky Mountains (compare Fig. 1b). The cave size and ice volume in these caves vary greatly. One of the most well known limestone solution ice caves in the US is the Decorah Ice Cave in Iowa. Here, meteorological measurements were already conducted before 1900 (Kovarick, 1898).

Lava Tube Ice Caves

Lava tubes are frequently found on the slopes of volcanoes, and ice formed in them may persist for large parts of the year. The necessary moisture and cold air masses penetrate through cracks, skylights, and collapsed parts of the lava tube caves (Halliday, 1954). These ice caves are primarily located in western parts of the US, from Washington to New Mexico (Fig. 1c), like the ice caves in the Craters of the Moon National Monument, Idaho. Publications on these ice caves by Stearns (1924) and Limbert (1924) are among the first reports about this ice cave type in America. Lava-tube ice caves are also found on Hawai'i (e.g., at the Mauna Loa volcano above elevations of 3,000 m) (Kempe, 1979; Halliday, 1991) (Fig. 2).

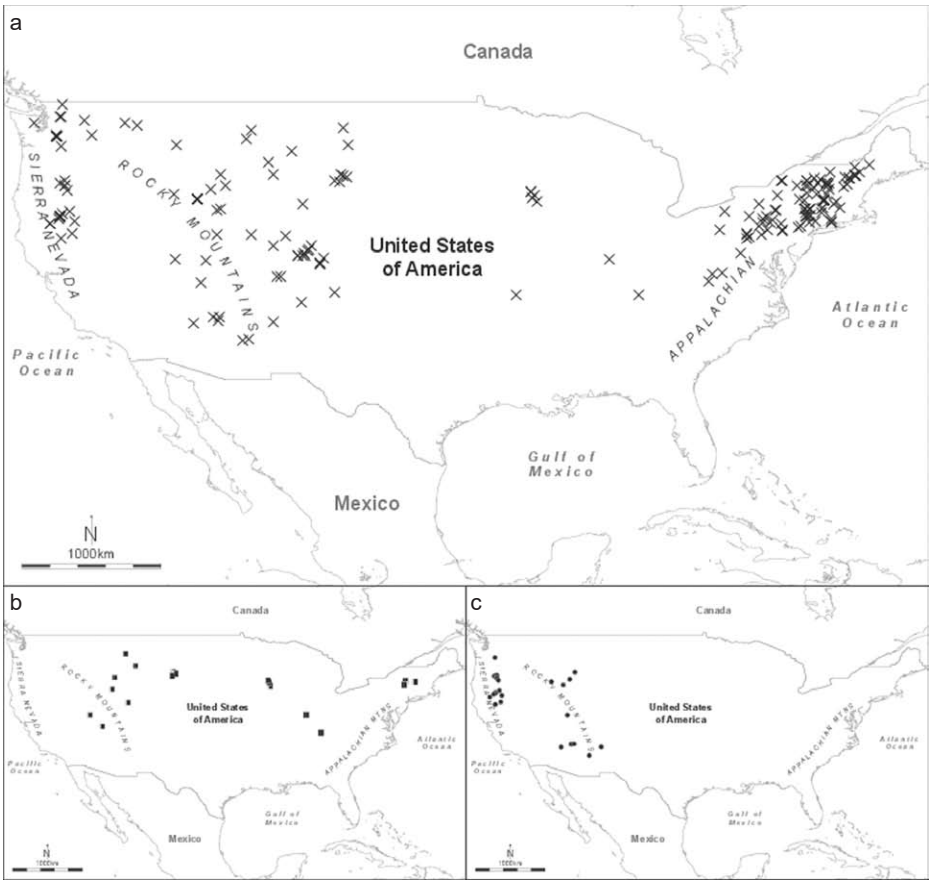


Figure 1. a, Top, distribution of ice caves in the contiguous United States. b. Lower left, ice in solution caves. c. Distribution of lava tube ice caves.



Figure 2. Frozen lake in a lava tube ice cave on Hawai'i.

Fissure-and-Sink Ice Caves

Fissure-and-sink ice caves are ice caves that feature smaller cave volumes. Ice deposits in cracks and sinks, mainly in higher latitudes, fall into this category. These ice caves can be found in the northeastern United States and in high elevation areas from North Dakota and Wyoming to New Mexico (Halliday, 1954) (Fig. 3a).

Talus-and-Gorge Ice Caves

An ice cave type that is further discussed in another study (Holmgren et al., 2017) is termed talus-and-gorge ice caves. This type is typified by ice deposits in debris and ravines, and the actual caves are relatively limited. The smallest ice caves of the world can probably be classified as this type. The occurrence of these caves is limited to only a few

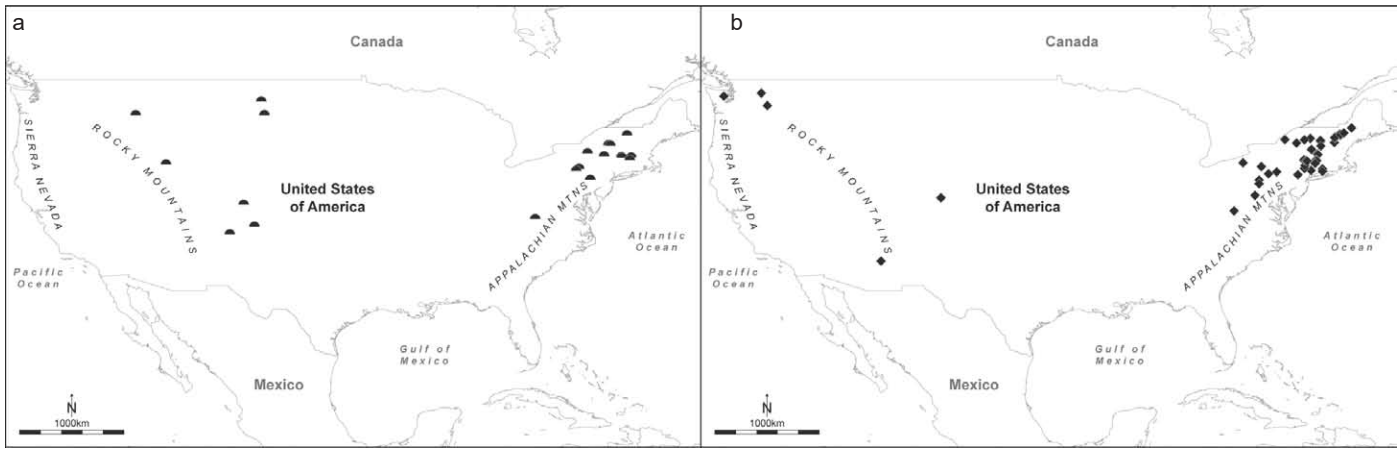


Figure 3. a. Locations of fissure-and-sink ice caves in the contiguous United States. b. Talus-and-sink ice caves.

regions in the US (Fig. 3b). On the west coast, observations of this cave type have been limited to the state of Washington. There are some documented caves in the Rocky Mountains such as Palmer Lake Ice Cave in Colorado, but most of these caves have been documented in the northeastern US (Holmgren and Pflitsch, 2012). An example is the Randolph Hill Ice Gulch in New Hampshire (Halliday, 1954).



Figure 4. Ice in an abandoned car tunnel, Alaska.

Artificial Ice Caves

Mine Ice Caves

One of two ice cave types that can be classified as anthropogenic or artificial is mine ice caves. These are ice deposits in mines and tunnels in cold climates (Halliday, 1954). The cave size is dependent on human activity (Fig. 4). These caves can be found in New Hampshire, New York, Vermont, Alaska, and especially in Colorado (Fig. 5a). Preliminary investigations and explorations by Andrews (1913) in Sweden Valley Ice Mine, Pennsylvania, are among the most important early American ice cave studies.

Ice-forming Wells

The ice-forming wells type includes ice deposits in artificial wells and shafts. Reports on these vertically oriented ice caves come solely from the northeastern US (Massachusetts, New Hampshire, New York, and Vermont) (Fig. 5b). While ice-forming wells might be more common than previously thought, they are one of the least studied ice cave types (Halliday, 1954).

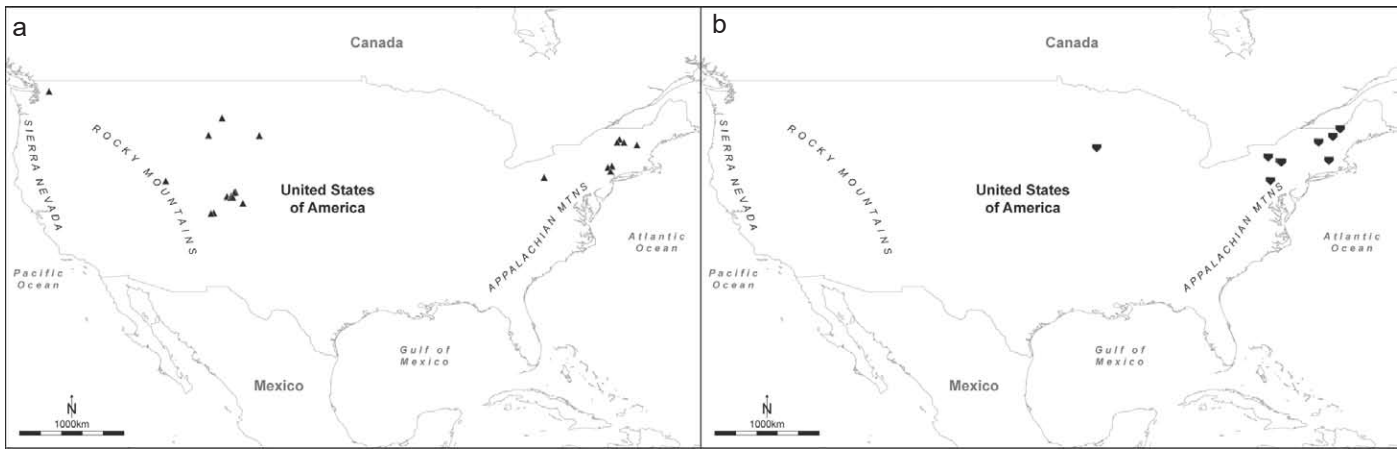


Figure 5. a. Mine ice caves in the contiguous United States. b. Ice-forming wells.

Glacier Caves

Glacier caves are the final cave type of this classification. Glacier caves consist purely of ice and are not influenced by, or dependent on, physical or chemical rock weathering. Glacial meltwater runoff creates and modifies these tunnels constantly (Fig. 6). Indeed, this is a defining feature, as the changes in the shape of the cave are much more rapid than in any other cave type. As these caves are bound to glaciers, they can mainly be found in Alaska, Washington, and Wyoming (Fig. 7). Glacier Caves are also sparsely scattered throughout California, Colorado, Montana and Oregon (Halliday, 1954). One of the most well known glacier caves in the U.S. is contained within the Matanuska Glacier in Alaska; it has been explored in multiple studies by Gulley and Benn (Gulley, 2009; Gulley et al., 2009).

Ice Cave Research of the United States

Global ice cave research is diverse. Students of a wide range of scientific disciplines, including biology, earth sciences, hydrology, and climatology consider ice caves in their research. Current ice cave research focuses mainly on European ice caves. In recent decades, studies about ice caves in the Alps are among the most essential contributions to ice cave research.

The world's first mention of an ice cave is in an Asian publication by the Indian Kalhana. In his book *Kalhaṇa's Râjataraṅgiṇî* (1148/1149), he refers to a cave that contains blocks of ice in the region of Kaschmir, according to a modern edition (Stein, 1961). It was more than 600 years later when the first accounts can be found for an ice cave in the US (Dearborn and Ives, 1822; Dewey, 1819). Starting in the year 1800, Dearborn, Ives, and Dewey visited the Snow Hole near Williamstown, New York, on multiple occasions.

In Europe, the distinct features of ice caves were recognized earlier than in North America. First written records come from a personal note by Leonardo daVinci about a cave in Italy in the late 1400s (Turri et al., 2009).

Previous Ice Cave Research in North America

Past ice cave research in North America can broadly be classified into two main eras. The first era includes extensive publications by Edwin S. Balch between 1880 and 1930. The second era began in 1930 with significant publications by William R. Halliday that extended through the late 1950s.

First Era of North American Ice Cave Research

The most important work of the first era of North American ice cave research is *Glacières or Freezing Caverns* by Edwin Swift Balch (1900). Balch began visiting ice caves in America and later visited ice caves around the globe. In late September 1877, he encountered ice in the debris of King's Ravine on Mt. Adams in the White Mountains of New Hampshire. Always accompanied by local hikers and local inhabitants, Balch sought ice caves of any kind for the following 22 years. At the end of that time, Balch pursued the goal of passing on his comprehensive knowledge about underground ice deposits. In addition to providing locations of ice caves around the globe, Balch put forward theories about the formation of ice in caves, while also reporting about his experiences and adventures in ice caves. With the simplest of means, such as cigar smoke and simple thermometers, Balch tried to determine air flows and temperature differences. In his books and articles (Balch, 1897; Balch, 1899; Balch, 1900), he also gathered information from locals, documenting their knowledge of ice caves back to 1725. Other scientists of this time limited their research to single caves such as the Decorah Ice Cave (Kovarik, 1898) or the Craters of the Moon (Stearns 1924; Limbert 1924), conducting more detailed research.



Figure 6. Glacier mouth of Pure Imagination Cave of Sandy Glacier on Mt. Hood, Ore. (June 21, 2015).

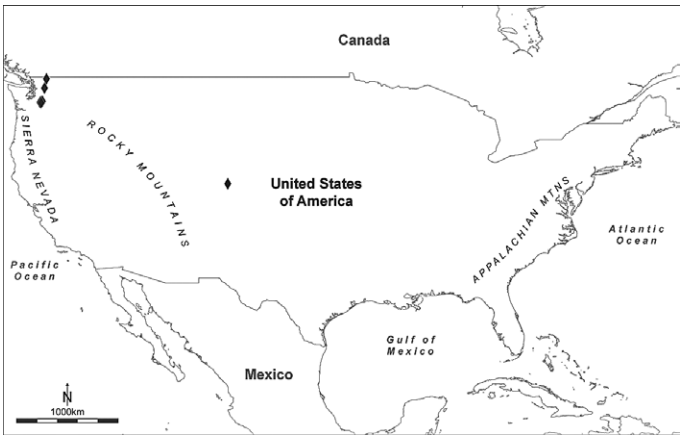


Figure 7. Glacier ice caves in the contiguous United States.

Second Era of North American Ice Cave Research

The results of this first era were followed up in the second era. In their publications, Merriam (1950) and Halliday (1954) compiled lists of American ice caves, trying to group them in different ways. In his article "Ice Caves," Merriam documented ice caves and grouped them by state to create a map illustrating the locations of the 36 known American ice caves. Halliday, however, classified ice caves into different categories, providing an example for each category. As outlined above, he based his classification on the cave type, independent of the type of ice (Halliday 1954). In addition to providing ice cave inventories, these publications dealt with problems of ice cave research, including enduring issues concerning a clear nomenclature. Different theories concerning the formation of ice were discussed, and air temperature data from within caves, as well as from their vicinity, were compared and analyzed. These had often been obtained by third parties. Besides those by these two authors, there were a few individual publications addressing ice caves, such as a report about an ice cave in the desert west of Albuquerque, New Mexico, by Kennedy (1938) and the note of a cave with ice in central Utah by Rogers (1942).

Current State of American Ice Cave Research

Following these two eras of American ice cave research that concluded in the 1950s, the interest in this phenomenon decreased. Research about various aspects of ice caves in North America has picked up again only in the last decade. These studies mainly focused on lava tube ice caves in California, talus-and-gorge ice caves in New England, glacier ice caves in Alaska, along with the possibility of ice caves on Mars.

The changes in ice level in various lava tube ice caves in the Lava Beds National Monument, California, have been observed since 1990. Fuhrmann (2001, 2007) and Kern and Thomas (2012) have analyzed the trends of ice levels in various caves, partially reconstructing ice levels based on photographs from the decades before the beginning of the time series of new measurements. Mineral deposits helped reconstruct previous ice levels (Fuhrmann, 2007).

Observations of the talus-and-gorge ice caves in New England began in October 2008 (Fig. 8). Since then, Holmgren and Pflitsch (2011) have continuously monitored air temperatures in the talus slopes and gorges, as well as air temperatures at different positions in the debris. Additionally, thickness measurements of the cave ice in different talus-and-gorge ice caves in New Hampshire and Maine are conducted at the potential time of minimum ice extent. In recent years, the ice thickness has been recorded by regular measurements (Holmgren and Pflitsch, 2011). These multi-annual observations of the alternation between phases of ice buildup and ice depletion over the course of a year serve as excellent climate indicators for short- and long-term changes in the climate of an entire region (Holmgren and Pflitsch, 2012).

Glacier ice caves (englacial drainage systems) continue to be heavily investigated by Gully and his colleagues. In Alaska, Gulley examined one of the longest valley glaciers in the world, the Matanuska Glacier, which is approximately 39 km long. The focus of his research is the formation and shaping of glacier ice caves, as well as the evolution of existing glacier ice caves. Factors that might trigger or amplify these processes are of particular interest (Gulley, et al., 2009; Gulley, 2009).

The southernmost ice caves in the world are located in Antarctica. These ice caves, located on Mt. Erabus on Ross Island are being studied by scientists from New Mexico Tech who examine the microclimate and morphology of fumaroles of ice. Special measurement techniques, such as temperature measurements using fiber optics to identify geothermal point sources should be highlighted (Curtis and Kyle, 2011).

A research field that has developed in recent years and is of special interest for the US is the research concerning the potential presence of extraterrestrial ice caves on Mars. Ice caves could prove the existence of water on Mars, potentially allowing life on Mars. This research asks whether ice caves exist and what their possible uses may be (Perşoiu et al., 2011; Pflitsch et al., 2011; Williams et al., 2010).

Summary

In the first era of American ice cave research, roughly from the 1880s to the 1930s, the highest number of previously unknown ice caves were mentioned in the literature. With intensifying industrialization, public and scientific interest in ice caves decreased. In the subsequent second era, from approximately 1930 to the 1950s, fewer new ice caves were described. During this era, publications mainly summarized previously known American ice caves, attempting to classify these by the cave type or the state in which they lay.

Only in the last decade has ice cave research regained some of its significance in the United States. However, only a fraction of American ice caves still exist. Today's scientists view ice cave research as an opportunity to obtain information about climate changes in the past. For climate scientists, ice caves can be a true treasure. As a natural climate archive, they contain information about the climate of the past and present. The scientific database of American ice caves is not yet on the same level as in Europe, but has constantly improved. Sufficient study areas featuring different ice cave types are available on the American mainland. Ice cave research provides a niche for a large variety of scien-

tific disciplines. In 2014, the 5th International Workshop on Ice Caves took place Idaho Falls for the first time outside of Europe. The preservation of these natural and cultural treasures is a major objective of ice cave research.

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

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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,

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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

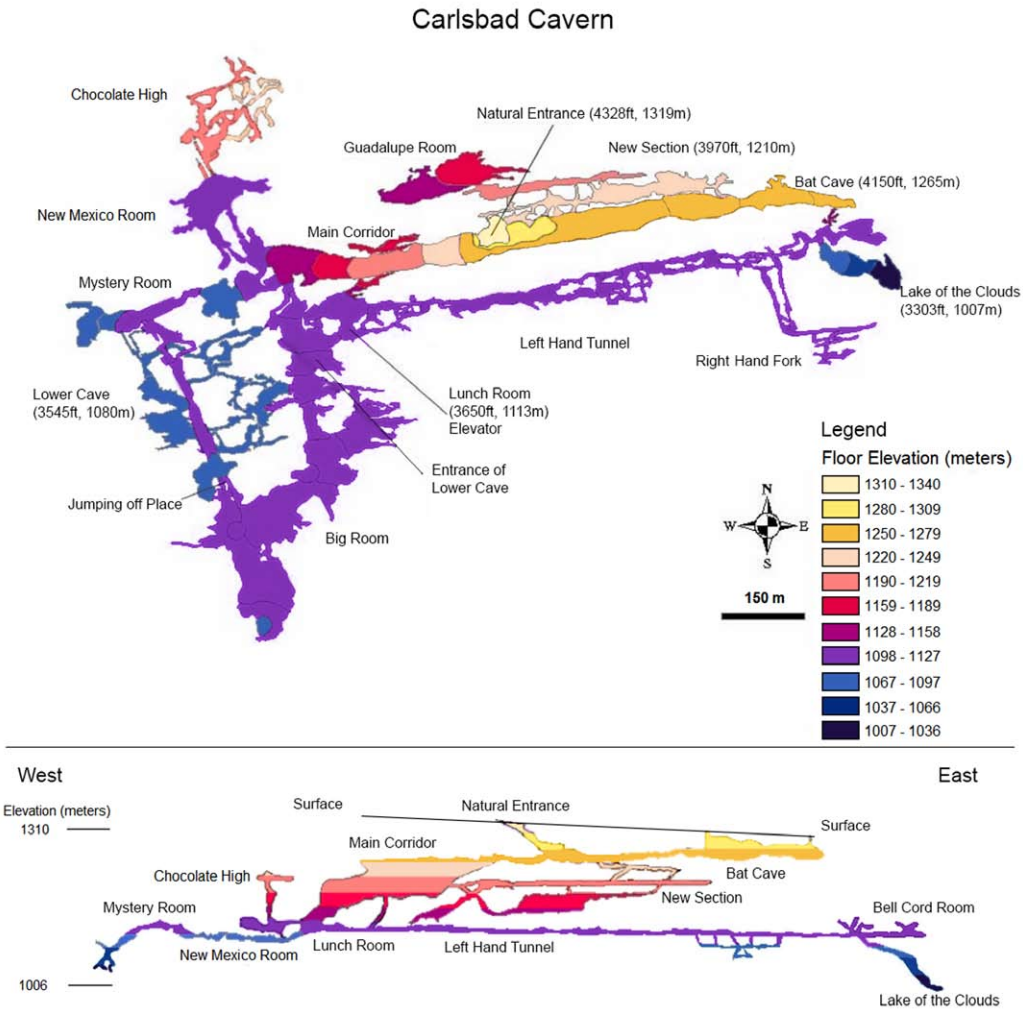


Figure 1. Plan view of Carlsbad Cavern and profile of its northern part, adapted from a figure provided by the Cave Research Foundation.

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.

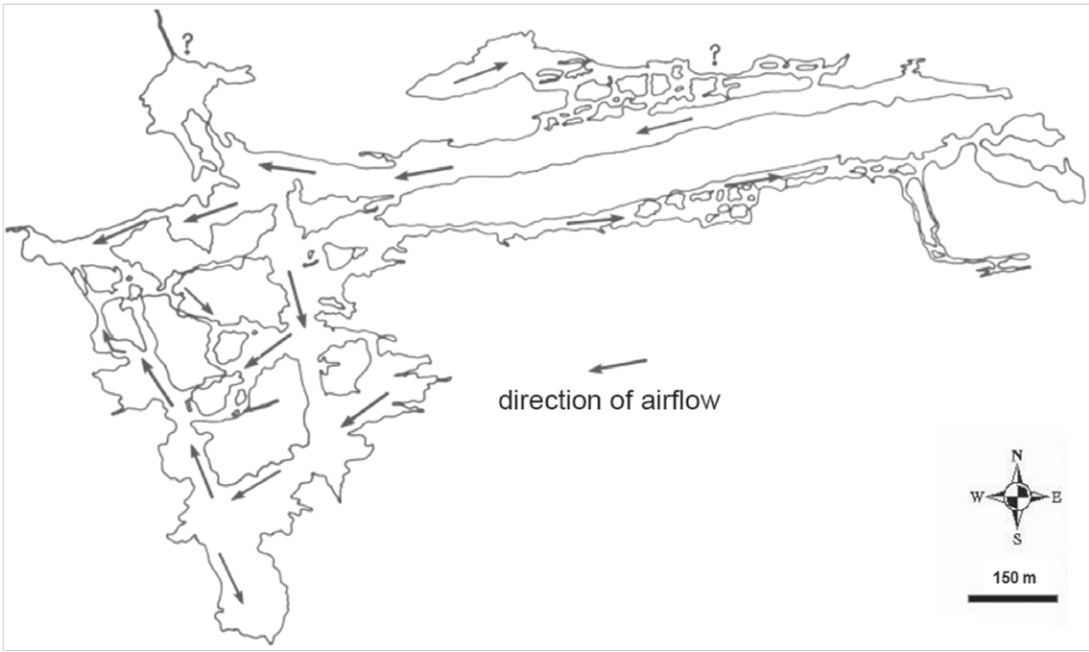


Figure 2. Dominant direction of convective flow of cold air into the cave during winter.

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

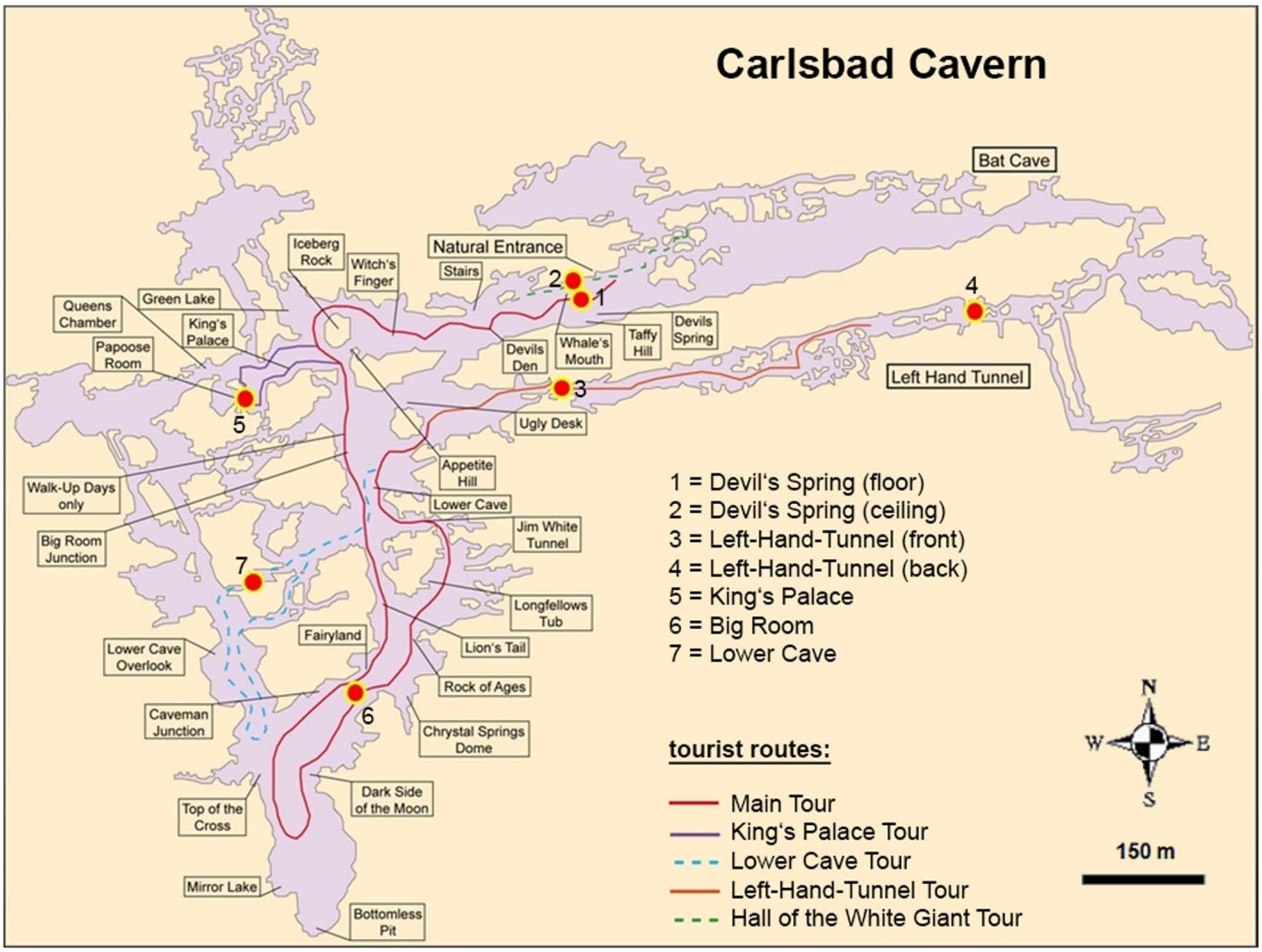


Figure 3. Positions of the data loggers used during the climate measurements inside Carlsbad Cavern and the various tourist routes through the cave system, adapted from a figure from the National Park Service.

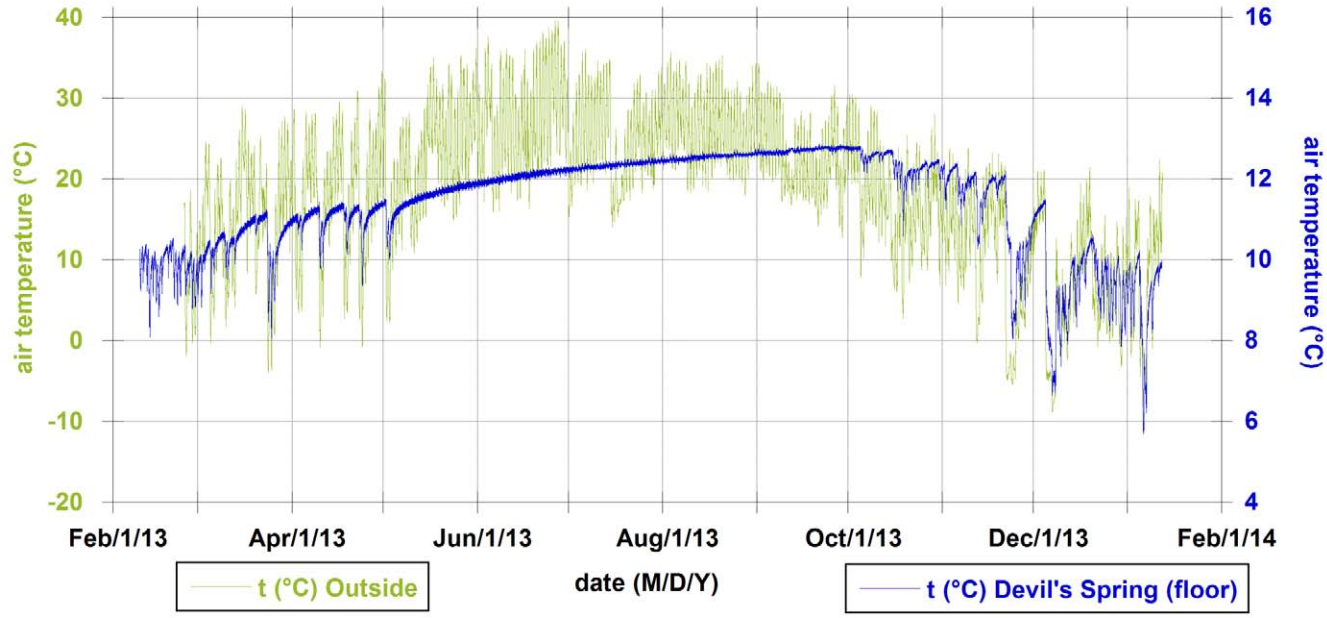


Figure 4. Records of the near-ground air temperature on the surface and near Devil's Spring inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes.

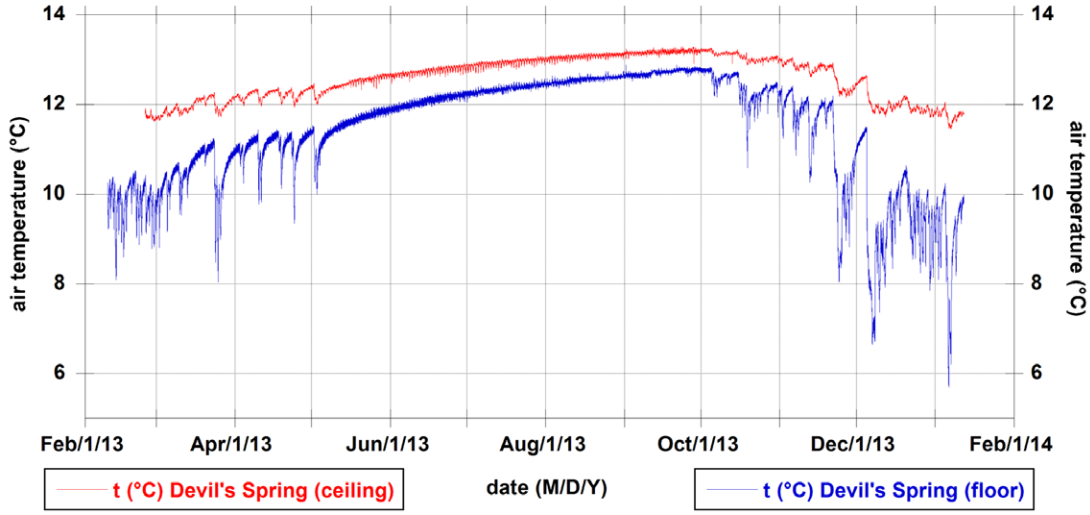
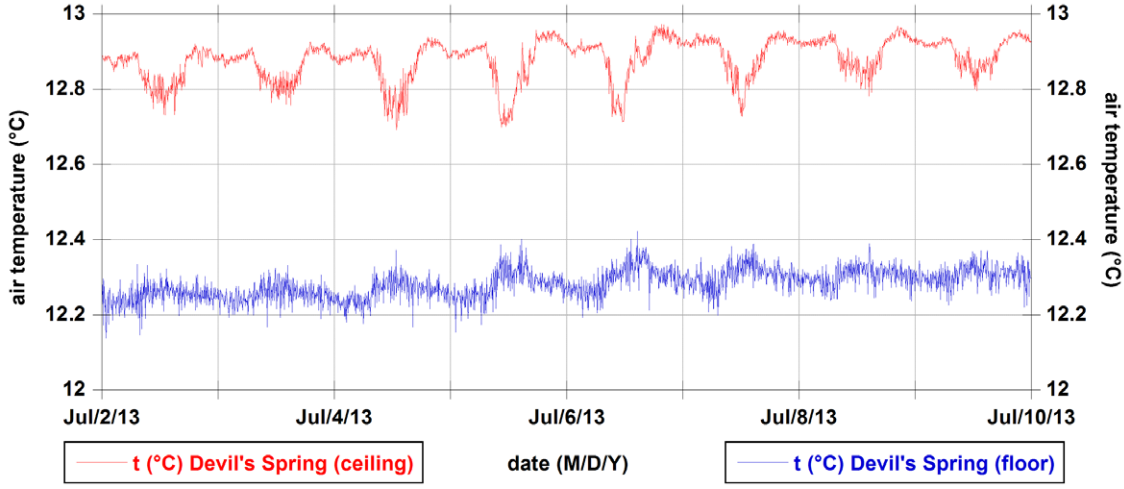


Figure 5. Records of the air temperature at the ground and the ceiling near Devil's Spring inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes.

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.



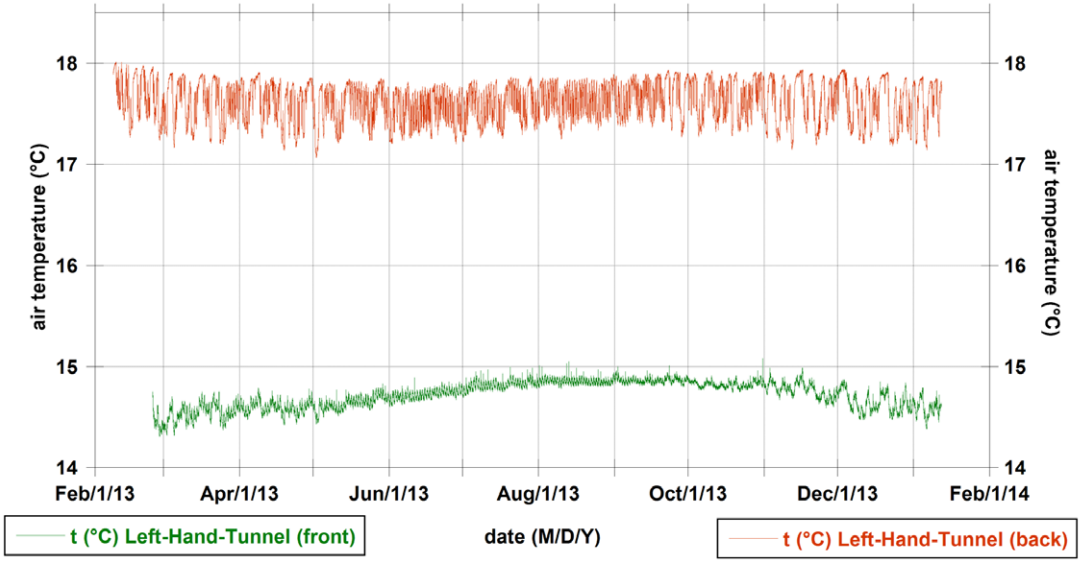


Figure 7. Records of the air temperature in the exterior (front, logger LHT-F) and the interior (back, logger LTH-B) parts of the Left Hand Tunnel inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes.

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

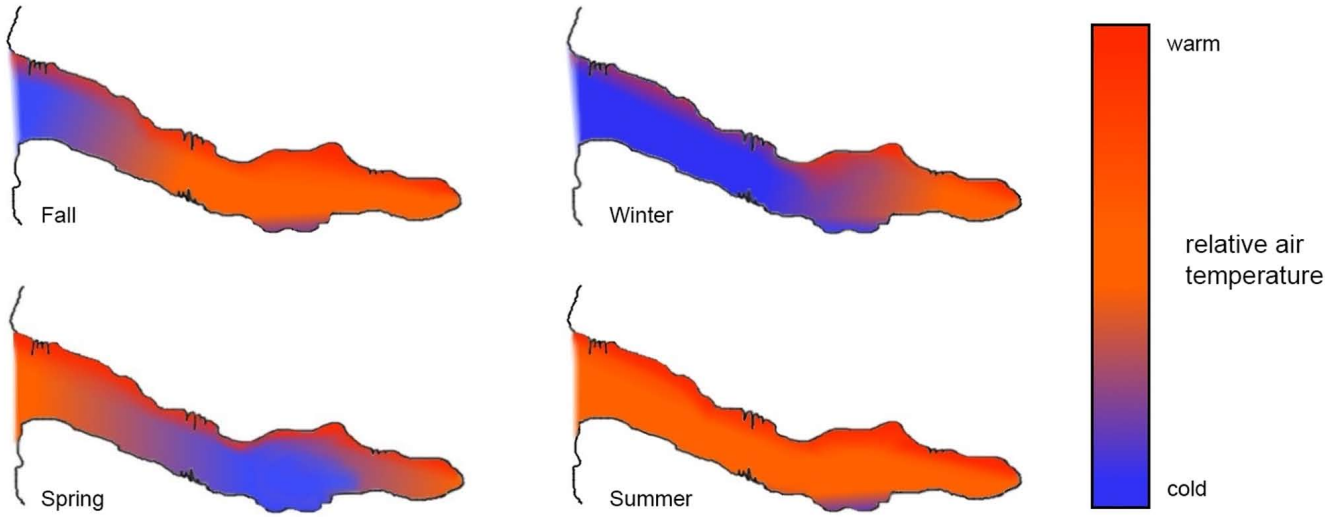


Figure 8. Schematic profile of the air temperature in a cold-trap cave influenced by the outside weather.

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

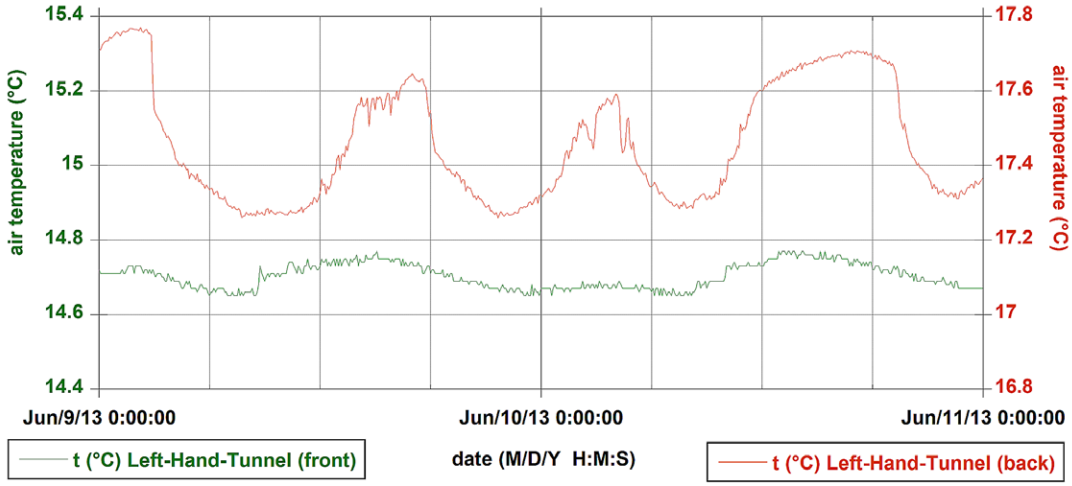


Figure 9. Records of the air temperature in the exterior (front, logger LHT-F) and the interior (back, logger LTH-B) part of the Left Hand Tunnel inside Carlsbad Cavern, on an expanded scale for June 9 and 10, 2013, recorded every 5 minutes.

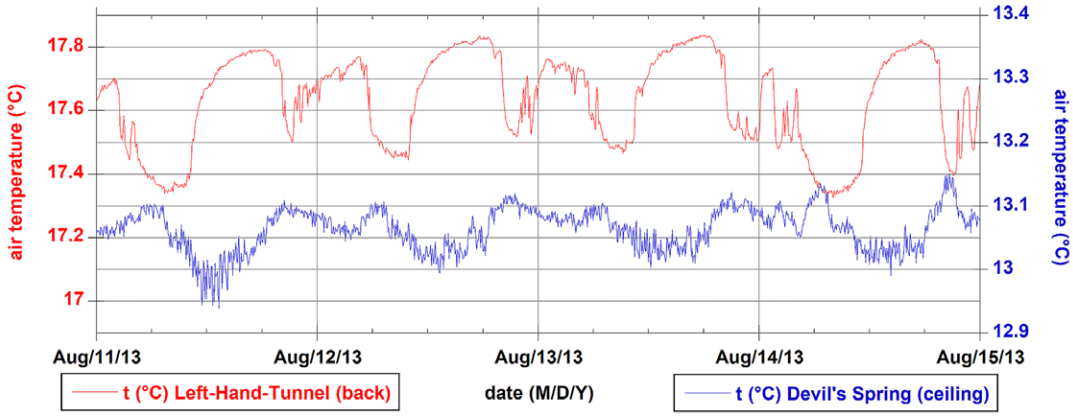


Figure 10a. Records of the air temperature in the exterior (front, logger LHT-F) part of the Left Hand Tunnel and the ceiling near Devil's Spring inside Carlsbad Cavern, on an expanded scale from August 11 through August 14, 2013, recorded every 5 minutes.

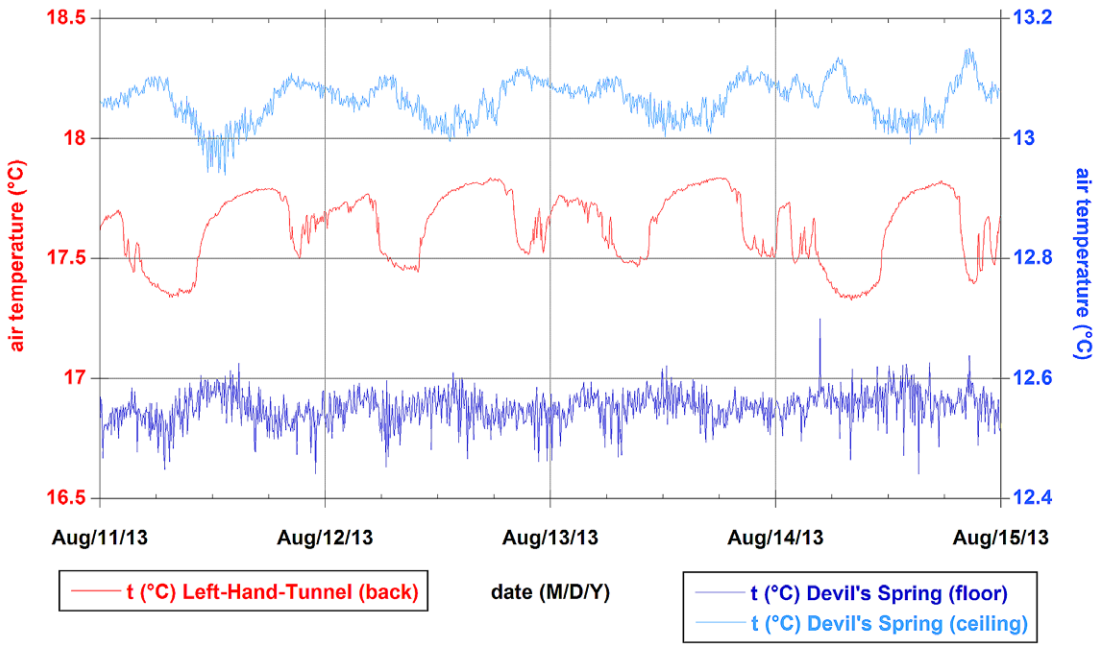


Figure 10b. Records of the air temperature in the interior (back, logger LTH-B) part of the Left Hand Tunnel and the floor and ceiling near Devil's Spring inside Carlsbad Cavern, on an expanded scale from August 11 through August 14, 2013, recorded every 5 minutes.

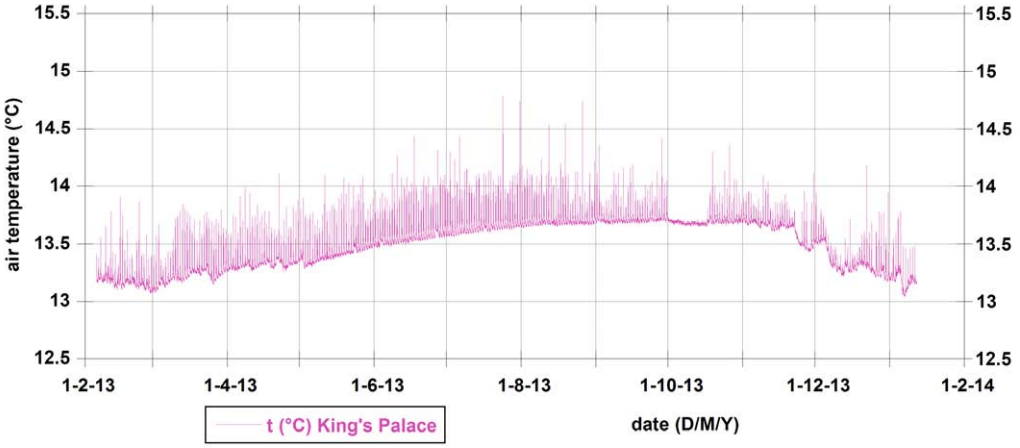
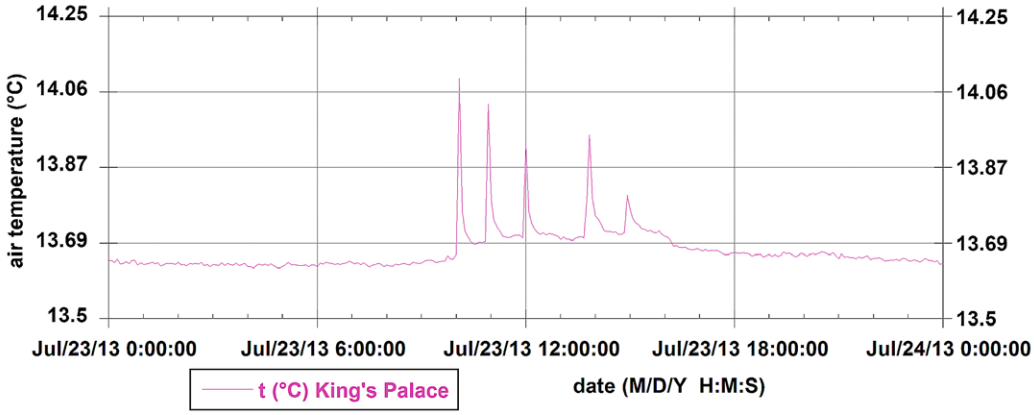


Figure 11. Record of the air temperature at a height of 3 m in the Papoose Room on the King's Palace tour inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes.

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.



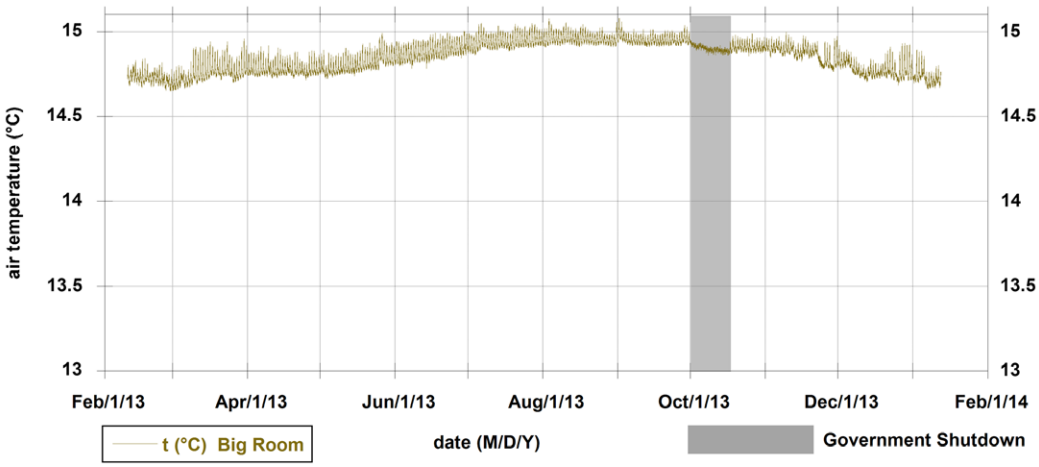
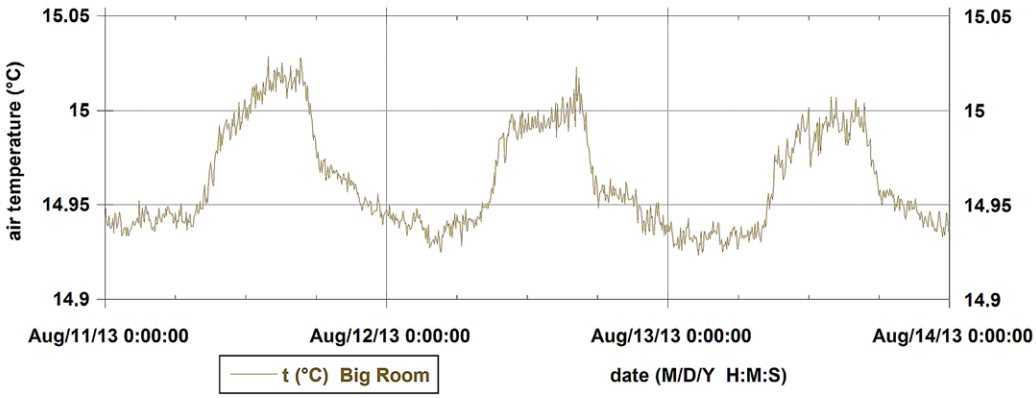


Figure 13. Profile of the air temperature in the Big Room inside Carlsbad Cavern from February 2013 to January 2014, recorded every 5 minutes. The period when the cave was closed to tourists is highlighted.

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

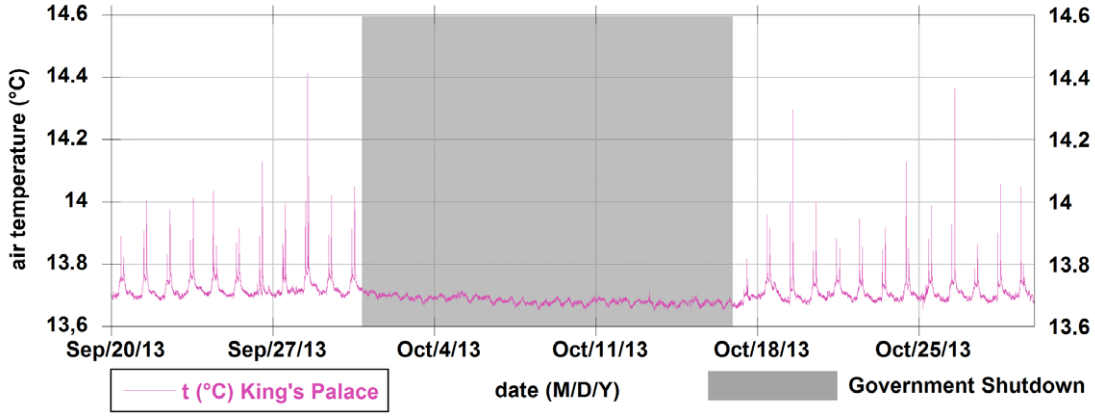
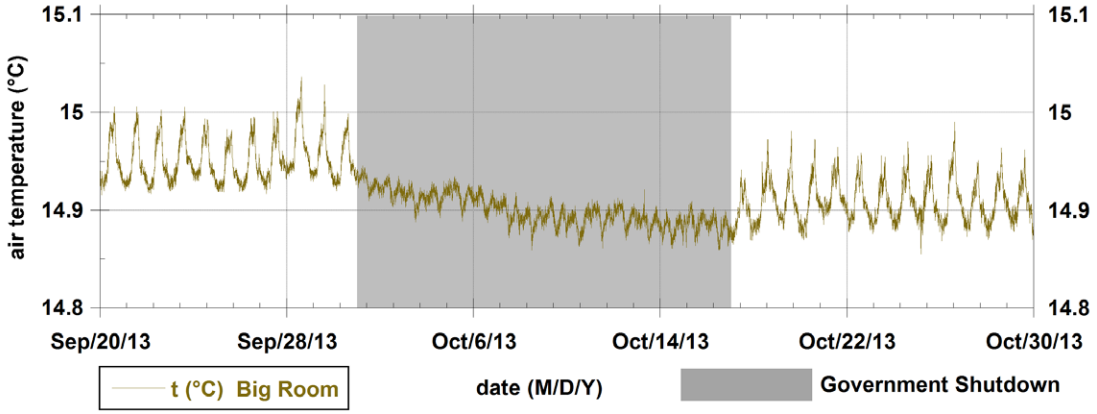


Figure 15. Record of the air temperature in the Papoose Room on the King's Palace tour inside Carlsbad Cavern on an expanded scale from September 20 to October 30, 2013, recorded every 5 minutes. The period when the cave was closed to visitors is highlighted.

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.



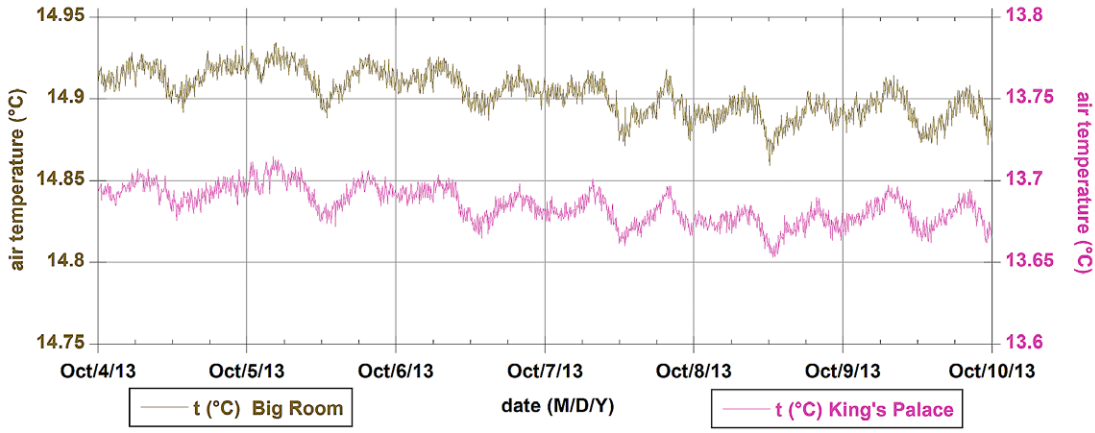


Figure 17. Records of the air temperature in the Big Room and the Papoose Room on the King's Palace tour inside Carlsbad Cavern on an expanded scale from October 4 through October 9, 2013, recorded every 5 minutes. The cave was closed to visitors during this time.

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.

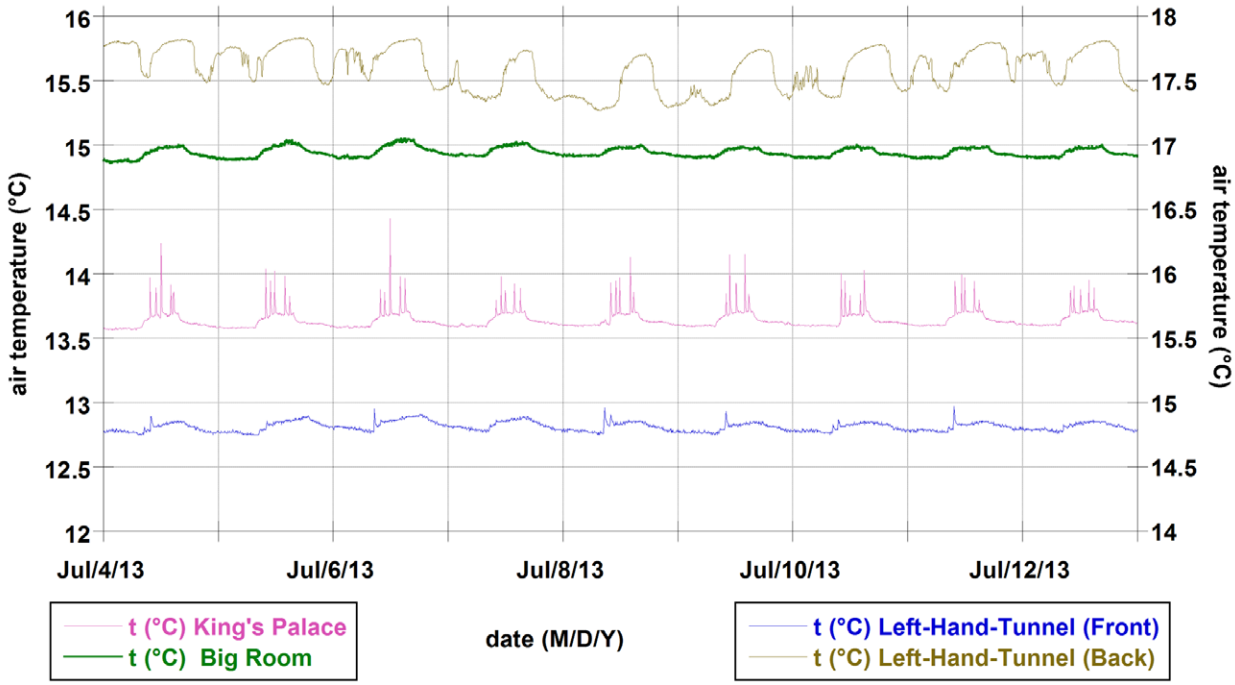


Figure 18. Records of the air temperature in four different parts of the Carlsbad Cavern on an expanded scale from July 4 through July 12, 2013, recorded every 5 minutes.

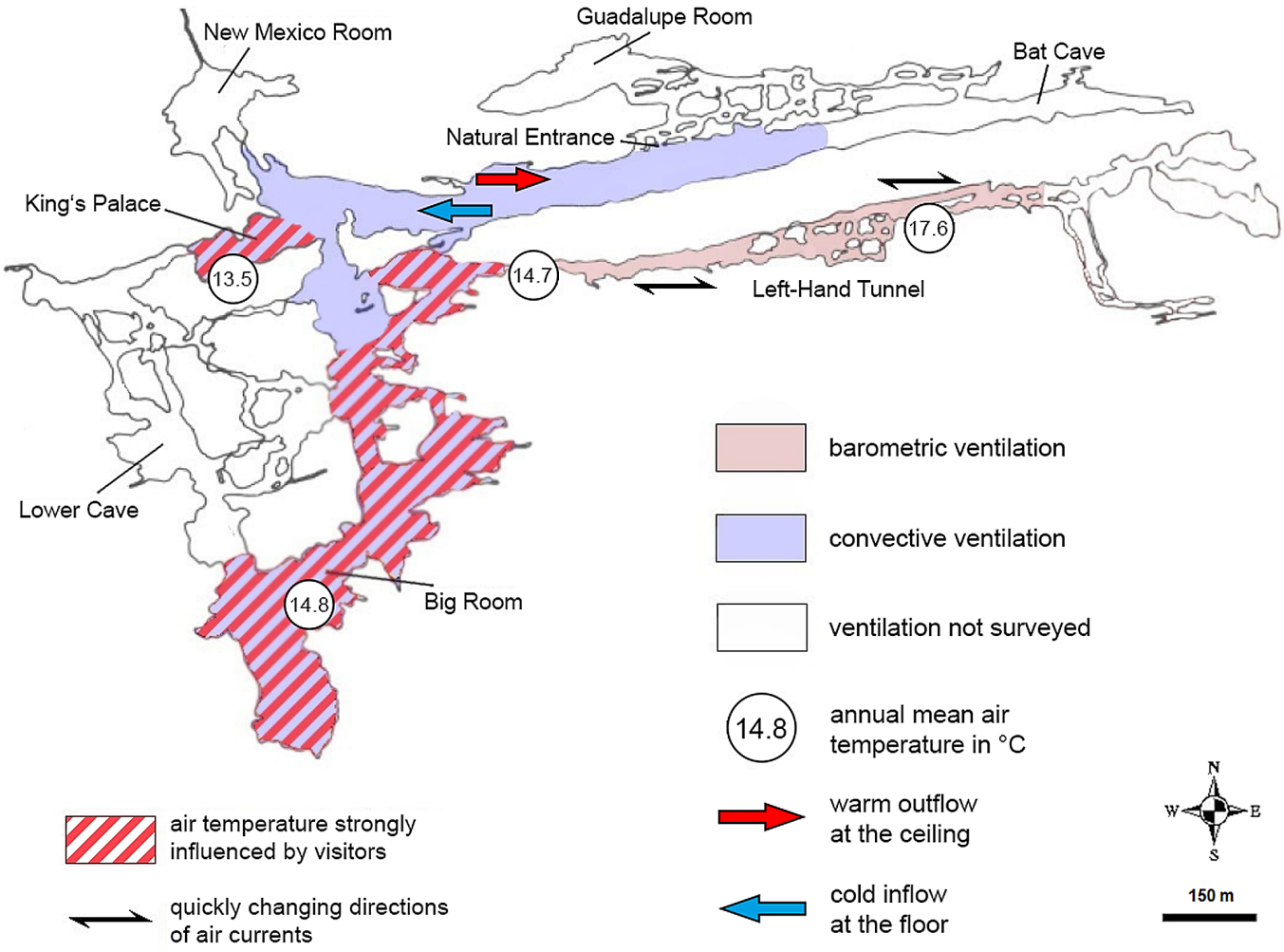


Figure 19. Spatial distribution of the predominant effects on the climate in Carlsbad Cavern studied in this paper. The underlying map of the system is based on Hill (1987).

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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The authors wish to thank the National Park rangers of Carlsbad Caverns for their valued support during the measurements. We also wish to thank Arthur Palmer for the provision of his very detailed maps of the cave and Josefine Häßler for her valuable support. Lastly, we wish to thank our two reviewers for making many important comments and improvements on an earlier version of this paper.

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A. Pflitsch, A. Adam, M. Schwabe, W. Furian, and S. Allison. A study on thermal dynamics inside Carlsbad Cavern, New Mexico, USA. *Journal of Cave and Karst Studies*, v. 79, no. 3, p. 168-178. DOI: 10.4311/2014IC0121

A STUDY ON THERMAL DYNAMICS INSIDE CARLSBAD CAVERN, NEW MEXICO, USA

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Abstract

The climatic conditions of Carlsbad Cavern, New Mexico, are particularly complex. Its variety of large, as well as very narrow chambers, tunnels, and remote areas is the reason for its diversity of microclimates and special climatic features that are the subject of this paper, which can be seen as accompanying the article "The importance of air temperature as a key parameter to identify climatic processes inside Carlsbad Cavern, New Mexico, USA" by Killing-Heinze et al. (this issue). Two studies measured the trends of temperature through much of the cave during March-April 2011 and February 2013. One of the studies also assessed airflow directions using puffs of smoke. The main result was the detection of the flow of cold outside air from the entrance down the floor of the Main Passage and into the Big Room, especially along its west side. Temperatures increased along the route from the entrance to the Big Room, but some locations in the Big Room showed temperature ranges as great as those in the Main Corridor.

Introduction

This paper, as well as the article "The importance of air temperature as a key parameter to identify climatic processes inside Carlsbad Cavern, New Mexico, USA" (Killing-Heinze et al., 2017 [this issue]), addresses the climatic conditions inside Carlsbad Cavern. Because the morphology and the climate of this cave system are extensively described in the other article, the authors will not give another introduction of the research area in this paper.

This paper relies on data and results of two independent studies (Schwabe, 2013; Adam, 2014) and aims at a better understanding of the temperature profile and the course of air currents inside the cave. This could be used to stop undesirable or negative impacts on the beauty of the cave or the bats that roost in the Left Hand Tunnel and Bat Cave sections of Carlsbad Cavern. This paper should add to the understanding of the cave's temperature regime by dealing with the following five questions: Which air temperatures and temperatures trends are measurable along the Main Corridor and inside the Big Room? Up to which point of the cave system is it possible to immediately track changes in the outside weather and how do these changes affect the different parts of the cave? Which airflow directions can be found inside the cave and how stable are they? Are there areas with increased wind velocity? Is it possible with the data available to draw conclusions on the prevailing thermal dynamic of Carlsbad Cavern?

For clarification of these questions, the results of two studies conducted in 2013 and 2014 were evaluated. In the course of the studies, measurements were conducted to assess the climatic conditions from the Natural Entrance to the Big Room. By using highly sensitive equipment, even small-scale changes of the air temperature could be detected. The results are presented and interpreted at first for each part of the cave individually and then for Carlsbad Cavern in its entirety.

Methodology

Both studies treated in this paper used data of the Bat Draw weather station of the Western Regional Climate Center located near the Carlsbad Caverns National Park Visitors Center to support their analysis and evaluation.

Methods in Schwabe (2013)

The equipment used during the period of measurement (March 9 to April 13, 2011) consisted of two TESTO 645 thermistors to measure the air temperature inside the cave, one TESTO Quicktemp 850-2 thermistor to measure the surface temperature, and one smoke wind indicator to visualize air currents. The TESTO 645 can measure the temperature with an accuracy of ±0.1 °C, whereas the TESTO Quicktemp 850-2 has an accuracy of ±1 °C. During the measurements a yardstick was used as a mounting device for the TESTO 645.

The measurement route started at the amphitheater near the Natural Entrance and followed the descending tourist path down the switchbacks and through the Main Corridor to the Big Room Junction and then continued along the circular path around the Big Room. The measurement points are grouped and named by their position.

The outside measuring points A_S1 to A_S12 are arranged as centrally as possible along the asphalted switchbacks of the Natural Entrance to reduce the potential influence of the cave walls and their different topography (Fig. 1; the sub-

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script S is used to distinguish Schwabe's outside measuring points from Adam's). Measuring point A_S1 is placed at the highest point of the descent, and therefore, is the farthest from the Natural Entrance. Point A_S12 was located at the deepest point and lay almost inside the cave. A_S6 to A_S12 were already beneath the ceiling of the cave entrance. The inner measuring points MP1–50 were placed along the tourist trail and cover the area of the Main Corridor and the Big Room (Fig. 2). To complement the measurement program with a cross profile of the cave, supplementary measuring points (P1–P7) were placed close to the Devil's Spring at a large breakdown pile that can be found there (Fig. 3).

Because during the study questions arose about the origin of some air currents in the front part of the cave, the measurement program was extended on March 21, 2011, by eight additional measuring points, and the numbering of the original points was changed to accommodate them. Four of these were positioned on the main tourist path (MP0, 1.5, 3, and 8), while the others are located a little apart (MP4, 5, 6, and 7) (Figs. 2 and 4).

The data acquisition started on March 9 and ended on April 13, 2011. The first measuring traverse of the day (MG1) commenced at 4:30 a.m. local time (UTC–7), or 5:30 after the switch to summer time, and covered the outside locations AS1–AS12 followed by the measuring points MP1 and MP2, the additional points in the range

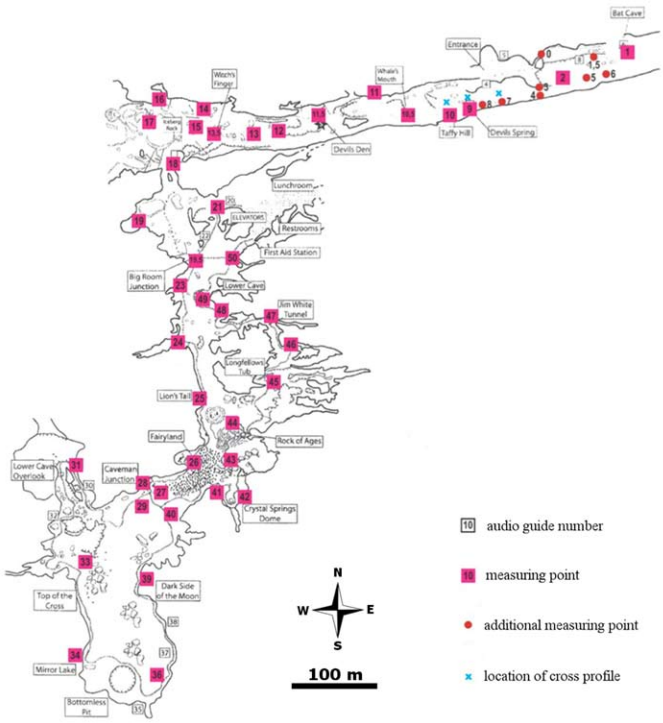


Figure 2. Plan of the main tourist part of Carlsbad Cavern showing the location of measuring points used by Schwabe (2013). The measuring points, both original and additional, are referred to in the text as MPn. The cross-profile was assessed by measuring points P1–P7. Most of the points are named for numbered stations in the audio guide to the cave supplied to visitors, although not all such stations were used.

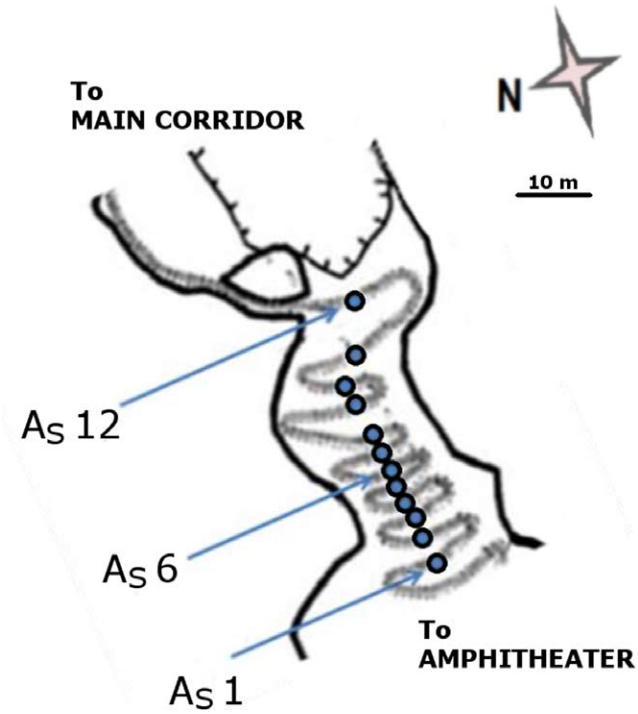


Figure 1. Positions of the outside measuring points A_S1–A_S12 in the area of the Natural Entrance of Carlsbad Cavern during Schwabe's study (Schwabe, 2013).

MP0–MP8, the measuring points of the cross profile P1–P7, and the measuring points MP9–50 along the Main Corridor and inside the Big Room. The duration of MG1 was approximately three and a half hours. The second measuring traverse (MG2) started at 4:30 p.m. local time (5:30 summer time) and covered only the outside locations AS1–AS12, the measuring points MP1 and MP2, the additional points MP0–MP8, and the measuring points of the cross profile P1–P7. This measuring cycle ended after approximately one and a half hours at P7 (Table 1).

For the outside locations A_S1–A_S12 and the measuring points MP0–50, data acquisition consisted of first measuring the air temperature at a height of 2 m (± 0.1 m) and then, except at A_S1–A_S12, assessing the flow conditions of the air with the aid of the smoke wind indicator. The data acquisition at the respective measuring points was performed in the middle of the main tourist trail and across its course. To determine the air current, smoke was set free by pressing the small bellows of the smoke wind indicator several times at a height of 1.5 m to 2.0 m (± 0.1 m). By observing the movement of the smoke, the wind direction could be ascertained for each location. Further, the wind velocity was evaluated qualitatively and assigned to one of three velocity categories: slow, fast, and turbulent/gusty. Afterwards, the surface temperature of the floor and the ceiling was measured. At the profile measuring points P1–P7, the temperature was measured beginning at a height of 20 cm and ending at a height of 3 m, with one measurement each 20 cm resulting in vertical profile at each of the locations across the passage.

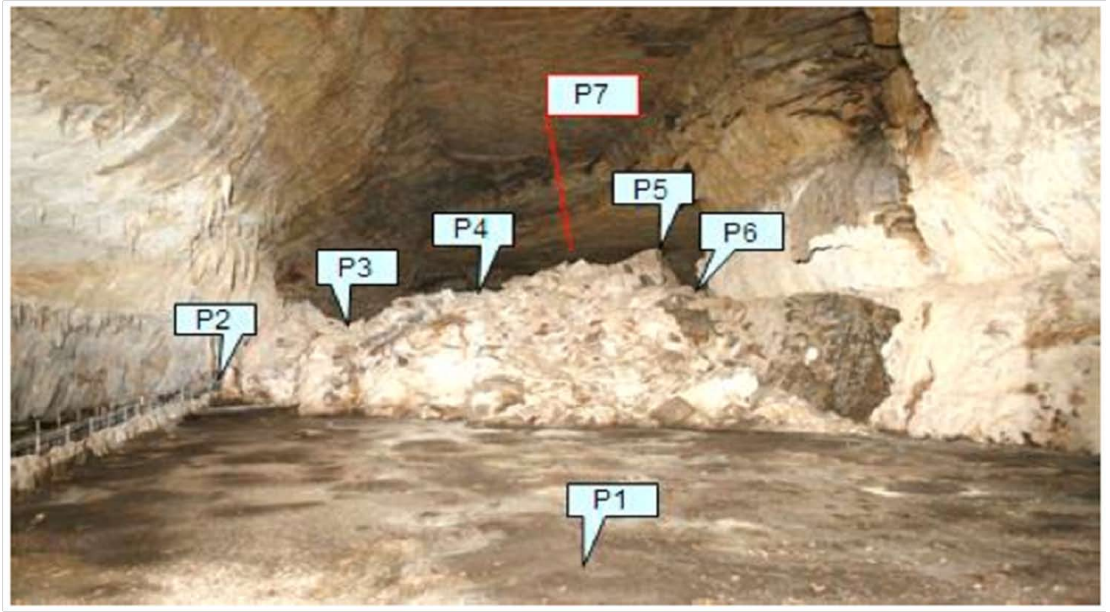


Figure 3. Positions of the measuring points P1–P7 of the cross section of Carlsbad Cavern, close to the Natural Entrance. P7 lies behind the rubble heap and cannot be seen in this photograph (Schwabe, 2013).

Methods in Adam (2014)

For the data acquisition, a TESTO 400 was used to measure the air temperature. Its two sensors cover a range from –20 °C to +70 °C with an accuracy of ± 0.1 °C. During the measuring cycles a yardstick was used as mounting device for the TESTO 400 and its temperature sensors were fixed at a height of 20 cm and 200 cm.

During the week of February 6 to February 11 in 2013 each day's measuring cycles (MG1–MG4) were conducted every six hours, at 2 and 8 a.m. as well as 2 and 8 p.m. Every measuring cycle took approximately one and a half hours. This structure served two aims: to cover a spectrum of times as widespread as possible and to conduct the data acquisition with minimal disturbance to visitor traffic.

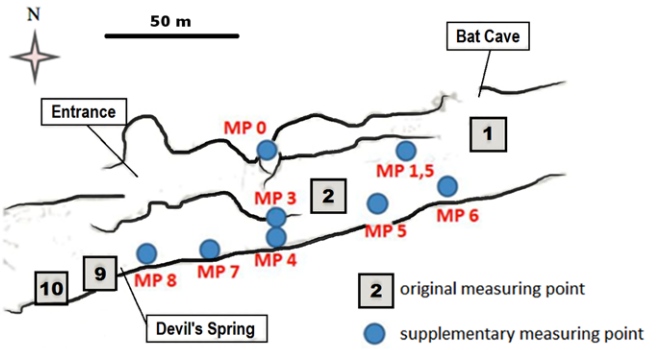


Figure 4. Location of the original measuring points MP1, 2, 9, and 10 and the later added points MP0, 1.5, and 2–8 in the front part of Carlsbad Cavern (based on Schwabe, 2013).

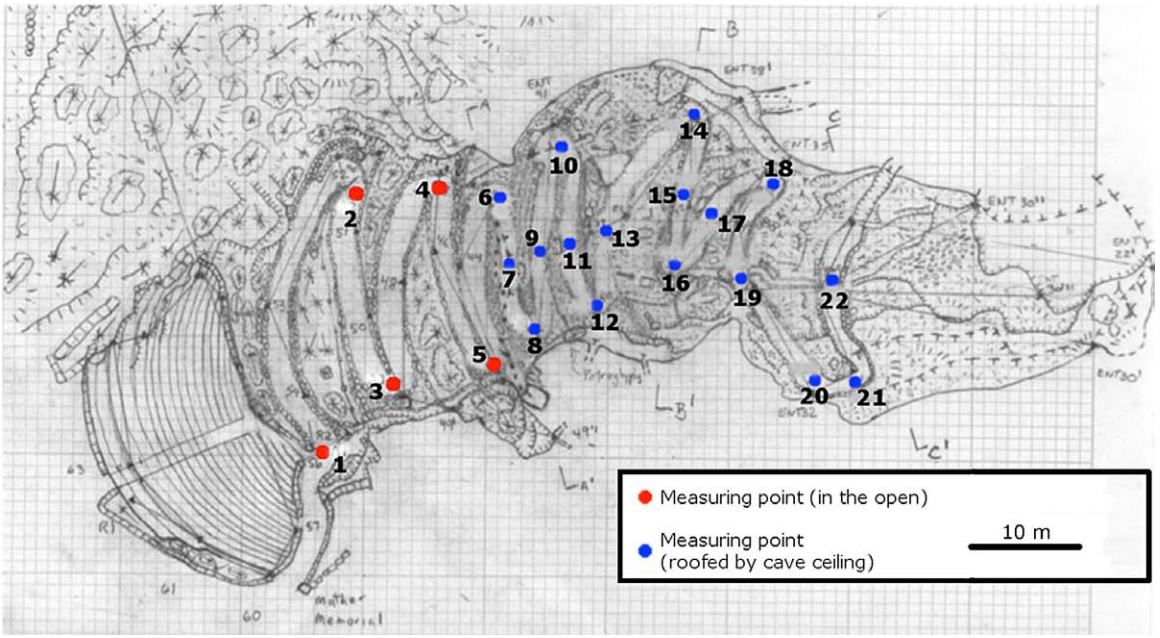


Figure 5. Positions of the outside measuring points A_A1–A_A22 in the area of the Natural Entrance of Carlsbad Cavern during Adam's study (Adam, 2014).

Table 1. Overview on the position, the label and the number of the daily measuring cycles for all measuring points (based on Schwabe, 2013).

Position	Original label	Label adapted to audio guide number	Measuring cycle (MG)	Special features
Outside, cave entrance	A1 – A12	A1 – A12	MG1+MG2	Roofed (A6 – A12)
Front section of cave	2nd gate	0	MG1+MG2	Additional
Front section of cave	Bat Cave	1	MG1+MG2	···
Front section of cave	Bat Cave/Guano pile	1.5	MG1+MG2	Additional
Front section of cave	Guano pile	2	MG1+MG2	···
Front section of cave	Next to Guano pile	3	MG1+MG2	Additional
Front section of cave	Apart from Guano pile	4	MG1+MG2	Additional
Front section of cave	Bat Cave 1st rock (apart)	5	MG1+MG2	Additional
Front section of cave	Bat Cave 2nd rock (apart)	6	MG1+MG2	Additional
Front section of cave	Trough (apart)	7	MG1+MG2	Additional
Front section of cave	Half way Devil's Spring	8	MG1+MG2	Additional
Front section of cave	Cross profile 1 – 7	P1 – P7	MG1+MG2	Cross profile
Main Corridor	9 – 10	9 – 10	MG1	···
Main Corridor	Whale's Mouth	10.5	MG1	···
Main Corridor	11	11	MG1	···
Main Corridor	J/K	11.5	MG1	···
Main Corridor	12 – 13	12 – 13	MG1	···
Main Corridor	Witch's Finger	13.5	MG1	···
Main Corridor	14 – 19	14 – 19	MG1	···
Big Room	Intersection Big Room	19.5	MG1	···
Big Room	21 – 50	21 – 50	MG1	···

With a length of approximately 2 km and an elevation difference of about 200 m, the measurement route started at the amphitheater near the Natural Entrance and followed the asphalted switchback into the cave and then the course of the Main Corridor up to the Big Room Junction. Along this route, 45 measuring points are placed: A_A1–A_A22 outside and MP1–MP23 inside the cave.

The outside measuring points A_A1 – A_A22 are spread across the asphalted switchbacks at the Natural Entrance; the subscript A identifies Adam's outside points (Fig. 5). Like in the study of Schwabe (2013), A_A1 is the highest point and the farthest from the entrance, while A_A22 is the deepest and nearly inside the cave. While A_A1–A_A5 were placed at the northern and southern vertexes of the switchbacks, the measuring points A_A6–A_A22, which are covered by the ceiling of the entrance, were positioned at the vertexes, as well as the more central part of the entrance sink to cover the whole area of the switchbacks. The measuring points MP1–MP23 were placed along the Main Corridor leading downwards to the Big Room Junction (Fig. 6).

Results and Discussion

The Outside Measuring Points and Devil's Spring

The air temperatures at measuring point A_A1, the farthest from the Natural Entrance (Fig. 5) showed a high correlation with the temperatures that were measured simultaneously at the BatDraw weather station; both showed strong fluctuations. Conversely, the air temperatures at the measuring point closest to the cave entrance (A_A22) were distinguished by relatively high thermal stability and reacted far more slowly to changes in the temperature of the outer atmosphere. The mean air temperatures of this measuring point showed only a small deviation during measuring cycles in the morning and in the evening compared to the much greater deviation at measuring point A_A1. High temperature fluctuations at A_A22 can be observed mainly during the morning measurements and are connected to cold air events, while the air temperatures during the evening measurements are very close to the mean temperature of the whole week. The contrast between A_A1 and A_A22 vanishes nearly completely as soon as the outside temperature approaches the mean temperature of A_A12.

The sinking and varying influence of the solar radiation in the course of the switchback down to the Natural Entrance becomes clear in the mean air temperatures. The highest measuring points are the most exposed to sunlight, and

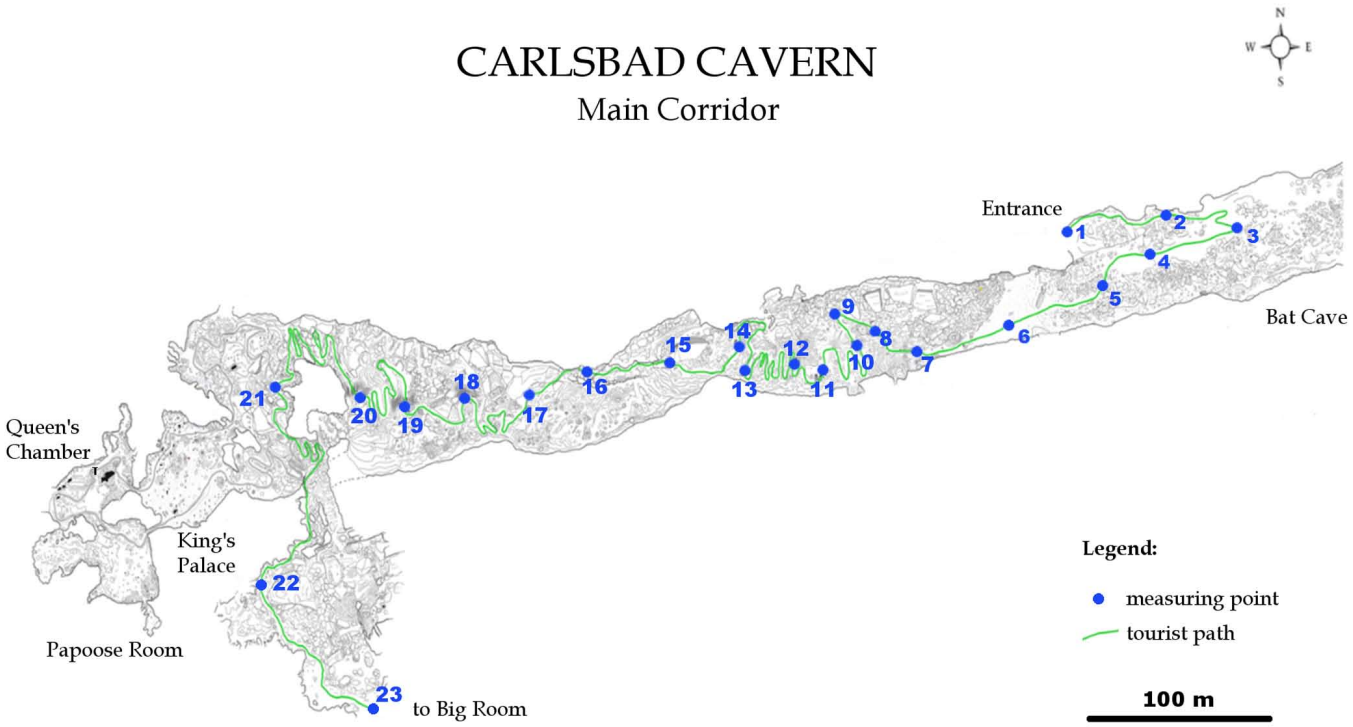


Figure 6. Positions of the 2013 measuring points MP1 – MP23 along the tourist route from the Natural Entrance to the start of the Big Room (based on Adam, 2014).

therefore, become the warmest during the day. The stronger and terraced decrease of the air temperatures from A_A6 onwards can be ascribed to the shadowing by the ceiling of the cave entrance. In the evening, the ranges of the air temperatures are much more balanced in their scale, as well as in their course during the period of measurements than they are in the morning.

The outside measuring points of Schwabe (2013) (see Fig. 1) can be grouped into several temperature clusters (Fig. 7). To avoid the chaining of clusters, the complete-linkage method (CLINK) was employed for this step, also known as farthest neighbor clustering (Krebs, 1999). This agglomerative clustering technique uses a bottom-up approach, first combining similar elements to one cluster and then integrating similar clusters into bigger ones. For this, the crucial characteristic is the distance between those two elements in different clusters that are farthest away from each other. Where this distance is shortest two clusters are merged into one.

After the analysis of the characteristic course of the air temperatures during the morning measurements, four main clusters can be created (colored in Fig. 7a). The highest measuring points A_S1 to A_S7, most of which are not under the roof at the entrance, show very similar temperatures, and therefore, form the biggest cluster. A smaller cluster consists of the fully roofed measuring points A_S8 to A_S11, despite the fact that the air temperature is notably different at A_S11 because of the lower ceiling there. Most conspicuous is the great similarity between A_S12 and the inner measuring points MP1 and MP2. Because of this, A_S12 forms a separate cluster that is more closely related to the cluster of the two inner points than to the other external points on the switchbacks. This exceptional status is caused by the strong influence of the cave atmosphere and by the lesser, but still existing, influence of the outer atmosphere, especially during cold air event.

For the evening measuring cycle, five main clusters can be found (colored in Fig. 7b) that differ distinctly from the ones of the morning cycle. Very similar are the air temperatures at the locations exposed to direct sunlight A_S1 to A_S5. The measuring points A_S6 and A_S7 that belonged to the same cluster during the morning cycle now form a separate cluster because of the shadowing influence of the cave entrance's ceiling. The cluster consisting of the measuring points A_S8 to A_S11 still exists, but with shifted similarities because of the different solar radiation. A_S12 shows an even greater similarity to the inner measuring points, especially to MP1, that can be attributed to the similar elevation of the two locations. The most noticeable pattern is a cold air tongue that starts at the front part of the Natural Entrance and flows in direct line of sight down to and around MP2, which is located close to large pile of bat guano several meters lower than the measuring points A_S12 and MP1. From there the colder air moves near the ground in the directions of both the Bat Cave and the Main Corridor. The measuring point MP2 is hardly influenced by the warming of the outer air during the day. The resulting temperature differences between MP2 and both A_S12 and MP1 are reflected in the creation of an independent cluster for MP2.

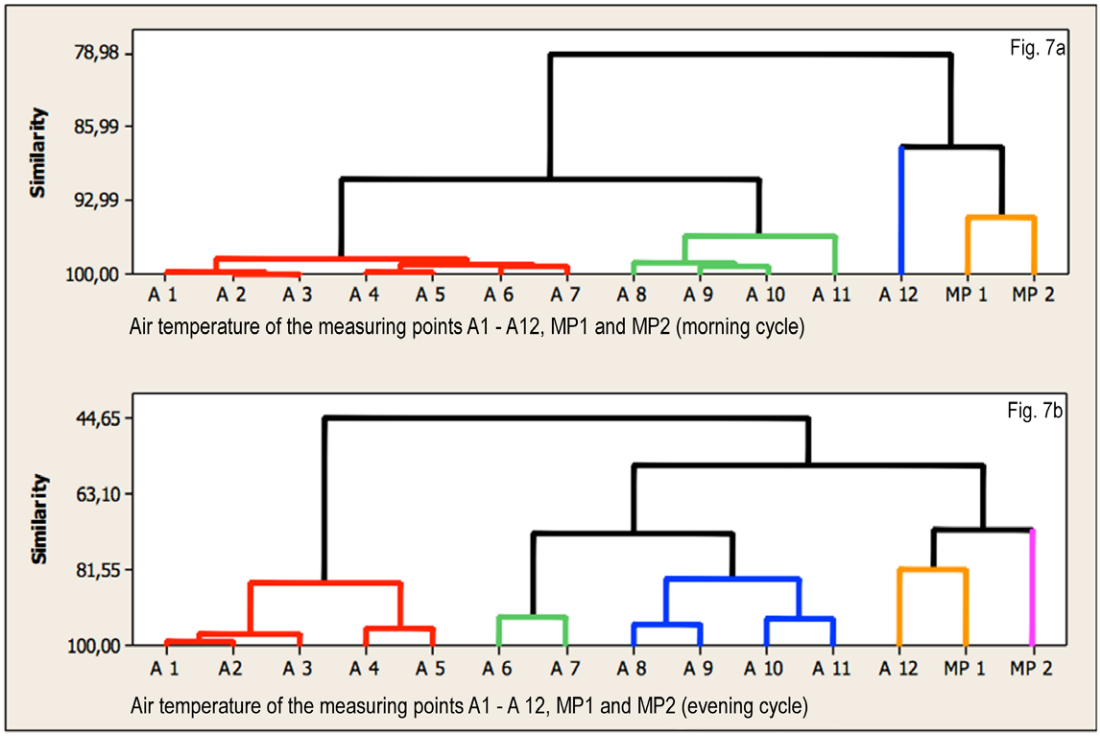


Figure 7. Results of the cluster analysis (complete linkage-method) for the air temperatures of Schwabe's measuring points A_S1–A_S12, MP1, and MP2 as a dendrogram for the morning (Fig. 7a) and the evening (Fig. 7b) measuring cycles (based on Schwabe, 2013).

With the aid of the cross cross-section data provided by P1–P7 the origin of the air currents flowing in the direction of the Main Corridor can be determined. Two flow paths can be conjectured (Figs. 8a and b). In the first version, the inflow of air is completely on the left side of the guano pile beneath the cave entrance and does not expand to the right side of the cave until just ahead of the breakdown pile (Fig. 8a). The second possibility would be that only the main part of the inflowing air moves around the left side of the guano pile, while a small amount flows over it at the right and then down to the Main Corridor (Fig. 8b). Consideration of the seven locations in the cross-section illustrates the complex streaming and temperature patterns possible in this small part of the cave and gives an impression of the general prevailing circulation system inside Carlsbad Cavern during the measuring period.

Main Corridor

With increasing distance from the Natural Entrance, an overview of the measuring points clearly show a zoned structure with increasing air temperatures and decreasing temperature differences. The lowest temperatures were measured at the point closest to the entrance, while the highest temperatures belonged to a point in the Big Room level that is the farthest from the entrance. The increase in the air temperature shows a cascading course and can be attributed to a combination of the declining influence of the outside weather, the sloping Main Corridor, and the three dimensional shape of the cave.

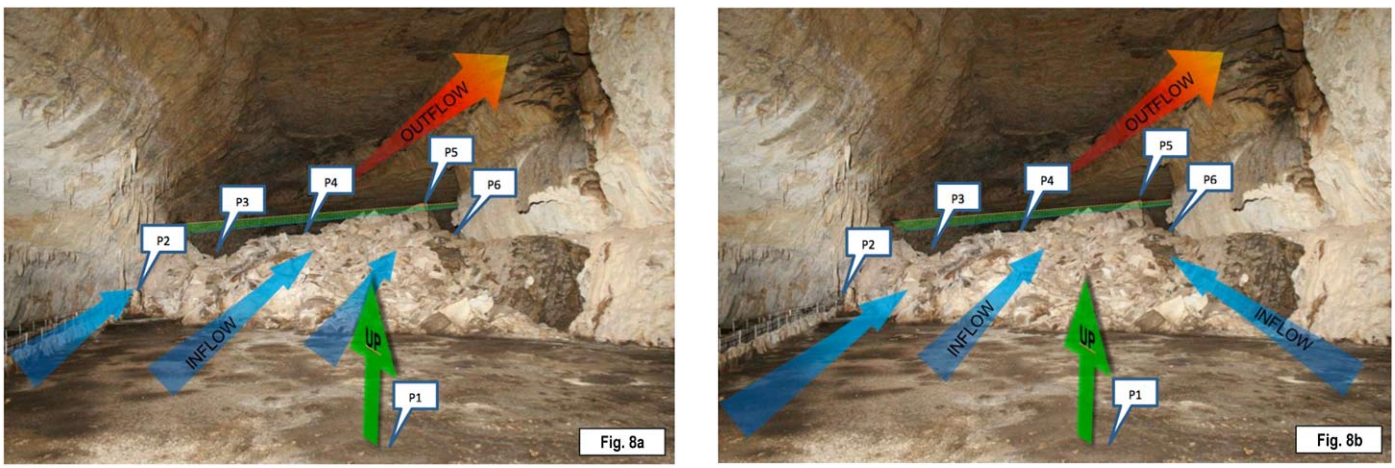


Figure 8. Alternative models of the airflow past the rubble heap at Devil's Spring that were investigated using the profile stations P1–P6. The second model (8.b) adds flow over the right side of the obstruction (Schwabe, 2013).

The strong impact of the near-ground inflow from Natural Entrance and the Bat Cave through the Main Corridor on the air temperature at the measuring points in the Main Corridor starts behind the constriction at Adam's point MP7 that is caused by the breakdown pile near Devil's Spring. The increased velocity of the air, accompanied by a certain drift to the left side of the Main Corridor, was noticeable. Beyond the constriction the air currents move through a breach in a low rock formation and flow into a lower level close to MP10 (Fig. 9). As a result the profiles of the air temperature at MP8 and MP10 were quite similar, while at MP9, which is located away from the direct flow path, higher air temperatures could be measured during all measuring cycles.

According to Schwabe's data from 2011, increased velocity of the air currents is present up to the Witch's Finger formation, but suddenly not at the next measuring point, close to the Iceberg Rock, even though these two form a straight line (Fig. 2). The reduction of the air velocity can be explained by the strong blocking effect of a limestone formation directly behind the measuring point. Because of this formation, most of the inflowing air is led off to the right near Witch's Finger with further reduced velocity. The slower moving air then forms vertical currents in the following part of the cave (Fig. 10).

Big Room

Schwabe's measuring points inside the Big Room are located approximately 230 m beneath the surface and at least 1.8 km away from the Natural Entrance representing the deepest study locations. Considering their great depth below ground level and distance from the cave entrance, the measuring points of the Big Room show relatively high temperature fluctuations, both individually and in comparison to the others.

Figure 11 shows that the air temperature at a measuring point was lower the closer it was located to the junction of the Main Corridor and the Big Room, reflecting the influence of the cold inflow that is still present at this depth. Also the points nearer the entrance in general showed the greatest ranges of air temperature (> 0.8 °C).

Deeper inside the Big Room, the air temperature increased, whereas its range decreased, underlining the declining influence of the air currents flowing down from the Main Corridor. Nevertheless, a certain shifting of the cooler measuring points was noticeable: Although all were colder the closer they were to the junction, the area of colder measuring points reached farther into the Big Room on the west side of the room (MPs in the twenties), which is more exposed to direct air flow from the Main Corridor.

Overall, in the Big Room only small fluctuations of the mean temperatures were visible when comparing the separate days; the outside weather could hardly can be detected inside the Big Room. Cold air events were visible with a one-day delay, but disappeared as time went on.

The air currents streaming through the Main Corridor fanned out broadly at the junction area. As mentioned above, the main part of the air seemed to flow into the Big Room on the western side. A small amount veered east in the direction of the elevators and the Lunch Room. The measuring points between the Big Room Junction and Lion's Tail were located on the main flow path of the air currents and were characterized by higher wind velocities. The other measuring points generally displayed slower and more likely vertical air currents (Fig. 12).

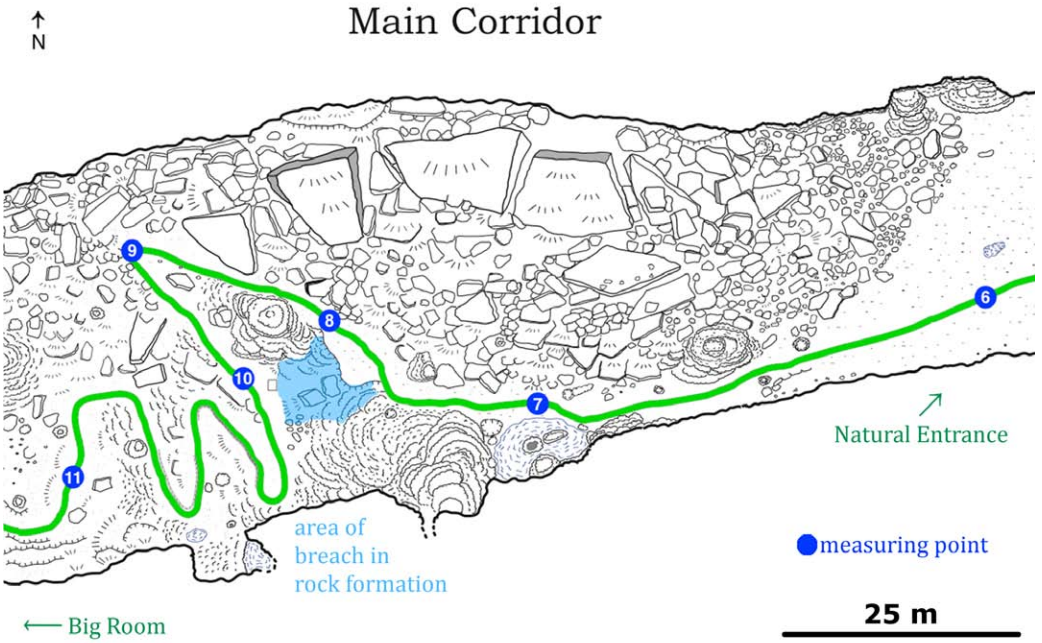


Figure 9. Map of the Main Corridor close to the Devil's Spring inside Carlsbad Cavern with the positions of Adam's measuring points MP6–MP11. The main airflow bypassed the tourist trail through the gap in the wall of formations (based on Adam, 2014).

Figure 10. Depiction of the dominant air currents from the Natural Entrance through the Main Corridor to the Big Room according to the study in March-April 2011 (based on Schwabe, 2013). The relative velocity of the flow is coded in the thickness of the outline of the arrow.



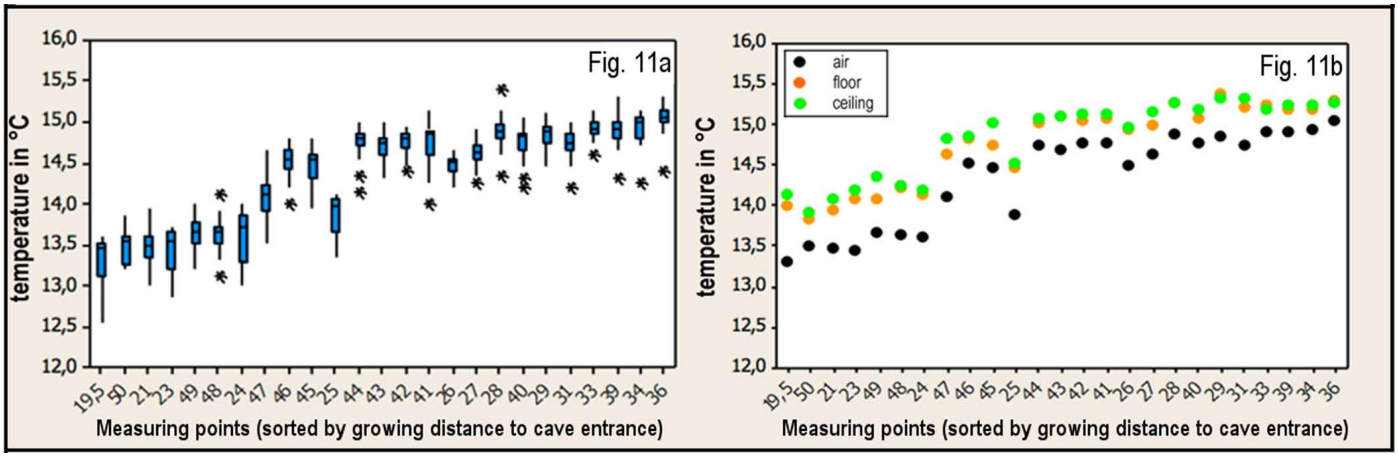


Figure 11. Air temperature ranges (box plot diagrams, part a) in the Big Room of Carlsbad Cavern for Schwabe's measuring points ordered by their distance from the Main Corridor and the cave entrance, as well as the mean temperature of the air and the rock surfaces (b) (based on Schwabe, 2013).

The inflowing air masses continued their course with the described western drift until the area around Caveman Junction. On the wet side of the Big Room, rock formations deflected inflowing air that then streamed into the back of the Big Room with an eastern drift. Near the Lower Cave Overlook, air currents were apparently rising from the Lower Cave into the Big Room. Most likely this air sank into Lower Cave along the ladder route near the start of the Big Room (Fig. 12). This cooler air would be warmed by the bedrock of the smaller passages in Lower Cave, which would explain the warm air rising from Lower Cave at the Lower Cave Overlook, more commonly referred to as the Jumping Off Place.

The most interesting measuring point was located in the rear part of the Big Room east of the Bottomless Pit (MP36). Despite its very deep position inside the cave and the great distance from the Main Corridor, it displayed the greatest variety of airflow directions. Vertical airflows dominate, but there are also air currents directed back into the Big Room.

To make room for the inflowing air there has to be an outflow of air. The air currents measured both at the more

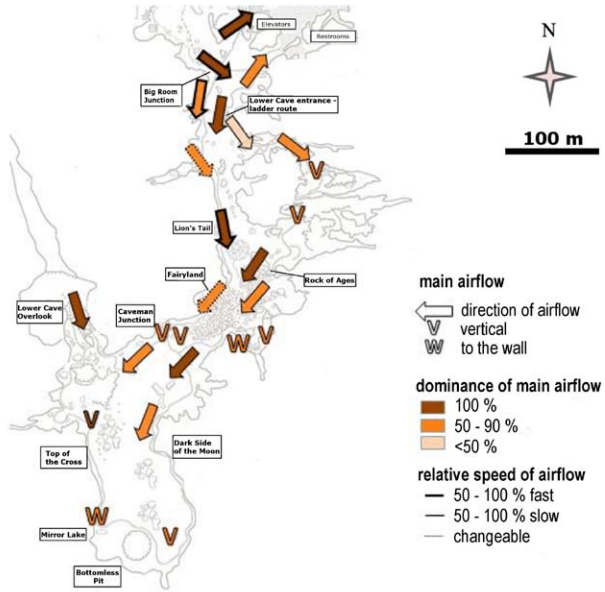


Figure 12. Depiction of the dominant airflow conditions at Schwabe's measuring points inside the Big Room, Carlsbad Cavern during March-April 2011 (based on Schwabe, 2013). The relative velocity is shown by the borders of the arrows.

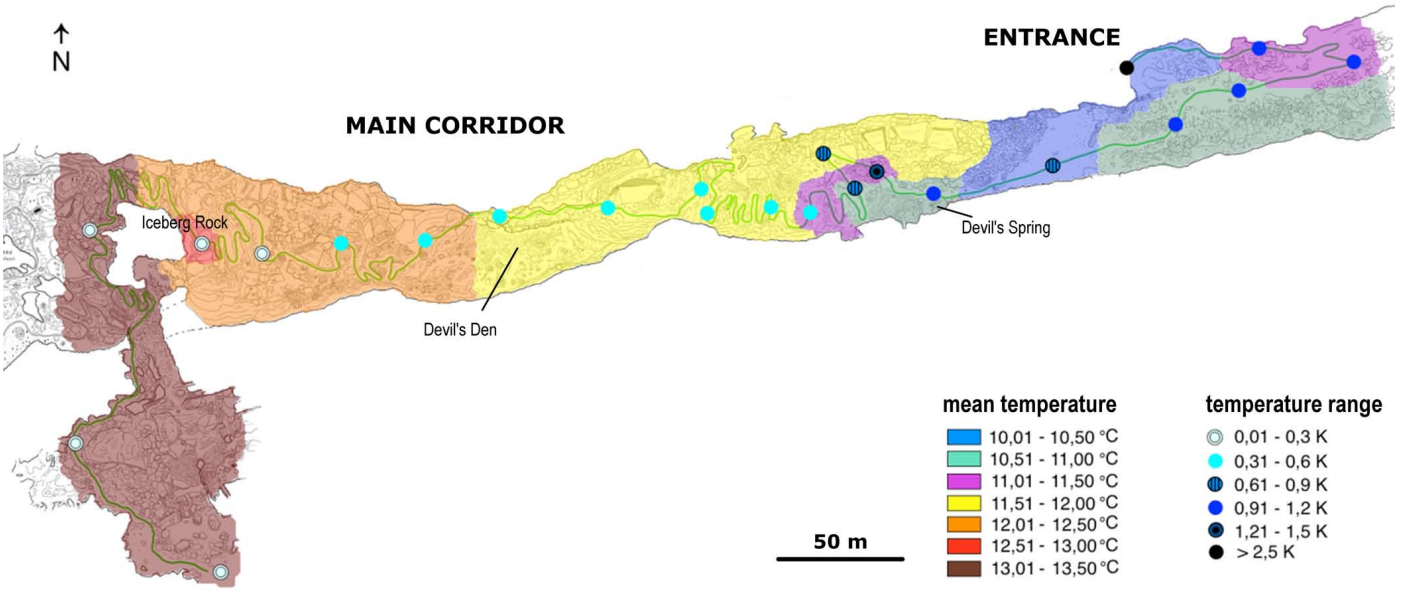


Figure 13. Depiction of the temperature conditions along the Main Corridor of Carlsbad Cavern by temperature zones (colored areas) and the temperature ranges at Adam's measuring points (circle icons) during February 2013 (based on Adam, 2014).

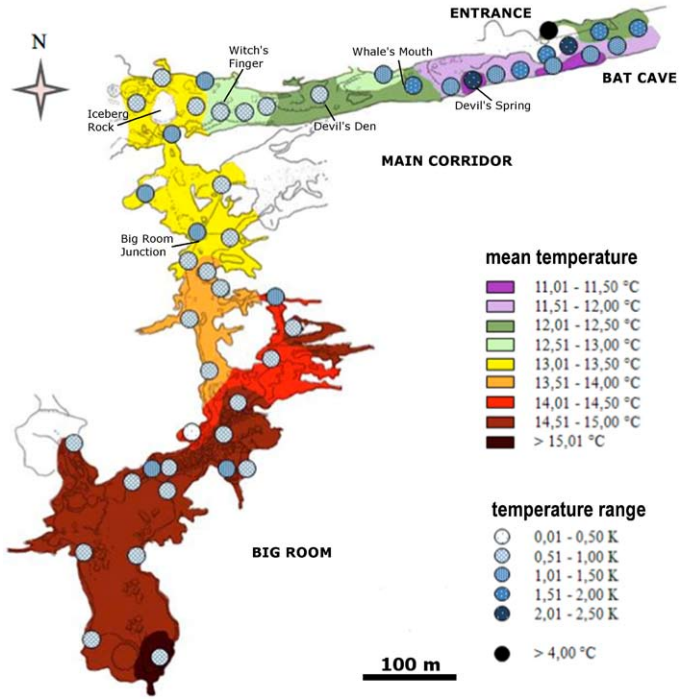


Figure 14. Depiction of the temperature conditions inside Carlsbad Cavern by temperature zones (colored areas) and the temperature ranges at Schwabe's measuring points (circle icons) in March-April 2011 (based on Schwabe, 2013).

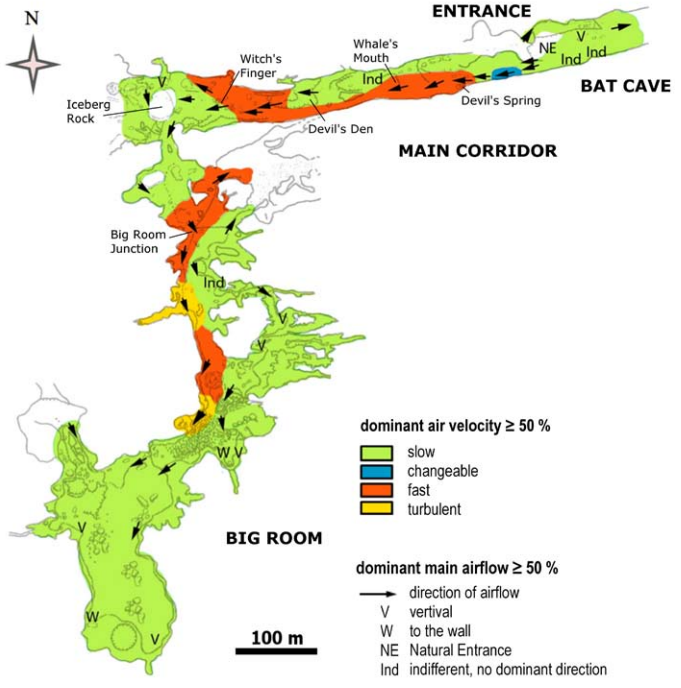


Figure 15. Depiction of the dominant airflow conditions (during at least 50% of the measurements) by using velocity zones (colored areas) and the dominant wind direction (arrows or letters) at Schwabe's measuring points inside Carlsbad Cavern during March-April 2011 (based on Schwabe, 2013).

sheltered locations and in the rear part of the Big Room could be an explanation for this phenomenon. The relatively warm air rises vertically and streams along the ceiling to the Main Corridor, which it then follows upward. Measuring the presumed warm air at the ceiling of the cave is logistically challenging due to the height of the Big Room and Main Corridor, which varies from 15 m to 70 m, but most probably it is this air that forms the air currents observed at Devil's Spring streaming in the direction of the Natural Entrance and Bat Cave.

Summary

By using the mean air temperatures and the mean air temperature ranges based on Adam's data (Fig. 13), and based on Schwabe's data (Fig 14), were created. Both show the mean temperatures as differently colored regions, as well as the temperature ranges at each measuring point in the form of a circle icon. The ranges show a distinct trend, with rising mean air temperatures coinciding with a decrease in the temperature ranges, but the front section of the cave paints a much more differentiated picture concerning the mean air temperatures than concerning their ranges. It displays the complex and changeable properties of the air temperature at the measuring points despite their spatial proximity.

Additionally, the average of each measuring point reflects its elevation, leading to increasing or decreasing air temperatures along the measuring route. Along the Main Corridor, the mean air temperatures and ranges of the measuring points after Devil's Spring show the strongest response to changes in the outside weather. Farther along the route deeper into the cave this response weakens until beyond the Iceberg Rock it is nothing more than a small fluctuation.

Air currents coming from the Main Corridor and flowing into the Big Room and their impact on their nearest surroundings are shown in Figure 14. Despite the fact that the measuring points inside the Big Room display much higher temperatures and are located very much farther from the entrance than the measuring points inside the Main Corridor, many of both belong to the same categories of temperature ranges. Especially surprising is the extent of the temperature differences (up to 1.5 K) that were measured inside the Big Room.

In contrast to Figure 13, based on data taken in February, the mean air temperatures in Figure 14, based on data from March and April, are approximately 1 °C higher, while the range of the air temperatures at some locations differs by 1.5 K. This can be attributed first and foremost to the period of the data acquisition. It reflects different outside weather conditions and the increased air exchange between cave and free atmosphere during the transition from winter to spring. But despite the weather conditions outside the cave, the mean air temperatures inside approach each other with growing distance from the Natural Entrance until they reach a similar level in the area of the Iceberg Rock. Measurements by Adam and Schwabe resulted in slightly different absolute values (12.51–12.50 °C for Adam and 13.01–13.50 °C for Schwabe). However, both Figure 13 and Figure 14 show the reduced fluctuations at this point of the cave. This shows on the one hand that at this point there is almost no response to the meteorological conditions outside the cave. On the other hand it emphasizes the appearance of the Big Room as cold trap or Eiskellertypus (ice-cellar type) after Trimmel (1968) and Furian (2014).

Regarding the wind velocity (Fig. 15) the front section of the cave, surprisingly, is an area of relatively slow speeds, but there is a small part away from the tourist path where elevated turbulences and gusts can be measured. Regardless of their slow or turbulent streaming properties, all measuring points display a variety of intertwining air currents, which is why a predominate wind direction could only be ascertained for a small number of locations in the front section (> 75% of the measuring period). This emphasizes the vicissitude of the air circulation in this area. The air currents observed at Devil's Spring that seemingly originate in the Bat Cave continue their course deeper into the cave and can be measured at nearly all measuring points of the Main Corridor. In the Main Corridor two areas of increased wind speed stand out, directly after Devil's Spring and between Devil's Den and Witch's Finger. These are flanked by zones of slow velocities. The increased wind speed can be explained by the proximity to the entrance and by the constricted passage size of this section.

Other than the front part of the cave, the Big Room shows the most complex flow pattern. The air flowing out of the Main Corridor pours delta-shaped into the chamber at the Big Room Junction and continues its course with the described drift. These flow paths too are an area of increased and turbulent wind velocities. But this has to be seen as relative, because these faster air currents do not reach the speed of those close to the Natural Entrance. Nevertheless they clearly exceed the speed of the air currents at other measuring points in the Big Room. From the streaming patterns at some measuring points meaningful evidence can be deduced suggesting a permanent connection of the air movements between the Big Room and other cave sections such as the Lower Cave and the Left Hand Tunnel.

The collected data displayed general trends and specific characteristics for the surveyed periods of time, reflecting the complexity and vicissitude of the thermodynamic processes inside and outside the cave. But they merely are a snapshot in time, as they only can describe the condition of the cave climate during the measurement periods. Nevertheless, the results of previous studies could be confirmed and extended by new knowledge, thus forming a promising basis to build upon with future research. Through greater understanding of the temperature and streaming patterns inside the cave, consequences can be predicted that might affect the beauty of the cave.

Acknowledgements

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TALUS-AND-GORGE ICE CAVES IN THE NORTHEASTERN UNITED STATES PAST TO PRESENT—A MICROCLIMATOLOGICAL STUDY

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Abstract

The focus of this article is both a region and a type of cave not typically associated with ice caves. Nevertheless, both the region and the type play an important role in American ice-cave research. Talus-and-gorge ice caves in the northeastern United States can be used as climate indicators for a whole region; and therefore, they are the target of this young field of research. Ice caves, in general, are sensitive climatopes that can serve as excellent indicators for short and long term changes in the climate of a region, principally because of shifts between phases of increasing ice growth and melting during a year and over time. This research started with an investigation of known talus-and-gorge ice caves, followed by environmental monitoring of selected caves with perennial ice that were equipped with temperature sensors recorded over four years. This is one of the world's longest high-resolution climatologic monitoring record of such caves. In addition, the height of the ice was surveyed annually at a time when ice would most likely be at its minimum, the start of November. This allowed for investigation of the annual changes and the influence of the temperature over the previous year. Some predictions for the future of the ice caves and the whole region could be deduced from the data. At the moment, there is no sign of either a renewed increase in the number of talus-and-gorge ice caves or an increase in ice accumulation within the existing ones.

Introduction

The northeastern United States is not well known for large ice caves, and only a few know that it is the region with the most fossil and recent ice caves in the United States. The most common type of ice cave in this area is the talus-and-gorge ice caves (TGICs), which are caves with perennial ice formed within scree accumulations of huge boulders (> 1 m) and located in talus at the bottom of steep cliffs or in narrow gorges. After completing a literature search and initial reconnaissance visits in 2008, it became clear that the TGICs of New England are at the risk of thawing. To better understand the melting of the ice, a monitoring network of climatic measurements and ice volume observations was established. During this investigation, maps were created that made it possible to draw conclusions on the historical development of ice in these unique settings from 1818 to the present. The scree accumulations were divided into three basic categories: those containing perennial ice, those containing seasonal ice, and those containing no ice (Holmgren et al., in press). The ice caves are in an area without permafrost. The closest isolated patches of permafrost below 1800 m asl are approximately 900 km north of the study sites (Brown et al., 2002). Only one spot of mountain permafrost is merely known from Mt. Washington (1909 m) in the Appalachian Mountains (Walegur and Nelson, 2003).

In the year 2007, initial research began on a scree-accumulation site in the White Mountains of New Hampshire. After the first year, a systematic and continuous record of the climatic data in scree accumulations with perennial ice was launched to investigate the microclimate of these special climatopes. Annual measurements of the ice volume during the likely ice minimum are contributing additional information on the climate of these ice caves.

The climatic features of TGICs are presented in the course of this article. The climate inside scree accumulations in the northeast of the U.S. is explained by assessing annual conditions and variations and by taking special short-term meteorological incidents, such as the influence of hurricanes on the climate of a talus ice cave, into consideration. Finally the factors favoring and discouraging ice accumulation in TGICs are summarized.

Background

A review of the literature shows that the northern Appalachians and the northeastern U.S. from New Jersey to Maine and from Pennsylvania to Massachusetts can be described as the region with the highest density of ice caves in the U.S. (Fig. 1a), especially the area in the Appalachian Mountains. Ice caves can be divided into natural and anthropogenic ice caves. The natural caves are solution ice caves, fissure-and-sink ice caves, talus-and-gorge ice caves, lava tube ice caves, and glacier caves. Ice forming wells and mine ice caves are anthropogenic caves in which ice has built up (Holmgren et al., 2017) Due to the lack of volcanism and glaciers in the area, lava tube ice caves and glacier caves are not present in this part of the U.S. (Halliday, 1954). All other ice cave types can be found in this area: solution ice caves, ice forming wells, fissure-and-sink ice caves, mine ice caves, and talus-and-gorge ice caves (Halliday, 1954; Holmgren et al., 2017).

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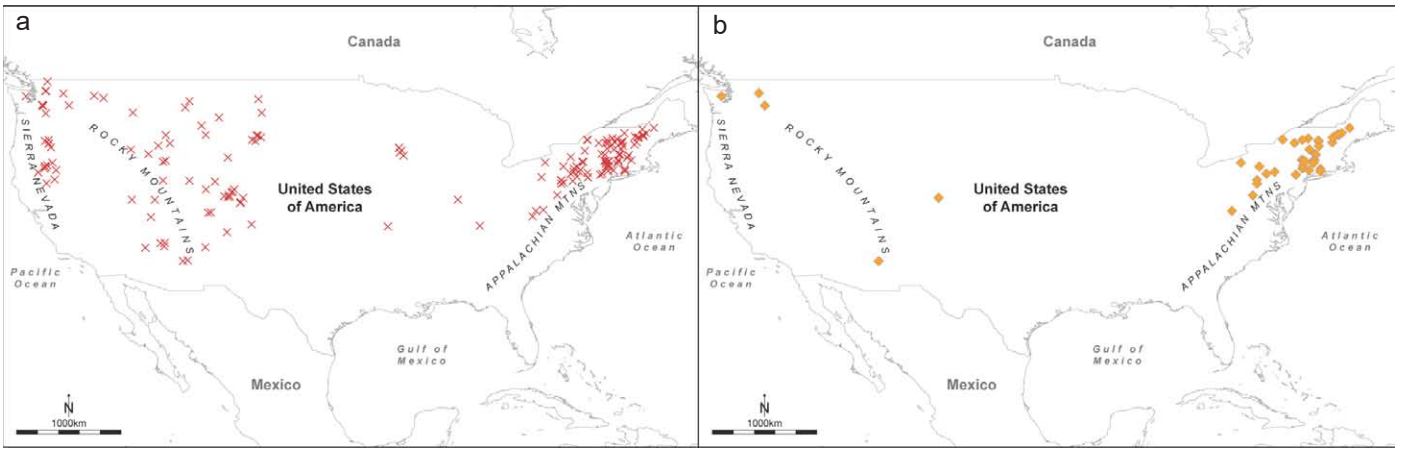


Figure 1. a: Distribution of ice caves in the United States. b: distribution of talus-and-gorge type ice caves in the United States (Holmgran and Pflitsch,in press).

The earliest references to subterranean ice in the U.S. refer to our study area, which extends from New Jersey to Maine. In 1818, Dewey visited the Snow Hole in the state of New York at the border of Vermont and Massachusetts. It contains accumulated snow masses until the late summer or even the early fall (Dearborn and Ives, 1822; Dewey, 1819). The publication of Dewey's research generated early interest in this phenomenon. This interest was at first mainly based on practical rather than scientific reasons, as the ice deposits could be used for extending the storage of food. Edwin Swift Balch was one of the first to investigate the phenomenon of ice caves for purely scientific purposes. He visited numerous ice caves and reported all his observations in various articles and a book (Balch, 1897; Balch, 1899; Balch, 1900).

Talus-and-Gorge Ice Caves

Boulders, often up to 5 m in diameter, deposited by weathering processes can sometimes form man size caves. Depending on the local climate and topographic relief, these caves can contain seasonal or perennial ice, especially if they are covered by vegetation or soil. The climates inside such scree accumulations are highly diverse and are discussed in this article with the aid of two locations inside a scree accumulation at the Cannon Cliff in New Hampshire. The size of a talus-and-gorge ice cave is strongly dependent upon the size of the boulders: In general, the larger the debris, the larger the air volumes among the boulders. One characteristic of these ice caves is that they are located at relatively low elevations for ice caves, as most of them can be found between 600 and 700 m above mean sea level. This is especially notable because the surrounding peaks of the Appalachians, like the highest point in New England, Mt. Washington in New Hampshire at 1917 m, are free from snow and ice from May to September (Holmgren and Pflitsch, 2011a; Holmgren and Pflitsch, 2011b).

The most frequent mentions in the literature to this type of cave are to be found in the northeastern U.S. (Fig. 1b; Holmgren and Pflitsch, 2012). There are also references to TGICs on the west coast of the U.S., in Washington (Halliday, 1954).

Development of Talus-and-Gorge Ice Caves in New England

An analysis of historical reference to talus-and-gorge ice caves throughout the literature, together with our physical inspections, not only resulted in the development of a map of TGICs in New England, but also made it possible to deduce a rationale for their locations. Figure 2 shows the location of TGICs in the northeastern U.S. from the earliest references up to the present day, as well as the location of the monitoring network for our current talus-and-gorge ice cave research. References to the first nine of the caves were published during the years 1818–1849 (Fig. 2a). For instance, the first talus caves with ice were described by Dewey (1819), Dearborn and Ives (1822), and Lathrop (1844). From 1850–1899 and from 1900–1949 (Fig. 2b,c) fifteen further TGICs were reported for the first time. In the 64 years since 1950, only three more ice caves of this type were described from the northeast (Fig. 2d; Holmgren and Pflitsch, 2012).

Mentions in the literature allow conclusions to be made about ice deposits only near the time the respective authors visited the sites. Therefore, an inspection of described locations since 1818 was started, and 16 of 39 TGICs were investigated in the last few years. The first results show an apparent decline of this subalpine, cold-air talus shrubland ecosystem, as five of the visited caves showed no signs of ice during the time of our visits (Fig. 2e). Indigenous plants appropriate to elevation have reconquered these niches. Alpine flora that are normally found in the immediate surroundings of TGICs and that can be used as an indicator for these types of ice caves, were completely suppressed. Examples of alpine flora in TGICs, as can currently be found in the Randolph Hill Ice Gulch in New Hampshire, are the alpine

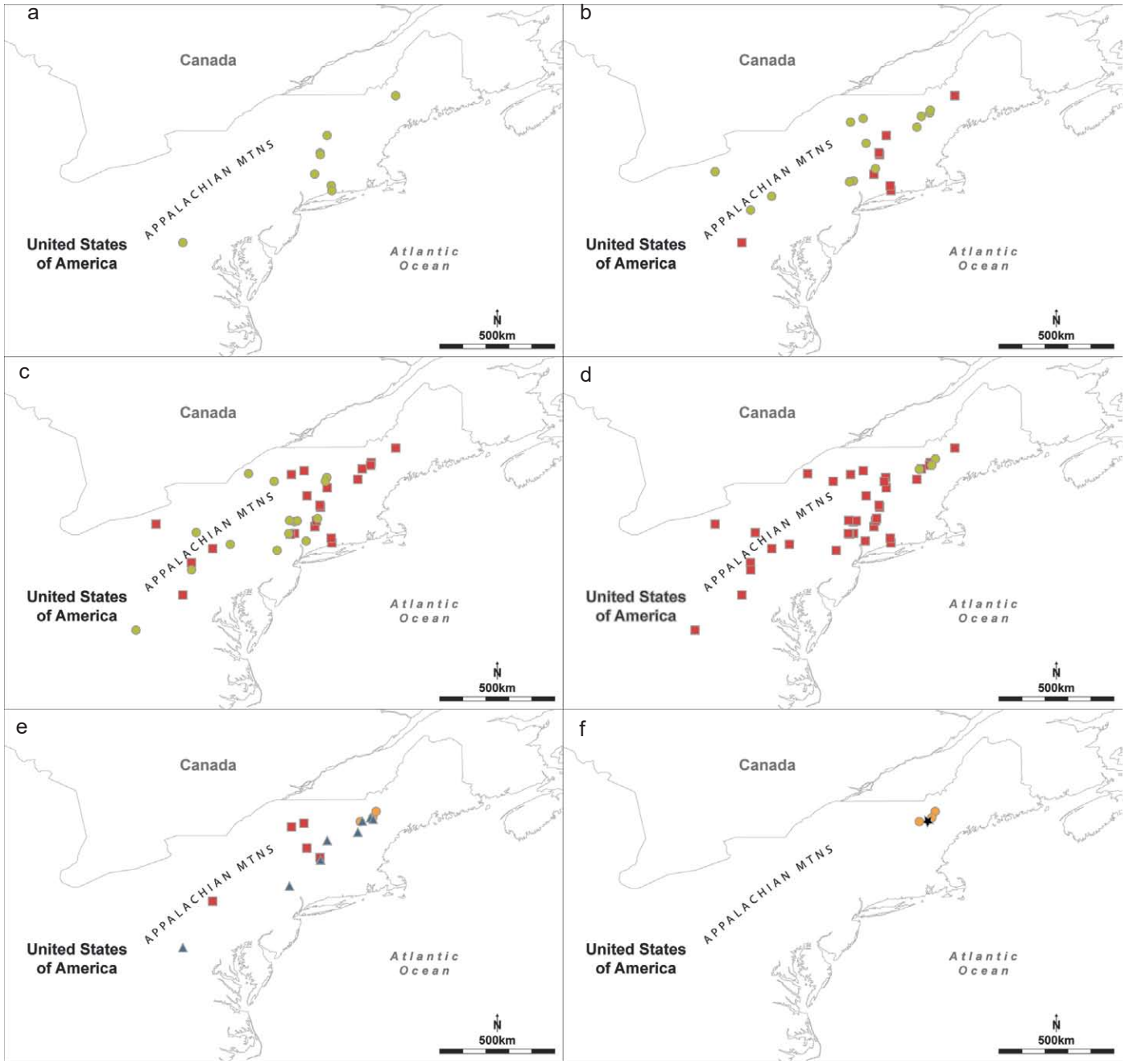


Figure 2. a–d: Locations of talus-and-gorge ice caves in the northeastern United States first described in the literature (green dots) during the periods a. 1818–1849, b: 1850–1899, c: 1900–1949, d: Since 1950. Red squares are locations of caves described in the previous periods. e: Current status of 16 historically described sites revisited for this study. Blue triangles are sites with seasonal ice; orange circles are sites with perennial ice. No ice was seen in the sites with red squares. f: The three gorge-and-talus ice caves monitored. The star is the reference weather station at Mt. Washington.

bilberry Vaccinium uliginosum and the Labrador tea Ledum groenlandicum (New Hampshire Natural Heritage Bureau, 2009). Figure 2e shows the current situation, where seasonal ice deposits lasting until mid-summer were found in eight of the examined caves and only three of the caves still contain perennial ice today. The caves that still have perennial ice are in the monitoring network (Fig. 2f).

Gorge Ice Caves

Gorge ice caves can be found in narrow cuts in valleys or ravines with scree accumulations. In the scree-accumulation zone, debris falls to the bottom of the ravine due to various weathering processes. The ice deposits of these ice caves can be found within the debris (Fig. 3a). Because of continuing frost action, the majority of new boulders fall into the gorge during the frequent freeze/thaw cycles. The sidewalls of a gorge are very steep and quite often reach 80 or 90 m in the study area (Fig. 4a). With the width of the gorge not exceeding 30 to 35 m, the walls significantly reduce the

incoming solar radiation. Usually the scree accumulation is only heated by direct sunlight at noon.

Research on TGICs is common in Europe (Juliussen and Humlum, 2008; Růžička et al., 2012), especially in the European Alps (Morard et al., 2008; Zacharda et al., 2007), and also in Asia (Byun et al., 2011; Gorbunov et al., 2004). Different climatological processes based on the topography, for example the chimney effect, have been detected in scree accumulations (e.g., Sawada et al., 2003). But only a few studies concentrate on long-term investigations over several years (e.g., Byun et al., 2011, and Delaloye and Lambiel, 2005). While we concentrate on the ice development in small caves among the TGICs, Byun et al. investigated some anomalous winter warming and summer cooling in the Miryang Eoreumgol (Ice Valley) in Korea and Delaloye and Lambiel measured the temperature of whole scree slopes at different depths up to 5.75 m.

Site Characteristics and Measurement Setup

The scree accumulations with perennial ice are located in the northeastern states of the Appalachians, New Hampshire and Maine. The study sites (Fig. 2f) can be found in a 40-km perimeter around Mt. Washington (44°16′12″N / 71°18′11″W). The exposure of the individual locations varies from northeast at Mahoosuc Notch, to southeast at Cannon Cliff; the Ice Gulch has an exposure towards the east-southeast. The subcategory of gorge ice caves is represented by the Ice Gulch and the Mahoosuc Notch sites, while the talus of the Cannon Cliff belongs to the subcategory talus ice

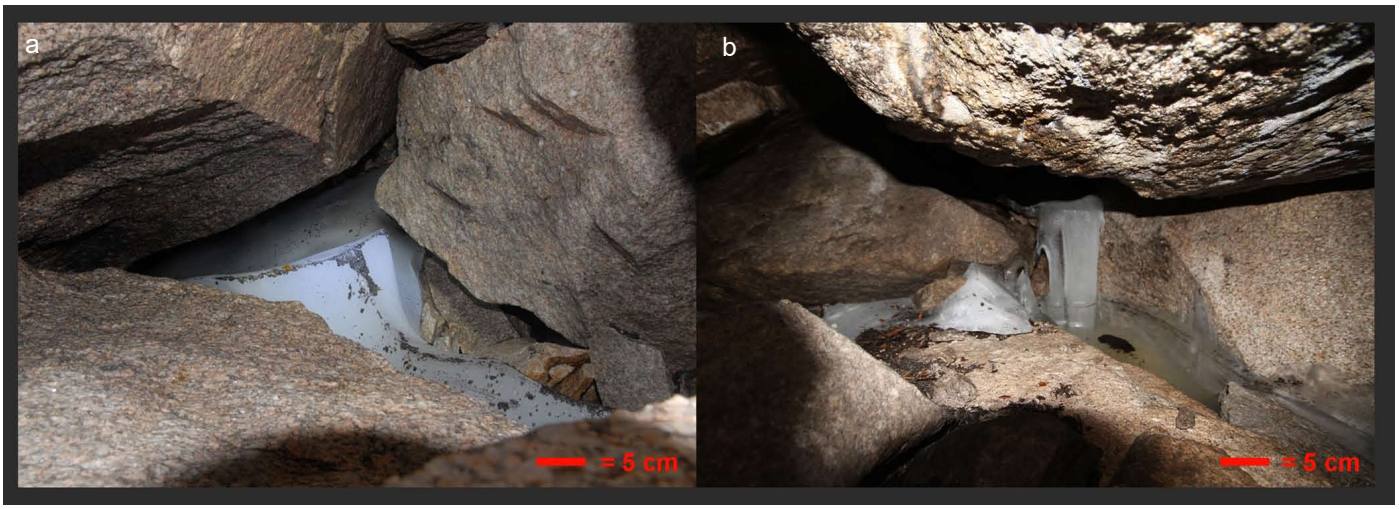


Figure 3. a: Talus with ice in Randolph Hill Ice Gulch, New Hampshire (October 2008). b: Debris with ice in the talus below Cannon Cliff, New Hampshire (June 2010).

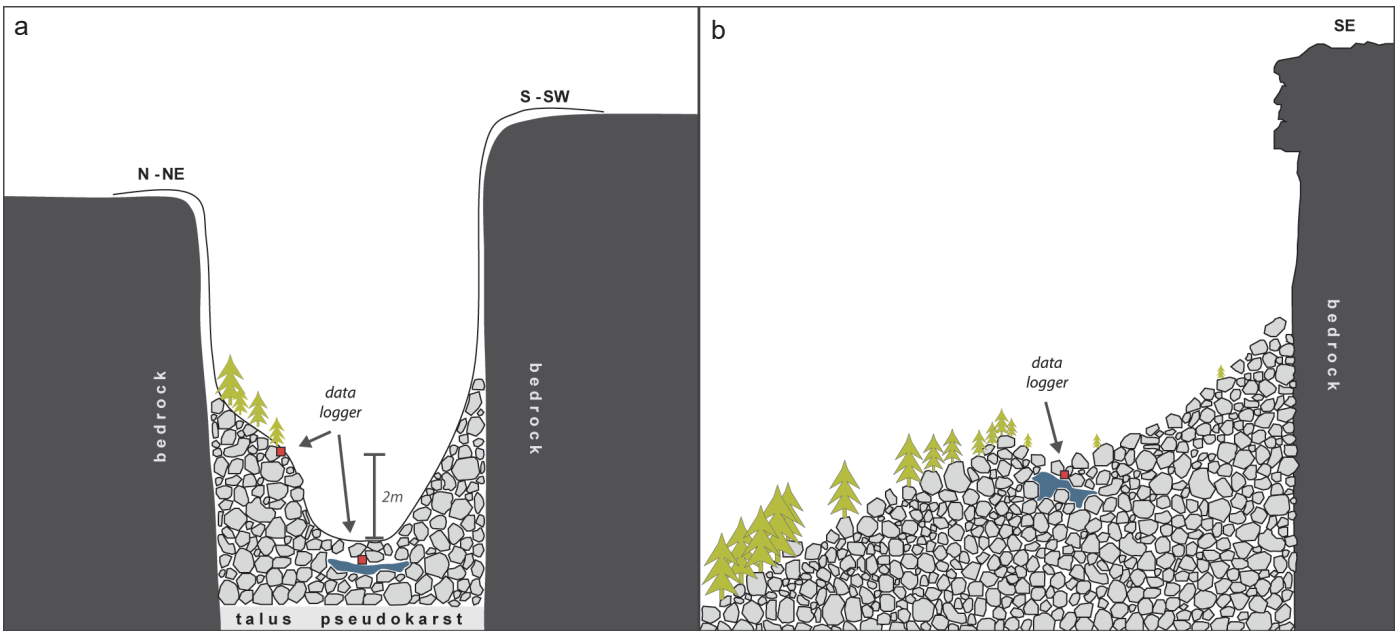


Figure 4. a: Profile of a gorge ice cave showing protective sidewalls and typical positions of instruments to record temperatures, based on Holmgren and Pflitsch (2011b). b: Schematic section of a talus ice cave showing location in scree where cold air accumulates; cliff orientation shown for Cannon Cliff.

caves. In the case of the gorge ice caves, it has to be taken into consideration that high sidewalls of 80 m to 90 m height, not uncommon, strongly reduce the incoming solar radiation. Therefore, direct sunlight might only reach the debris at noon, and then for only a short period of time. In contrast, the scree of the talus ice caves on Cannon Cliff is exposed to incoming solar radiation during many hours of the day. The locations of the ice deposits, and thus the locations of the measurements, can be found over a narrow range of elevations, 668 to 689 m.

The measurements started in October 2008 to generate an analysis of the micro-climate inside the Ice Gulch at 670m elevation in New Hampshire. This gorge ice cave was equipped with high-resolution temperature sensors (resolution of 0.01 °C; accuracy of 0.1 °C). The air temperature sensors were placed at the vegetation boundary and within the ice cave some centimeters above various ice deposits. In October 2009, the monitoring network was extended by the addition of another gorge ice cave. The Mahoosuc Notch in Maine was similarly equipped with sensors measuring the air temperature close to the ice deposits. Finally, in July 2010 the scree accumulation at Cannon Mountain, New Hampshire, was also equipped with high-resolution temperature sensors at similar positions to the other caves. Unlike at the other sites, we also investigated two sites inside the scree accumulation of Cannon Mountain that contain both seasonal and perennial ice. Additional visits on a regular basis during the potential ice minimum and occasional visits during the potential ice maximum were made to better understand and document the development of the thickness of the ice.

The data gathered by numerous climate stations of the Mount Washington Observatory Meso-Net served as local long-term reference values. The auto road station at 701 m on Mount Washington has a similar elevation as the Ice Gulch and has the same exposure. This reference station delivers high resolution data on both temperature and humidity. In addition, the summit station delivers wind direction and velocity.

Since 2008, the air temperature in the Randolph Hill Ice Gulch has been recorded every 15 minutes. The four-year means in the Ice Gulch for 2008–2012 were an air temperature of −0.91 °C at the vegetation boundary and −3.75 °C inside the caves close to the ice deposits 1 to 2 m under the surface of the debris (Fig. 4a). In comparison, a reference station at a similar elevation above had a temperature mean of +4.83 °C, while the mean air temperature of the summit of Mt. Washington (1247 m higher than Ice Gulch) was −1.75 °C during the same time period. That means the gulch ice caves have a lower mean air temperature than the highest mountain tops in the northeastern U.S. Therefore, the measurements at the Ice Gulch are comparable to areas in this region with an elevation much higher than 1500 m above sea level. The low temperatures in the Ice Gulch are responsible for the presence of alpine flora such as alpine bilberry and Labrador Tea. Monthly means are shown in Figure 5, which shows the air temperatures at the reference station (Mt. Washington auto road station, 701 m), at Mt. Washington's summit, at the vegetation boundary at the Ice Gulch, and at an ice deposit inside Ice Gulch. The similarity between the air temperature at the Ice Gulch (670 m) and the peak of Mt. Washington (1917 m) is clearly seen. The differences in the monthly mean temperatures between the Ice Gulch and the summit station of Mt. Washington are in a range of 3.3 K, whereas the reference station at 701 m on Mt. Washington is at least 2.5 K and up to 7.4 K warmer than the Ice Gulch in every month. From May to November the mean air temperatures of the region stay above the freezing point. Inside Ice Gulch, positive air temperature values can be found from May to October, but close to the ice deposits the mean air temperature only exceeds the freezing point for three months. From August to October the mean air temperature is between 0 °C and +1.5 °C.

During a single year the temperature profile of the Ice Gulch exhibits distinct annual phases: the cooling phase, a zero-curtain phase, and the warming phase, before the cycle starts again with another cooling phase (Fig. 6). During the cooling phase, from October to the end of April, temperatures stay continuously under 0 °C. This phase can be further divided into three periods. It is a characteristic of the first half of the cooling phase that the air temperature inside Ice Gulch follows the negative temperature of the surroundings without delay because the debris begins to cool down instantly. Lighter and warmer air masses are displaced by heavier and colder air during this period, the phenomenon also described by Delaloye and Lambiel (2005). In the second half of the cooling phase snowfall accumulation plays an important role. The temperatures inside the scree accumulation then have a delayed reaction to the influence of colder air as the pores in the snow blanket are closed more and more by the increasing snow depth. When the snow blanket is nearly fully closed, the debris only reacts to temperature extremes, which normally occur from the end of March to the end of April.

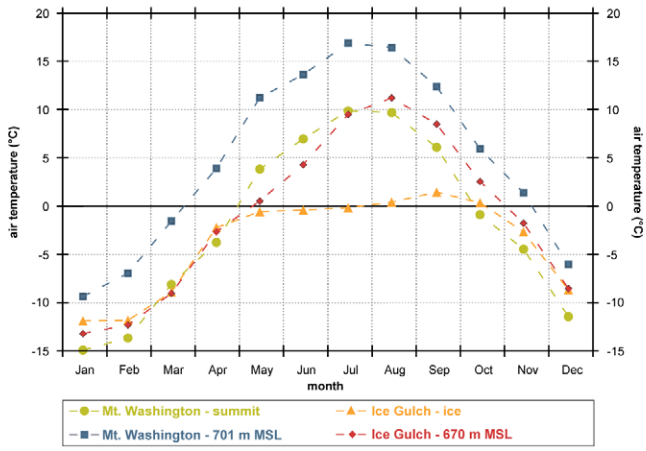


Figure 5. Monthly mean temperature records in Randolph Hill Ice Gulch, both at the top of the scree deposit (red) and at the ice (orange), compared to temperatures at a similar elevation on Mt. Washington (blue) and at its summit (green).

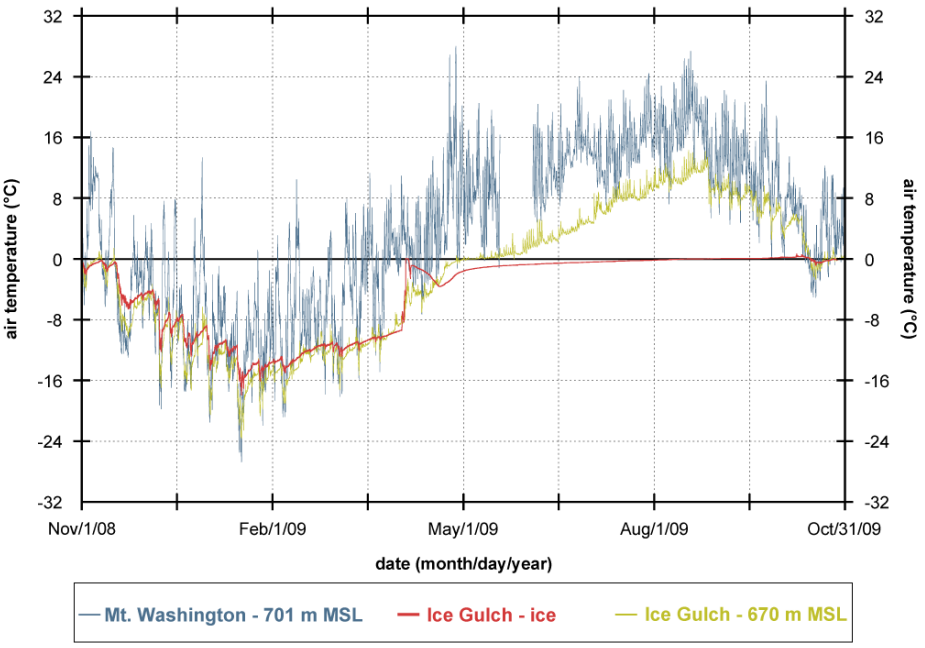


Figure 6. Detailed temperature records for November 2008 through October 2009 for Randolph Hill Ice Gulch, both at the top of the scree deposit (green) and at the ice (red), compared to the temperature at a site on Mt. Washington with similar elevation.

During the second phase, the zero-curtain, which typically starts in May, the air temperature slowly rises to the freezing point independent of the surrounding temperatures that already show daily means of up to 10 °C. The zero-curtain arises during the phase transition of H_2O. Snowmelt runs into the debris and freezes again when meeting the colder air and boulders, creating new layers of ice. During the phase transition, energy is set free (Hanson and Hoelzle, 2004).

After the passing of 0 °C, hence the end of the zero-curtain, the last phase, the warming phase, begins. The regional temperature increases from the end of May to the end of August by up to 15 K. In the immediate area of the Ice Gulch, the temperature not uncommonly reaches 29 or 30 °C. On average, the temperature differences between the cave and the environment during the Warming Phase are approximately 14 K. In September, the temperature drops to the freezing point and ends the annual cycle. Then a new cooling phase can begin in October.

Analysis and Discussion

The phenomena of the great temperature differences between the debris and its surrounding area during summer and the small temperature differences during winter can be explained by using the theory of Rayleigh-Bénard convection, or in this special case, by using Horton-Rogers-Lapwood convection (Cheng et al., 2007). The Rayleigh-Bénard convection theory requires a liquid that is consistently heated. The warmer liquid will ascend because of decreasing density and a circulation will begin. By exchanging the liquid for a porous rock surface, such as a scree accumulation and the air pockets within it, you get the Horton-Rogers-Lapwood convection that better describes the wintery situation in scree accumulations. Colder and heavier air masses enter the debris because of density differences, suppressing the warmer air and starting a circulation (Fig. 7a). This process occurs in New England every fall, cooling down the scree accumulation. Due to the harsh conditions in winter and spring in the remote locations, we don't have visual observations of the snow cover and possible ventilation effects like melt holes in the upper part of slopes in the snow cover as described by Delaloye and Lambiel (2005).

The expected circulation inside the debris decreases during winter (Fig. 7b) due to the lower temperature differences until it reaches an equilibrium (Fig. 7c) in spring, when the outer air temperature exceeds the air temperature inside the debris. A likely snow blanket further isolates the air in the cave. The warming during the following summer is limited. This warming occurs by heat conduction and by warming in a mixed layer close to the surface (Fig. 7d). This layer deepens in the course of the summer and reaches its maximum in fall, when its influence on the debris is the strongest. The profile of the circulation inside the debris in the course of the year is the reason for the relatively high differences inside Ice Gulch between the air temperature at the vegetation boundary and in the debris, especially in summer (Bardan and Mojtabi, 2000; Cheng et al., 2007; Nield and Bejan, 1992).

By comparing the temperature profiles of the four consecutive years (Fig. 8a) of available data, significant differences catch the eye. These differences are mainly shaped by the climate of the region. Annual differences in summer and winter dominate the temperatures inside Ice Gulch. The first year, 2008−2009, was the coldest year of the measurement period. This year had a mean winter temperature (November–April) of −9.62 °C and a mean summer temperature (May–October) of +5.22 °C. This was a combination of the coldest winter and the mildest summer, and

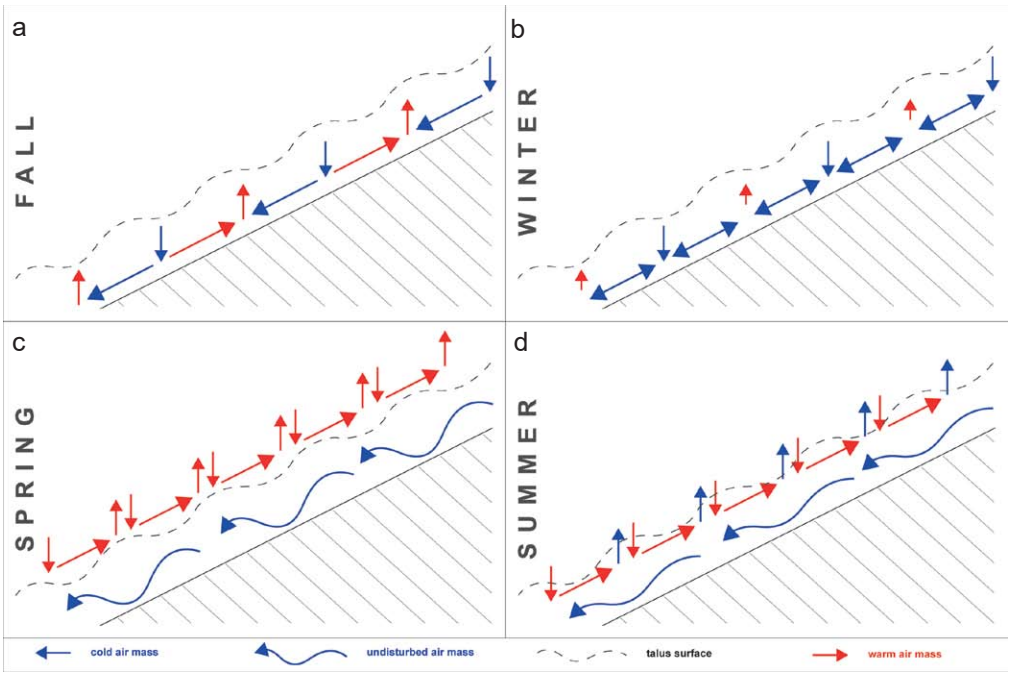


Figure 7. Schematic depictions of the air circulation in talus. In the fall, cold air sinks into the talus and displaces warmer air. In the winter, this process has been substantially completed. In the spring, the denser cold air, perhaps protected by snow cover, remains stagnant in the caves. In summer, much cold air remains, although there is some replacement by warm air in the upper parts of the talus deposit.

therefore, it was by far the coldest year, with an annual average of −2.20 °C (see Table 1). In contrast, the warmest year (2011–2012) had a positive mean air temperature of 0.14 °C (winter period −6.60 °C; summer period +6.88 °C), leading to a decrease of the ice thickness.

The different temperature regimes of each year are represented in the data on the ice's thickness. The observations of the thickness during the likely ice minimum resulted in irregular data, but still give the appearance of a negative year-to-year trend (Fig. 8b). Nevertheless, one fact could be ascertained clearly from the correlation of the data on the thickness of the ice deposits and the air temperature inside Ice Gulch: the air temperature is the driving force for the ice development. The data show that mean annual air temperatures lower than −1.25 °C lead to an increase in the ice deposits, while means above −1.25 °C lead to a decrease in ice thickness at similar humidity conditions. This relation is expressed by the formula $y = -0.639x^3 - 0.413x^2 - 10.335x - 13.543$, where x is the mean annual temperature and y is the excess or deficit in minimum ice thickness in cm compared to −1.25 °C. The results of this correlation have to be verified in subsequent years and supported by further data. Possibly the point of stagnating ice levels is off by some hundredths of a degree, but the calculation based on the last years looks plausible.

Talus Ice Caves

Scree accumulations that are protected only from one side by a cliff while the other sides are exposed to wind and sun can contain ice deposits and are named talus ice caves (Fig. 4b). The orientation of the exposed side is of great importance. The Talus Ice Caves at Cannon Cliff are exposed to the southeast; they receive the highest incoming solar radiation during the morning, and seasonal, as well as perennial, ice can be found in some of the caves. The perennial ice has a thickness of several meters, while the seasonal ice deposits can exhibit a thickness of up to one meter during

Table 1. Monthly mean and annual average air temperatures of Ice Gulch.

Month[a]	2008/2009	2009/2010	2010/2011	2011/2012	Mean
November	−3.56	−0.43	−1.98	−1.06	−1.76
December	−10.08	−9.08	−8.99	−6.01	−8.54
January	−15.58	−11.65	−13.16	−12.40	−13.20
February	−13.49	−10.93	−14.05	−10.69	−12.29
March	−11.34	−6.62	−10.44	−7.69	−9.02
April	−3.64	−0.73	−4.47	−1.73	−2.64
May	0.39	0.5	0.15	1.05	0.52
June	3.24	4.45	3.53	5.99	4.3
July	7.7	10.06	9.51	10.7	9.49
August	10.73	10.95	11.2	12.02	11.23
September	7.68	8.98	9.09	8.19	8.49
October	1.55	2.67	2.64	3.35	2.56
Annual Mean	−2.20	−0.15	−1.41	0.14	−0.91

[a] Measurements started October 18, 2008.

the annual maximum (Fig. 3b). The curves in Figure 8c show the various temperature profiles of the talus locations with perennial or seasonal ice deposits in the course of a year. Differences develop especially during the extremes of the year. In winter, the air temperature at the locations with seasonal ice is 2 to 3 K higher than at the locations with perennial ice. Furthermore the air at these locations is heated up faster in summer and reaches temperatures that are 5 to 6 K higher than at the locations with perennial ice.

The local shape of the scree accumulation is the reason for the different temperature profiles. Only in scree accumulations with protection for the cold is it possible for ice to build up in this region and elevation. This is found in all three study areas in the monitoring network. At the talus of Cannon Cliff this barrier is a protalus rampart (Whalley and Azizi, 2003) that is especially distinct at the location with perennial ice deposits (Fig. 4b). This is the main reason for the high temperature differences in winter and particularly in summer. Heavier cold air accumulating in a synclinal shape in the scree accumulation forms a protected pool of cold air. Another contributing factor is the biological growth at the rear of the barrier. Mosses, lichens, and other soil material protect the cold air from runoff. This system can only be disturbed by events with very strong winds, such as hurricanes.

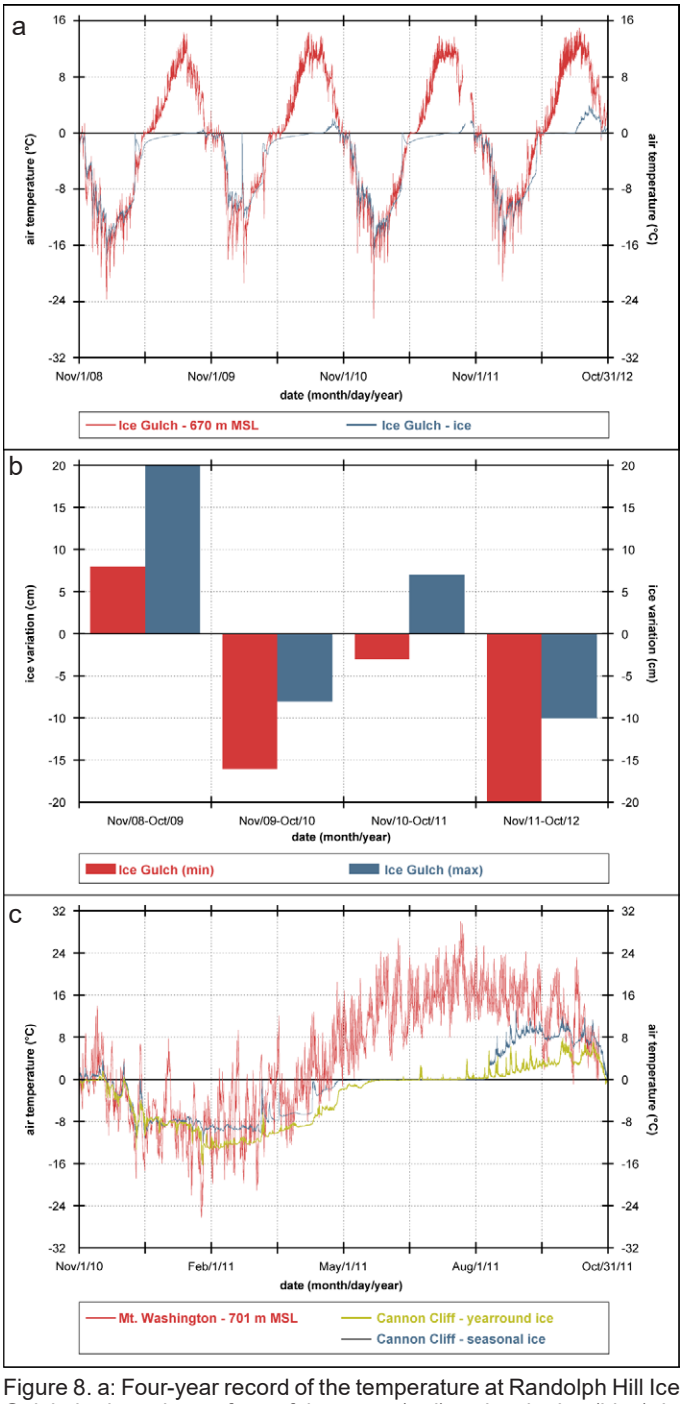


Figure 8. a: Four-year record of the temperature at Randolph Hill Ice Gulch, both on the surface of the scree (red) and at the ice (blue). b: The differences in thickness of the ice deposit inside Randolph Hill Ice Gulch from the previous year, based on visits when the deposit was expected to be at its minimum and maximum during the same year-long periods as in part a. c: Detailed temperature records at the Cannon Cliff talus ice cave deposits of seasonal (blue) and perennial (green) ice, compared to the air at a weather station with similar elevation on Mt. Washington.

The Influence of Hurricane Irene (August 2011) on the Cannon Cliff

Because one of their sides is especially exposed to the weather, talus ice caves like the ones on Cannon Cliff are more strongly influenced by weather events than gorge ice caves. At the end of August 2011, the impact of Hurricane Irene had a strong influence not only on the climate of the east coast, but also on the microclimate of the talus ice caves of New England. The effects of this storm can be seen in the temperature profile inside the scree accumulation of Cannon Cliff (Fig. 9). This figure shows an unusual increase of the air temperature near the ice deposits. Daily temperature fluctuations normally don't exceed 0.3 to 0.4 K. Two factors were responsible for the extreme temperature increase on August 28–29, 2011. There were winds up to 132 km h^{-1} blowing directly at the debris (orange dots), pushing warm air into the debris. Twelve hours after Irene first hit this region, the rear of the hurricane tore across the country. The wind direction reversed by 180°, and even with a wind velocity that was 31 km h^{-1} faster than the initial phase, the microclimate of the now leeward scree accumulation wasn't influenced at all, showing that the combination of the wind direction and speed was essential for the temperature jump.

Only one thing can protect the microclimate from such strong influences—a seasonal, deep snow blanket that lasts until the late spring or early summer protects the scree accumulation from warming and has a positive influence on the cave ice. The presence of an isolating snow blanket during spring and early summer prevents strong winds such as those from Hurricane Irene from pressing warmer air into the debris that would add to the warming of the cave air and the melting of the ice deposits. By the beginning of the hurricane season, the snow blanket doesn't exist, so such extreme events can lead to increased ablation rates.

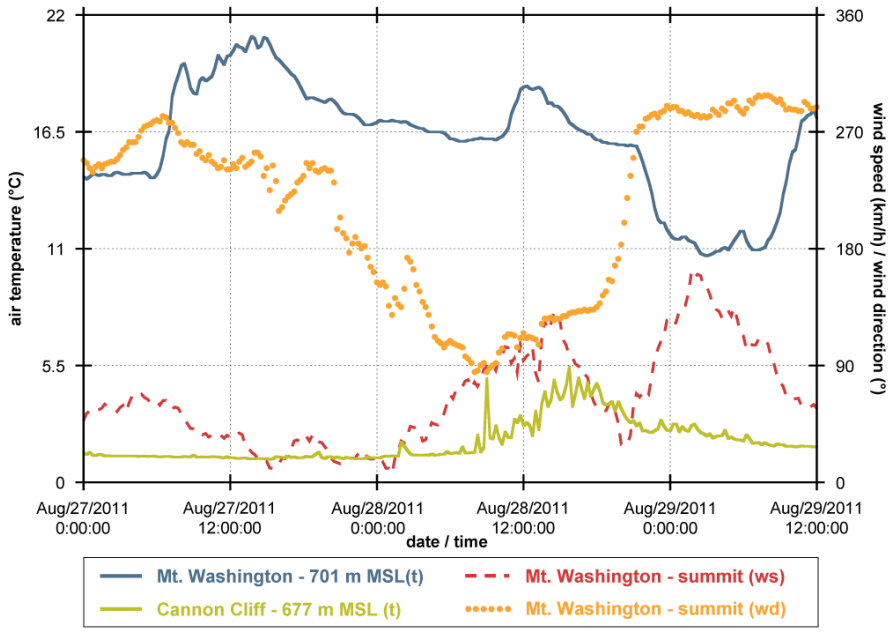


Figure 9. Detailed temperature record inside the scree accumulation at Cannon Cliff (green) during the passage of Hurricane Irene in August 2011, compared to temperature record (blue) at a site with similar elevation on Mt. Washington as well as the record of wind velocity (red) and direction (orange) at the summit of the mountain (both on right scale). The high winds affected the temperature in the scree only when the wind direction was favorable.

Conclusions

After visits to 16 talus-and-gorge ice cave locations in New England, the preliminary conclusion can be drawn that the number of TGIC is decreasing. Of the visited ice caves that researchers had noted since 1818, 31% are now ice free. Just 19% of the surveyed locations show perennial ice deposits. These results support the assumption that we had a maximum of TGICs at the end of the Little Ice Age in the fifteenth through nineteenth centuries. The large number of first descriptions in the literature matches perfectly with the end of this period.

The last place with permafrost other than in a cave east of the Rocky Mountains is the summit area of Mount Washington, New Hampshire (Osterkamp and Jorgenson, 2009). TGIC, or ice caves in general, can be considered as ground ice occurrences. That means that these three TGIC and ice caves of other types, if they have perennial ice, are the last lowland permafrost spots east of the Rocky Mountains in the U.S. These cave ice deposits clearly represent a peculiar type of ground ice, both in terms of volume, no more than 3 m³ per deposit and 14 m³ per ice cave, and by being in a climate not usually associated with permafrost. French (2007), Kern and Persoiu (2013), and Luetscher et al. (2005) have previously mentioned the important role of cave ice in terms of permafrost. Cave ice, enclosed in rock not soil, could offer new opportunities for ice cave and permafrost research if incorporated in the existing category of sporadic and mountain permafrost or made a new permafrost category.

The volumes of the ice deposits vary as a function of the climatic conditions of a year. An obvious long-term trend could not be deduced from the first years of this study. Therefore, no clear statement can be made concerning melting of the ice deposits inside the scree accumulations or risk to the current climatope in general. However, a plausible statement about climatic factors affecting ice deposits at lower elevations could be formed and is summarized in Table 2.

Cold temperatures in early fall cool down the debris relatively early and foster the buildup of ice deposits, provided that early snow falls do not create a snow blanket that seals the openings. Low minimum temperatures and high wind velocities all contribute to ideal winter conditions. A protective snow blanket in late spring strongly inhibits the warming temperatures from influencing the deeper parts of the scree accumulation. Meltwater entering the debris at this point is of fundamental importance for the buildup of the ice deposits. A summer with low precipitation and low wind velocities causes the least melting of the ice and warming of the debris.

Table 2. Factors in favor and disfavor of the build-up of ice deposits in talus accumulations.

Season	Positive Influence	Negative Influence
Fall	Early freezing temperatures	Early snow cover
		Persistent summer temperatures
Winter	Cold and windy conditions	High temperatures
	Light snowfall	Deep snow cover
Spring	Closing snow cover	High wind speeds
	High humidity	High amounts of precipitation
		Early summer temperatures
Summer	Dry conditions / Less precipitation	High amounts of precipitation
	Low wind speeds	Tropical storms

High temperatures throughout the year combined with high wind velocities have an extraordinarily negative impact on the cave ice. In addition, a snow blanket that is closed too soon in late fall or early winter prevents the invasion of cold air into the scree accumulation. Some of these factors affect gorge ice caves and talus ice caves to different extents. Gorge ice caves are nearly solely influenced by the air temperature, whereas the microclimate of talus ice caves also is depen-

dent on strong winds and other climatic or topographic features.

The results of this study have shown that the development of perennial ice deposits in caves depends not just the climate of a region. Topography influencing micro climates also play an important role. Landforms with cold air trapping functions are essential for the development and protection of cold air pools inside scree accumulations. In the areas near these pools, ice can be found.

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CLIMATOLOGIC STUDIES INSIDE SANDY GLACIER AT MOUNT HOOD VOLCANO IN OREGON, USA

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Abstract

Previous investigations of climatic conditions of glaciers primarily focused on the glacier's surface or on the moulin as the entrance to the glacier's interior. Many glaciers, however, contain far-reaching cave systems inside the ice that have been understood and investigated as drainage systems for meltwater. Until now, there have been no comprehensive climate studies inside a glacier cave. Thus, the climatic conditions, as well as their effects on the glacier, are unknown. The first climatologic investigations inside the cave system of Sandy Glacier on Mt. Hood in Oregon (USA) in June 2015 have shown that both thermic activity of the volcanic subsurface and chimney effects between the glacier snout at the base of the glacier and higher opening of the moulin can cause drastic melting inside the glacier. Those processes lead to considerably stronger melting from the inside than observations at the surface suggest and can cause an unexpected collapse over a distance of several hundred meters. We will present and assess the first measuring results of both the thermic and flow conditions inside Sandy Glacier.

Introduction

The research field of glaciology includes numerous disciplines. Studies provide extensive knowledge of the formation and the decay of glaciers, their characteristics and movement, and their impact on the underlying landscape, as well as records of historical and recent conditions (Barry and Gan, 2011; Benn and Evans, 2010; Singh et al., 2011). The relationship between glaciers and climatic events is also the subject of numerous investigations. Interaction between air temperature, precipitation, and the conditions of glaciers are well studied (Alean, 2010; Aizen, 2011). Furthermore, glaciers are recognized as important archives of climate records (Sigl et al., 2016; Rhodes et al., 2016; Bourne et al., 2015; Blockley et al., 2014) and have been the subject of hydrological studies on, inside, and beneath glaciers (Andrews et al., 2014; Fountain et al., 2005; Greenwood et al., 2016; Unterfrauner, 2009). Moulins start as vertical conduits that channel water from supraglacial water courses to the bedrock of the glacier and are part of the hydrological system (Holmlund, 1988). While this may be the primary function early in their development, it has to be questioned for their further evolution. Bhutiyani's (2011) short chapter about "Ice Caves" also points out that the caves evolve from meltwater channels or by rising heat of an underlying volcano.

The term ice cave, while frequently used to describe caves in ice, is correctly associated with natural bedrock caves formed entirely in rock, inside of which reside seasonal or perennial ice packs, floors, lakes, etc. (Barry and Gan, 2011). Glacier caves, by comparison, are formed inside the ice mass of a glacier or ice plug, either by water, air convection due to air pressure, temperature or density gradients, venturi effects, geothermal activity, sublimation, glacier movement and fracturing, or a combination of several mechanisms (Benn and Evans, 2010, Badino et al., 2007). The passages either occur at the contact of the ice and the underlying bedrock (contact caves), within the ice pack itself, or consist entirely of ice passages (englacial caves). Plastic deformation of the glacier also works in concert with these forces to either lengthen, close, or reshape the passages. Because both systems develop and function differently, we recommend a strict distinction of the two terms to avoid any misunderstanding

The effects of volcanic eruptions on glaciers has been studied intensely, especially for Mount St. Helens (Brugman and Post, 1998). Unfortunately, the influence of the weather outside the glacier, especially temperature, humidity, and wind conditions, to the air mass inside glaciers, which are important for internal melting or sublimation processes, has not been subject of research or intensively described to date.

Considering the spectrum of glacier research, it is surprising that there are only a few articles and no real investigations on the relationship between the subglacial air mass and glacial ice—the meteorology and climatology of glacier caves—despite the fact that glacial caves, also referred as subglacial or englacial meltwater channels or drainage systems (Greenwood et al., 2016, Vihma, 2011) may contain both air and water. The first and only available information about airflow in glacial conduits is from 1835. The description of Gletschergeblaese, which translates as "small openings with exhaling air out of a glacier." is more or less the explanation of the typical chimney effects of moulins and en-

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trances (v. Leonhard, 1835). Reported 172 years earlier, this first description is already close to Schroeder (2007), who describes a moulin as “a thermal anomaly of subpolar glaciers.” Although the article focuses on moulins as drainages for water and important factors for the circulation of intra- and subglacial meltwater, Schroeder presents a very detailed model about the impact of air inflow and trapped air inside a moulin during the different seasons and the importance of airflow for stabilizing the moulin covering snow bridges. He describes the interaction of ice, water, and air inside the moulin in comparison to airflow and convective processes. Even though the conditions found in the glacial caves on Mt. Hood are different, he gives some information about the interaction between water, ice, and air masses.

The lack of research in glacial caves could be related to the difficulties in making long-term measurements in an extremely dynamic environment with constant changes in cave morphology. The number and structure of entrances also changes constantly, and the potential for loss of instrumentation must be taken into account, even for a twelve-month period. The accessibility of the caves, the instability of the entrances and interiors, and the extensive amount of gear needed for a safe multiple-day expedition also make these studies difficult, and caving inside glaciers is dangerous in general (Benn and Evans, 2010), with experience in ice climbing and ropework necessary to doing this research.

While the shaping power of water is clearly visible in supraglacial channels, moulins, and englacial and subglacial conduits (Benn and Evans 2010; Holmlund 1988, Sudgen and John 1976), the effect of air currents is much more difficult to ascertain and not yet discussed or identified as an important key factor for the glacial energy and mass balance.

Looking into a moulin from the surface of a glacier, one can already see the formative power of water. A wild, rushing glacial stream visibly demonstrates the erosive capability and power of water, especially when loaded with sediments. Because of diurnal and seasonal air temperature changes, meltwater rates are constantly changing. Meltwater discharge peaks during the summer, and the lowest meltwater flow occur in winter or early morning (Schroeder 2007; Ben and Evans 2010).

Air currents inside a glacier cave, on the other hand, are not always noticeable. They can be too weak to feel or just flowing under the ceiling without being evident at the ground. Their direct impact on the ice can only be seen by means of shell-shaped patterns in the walls of the cave, the so called scallops. Scallops formed in rocks are usually related to flowing water (Gunn, 2004; Lauritzen, 1981). In ice they also develop under the influence of airflow (Pflitsch et al., 2016). Their positions all over the walls and the ceiling of the glacier cave clearly show the development of the scallops just by airflow, which underlines the importance of atmospheric climate studies inside glaciers.

When Fountain (2011, p. 258) states that “. . . the term generally implies that portion of the ice body which is not directly affected by the atmosphere. In this view, the englacial region starts below average crevass depth from the



Figure 1. Mt. Hood, Oregon, with the Sandy Glacier in 2013. The red lines show the location of the Snow Dragon Glacier Cave System.

atmosphere-ice interface." This might be correct for huge ice sheets, but has to be reconsidered for smaller glaciers or the edges of ice sheets. However, for the moulins and glacier caves, the larger the passage dimensions, the more substantial the influence of the atmosphere and the convective air inside the glacier caves becomes. At first glance, it appears the conduit development is chiefly controlled by water flow and sometimes cracks, in fact, the airflow through the system plays a much more important role in the morphology of the system, and in the subglacial ice mass balance (ablation) the bigger the conduits get in diameter. The conduits are not chiefly hydrological, but rather, chiefly conduits of air currents that have much more effect on the subglacial ice mass. So the moulin becomes more and more a part of a ventilation system of air currents inside the whole cave system.

An expedition to the Sandy Glacier on Mount Hood from June 21 to June 25, 2015, was the beginning to closing this research gap. The goals of the expedition included the spatial and temporal measurement of climatic conditions inside the glacier cave and the confirmation of first measurements from previous expeditions. Before the comprehensive data set will be analyzed completely and future research will give us a much better idea of climatic conditions and related processes, this article presents the first and most important results of the climatological investigations in two glacier caves on Mount Hood in Oregon, USA. These first results already show how the climatology within glacier caves can impact the characteristics of a glacier. We provide evidence that glaciers do not only melt from the outside, but that under certain circumstances glacial melting can also quickly progress from the inside.

The structure of the cave, and especially the effect of warm springs originating from volcanoes, were identified as important influencing factors on the impact of internal air masses. The large dimension made possible by volcanic activity influencing glacial caves was mentioned, but not measured, previously by Badino et al. (2007) when he described the large network of cave passages for the Paradise Ice Caves of Mt. Rainier (46.8159° N, 121.7165° W), which have melted down at a high rate already, as well as glacial caves in Iceland and the Arctic. That means large glacier caves are known at different places over the world. Besides the initial influence of the hot water or water vapor, no further climatic research has been done.

Even though necessary calculations, like melting rates and ice mass loss, cannot be presented right now, it is important to introduce the new field of "climatology of glacial caves" as soon as possible for further research, because it's an additional factor we have to take into account for glacier melting and retreat.

Short Introduction to Glacial Research at Mt. Hood Before Starting Intensive Climate Measurements

The Sandy Glacier on Mount Hood is located on the northwestern side of Oregon's largest mountain and less than 96 km from Portland, Oregon. The glacier was visited 31 times between June 6, 2011, and October, 2015. The goals were to survey, observe, and measure several glacier caves, with special focus on the changes of the glacier and its caves. Three of those visits were expeditions during which scientists investigated the glacier over a period of several days. The expeditions were July 6–14, 2012, July 13–21, 2013, and June 20–25, 2015.

Figure 1 shows the glacier in summer 2013; the red lines show the location of the Snow Dragon Cave System. The lower cave entrance is located at approximately 1950 meters above sea level. The upper end is close to 2250 meters above sea level.

The first two expeditions focused on surveying the glacier caves, as well as measuring climate data such as air temperature, air moisture, and air current in Pure Imagination Cave. We also collected rock, sediment and biomass oil-like samples along with collections of invertebrates, fir tree seedlings, feathers, and leaves.

Those measurements were first presented at the International Workshop on Ice Caves in Idaho Falls (Idaho, USA) in August 2014 and led to a lively discussion. Because the relatively high air temperatures of 7 °C inside the glacier cave were generally doubted, we decided to record the climatic conditions with a high temporal and spatial resolution during a subsequent expedition.

Besides the various measurements, photographs were taken during each visit to record any visible changes of the glacier. Unfortunately, a direct comparison of those photographs proved to be difficult due to varying snow cover and sites caused by the retreat of the glacier. The following selection of pictures demonstrates changes of Sandy Glacier between 2011 and 2015.

Figures 2 and 3 show the Sandy Glacier in 2012 and in 2015 with all visible cave entrances of the cave system. The retreat of the glacial entrances or collapsed cave parts are well visible. The entrances have been melting and collapsing up-glacier at a fast rate over the short period of observation.

During our five-year study from 2010 to 2015 we have observed cave ceiling heights and widths becoming larger. Figures 4 and 5 show the entrance areas of Pure Imagination Cave. Due to the best stability of the cave and the safest conditions, we intensified our investigation in Pure Imagination Cave, especially the climatologic research. Figure 4 shows the entrance and Figure 5 the crawl into the cave at its discovery on October 10, 2011. Thick firn layers above the glacier ice had kept the cave hidden until the 2011 summer melt.



Figure 2. Close-up of the cave entrances of Sandy Glacier in summer of 2013. All three cave entrances (Frozen Minotaur, left; Snow Dragon, middle; Pure Imagination, right) are visible.



Figure 4. Entrance of Pure Imagination Cave during discovery on October 20, 2011.



Figure 5. Pure Imagination Cave on day of discovery required crawling to get inside the cave, about 0.6 m high and 3 to 4 m wide.



Figure 3. Close-up of the cave entrances of Sandy Glacier in summer of 2015. Frozen Minotaur has collapsed, left; the upper part of Snow Dragon in the middle has collapsed while the retreated entrance is still intact; Pure Imagination on the right has retreated but still in good condition.

The first complete map of the Snow Dragon Glacier Cave System is shown in Figure 6. The total length in 2011–12 was 2184 m, and the vertical extent was 292 m.

Figures 7 and 8 showing the most recent entrance of Pure Imagination Cave were taken in June and October 2015. The entrance has moved 137 m above the location of the originally discovered cave entrance. The entrance changed from 0.6 m high and 3 m wide to about 4 m high and 15 m wide. This part of the cave lost so much of its length that it's possible to see the entrance to the moulin above (Fig. 8).

The Cerberus Moulin located in the middle of Pure Imagination Cave has increased in size at an alarming rate (Figs. 9 and 10). In 2012, the moulin had an air volume of about 2300 m3. In 2013 we measured a volume of 9600 m3.

Figure 9 shows ice over 30 meters deep, and Figure 10 shows ice thickness less than one meter at the same location. Due to changes occurring in a three-year span, one can observe the floor of the cave easily with the pile of collapsed ceiling. Figures 11 and 12, both views of the of inside of Cerebus Moulin, show that the overburden has greatly reduced in thickness.

The analysis of the extensive photographic material of the past years reveals that the glacier does not only decrease in length at the glacier front and in thickness at the surface, but also melts off from the inside at great speed, and therefore, loses mass. The latter was surprising and should be further investigated.

Short- and Long-Term Measuring Program Inside Sandy Glacier

The climatological measuring program was started on October 10, 2014, by the installation of the first sensors and was expanded by mobile measurements, as well as the installation of additional sensors in 2015 for the entire area of the caves (Fig. 13). The measuring program can

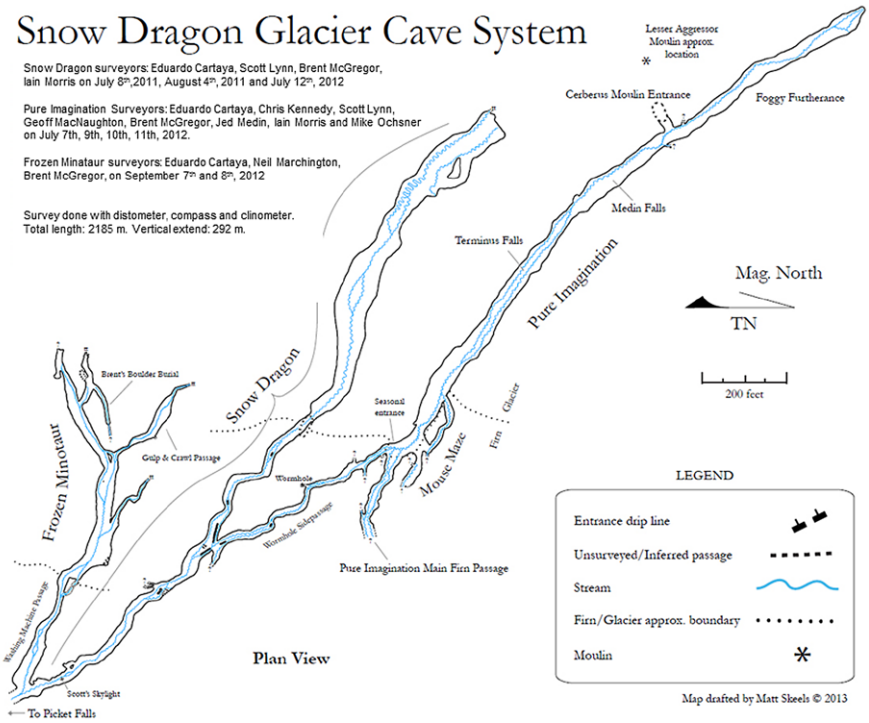


Figure 6. Map of the cave system (Frozen Minotaur, Snow Dragon, and Pure Imagination) inside the Sandy Glacier of Mt. Hood in 2013.



Figure 7. Lower entrance to Pure Imagination Cave on June 22, .2015. The entrance has increased in size 4 m high and 15 m wide.



Figure 8. Remnant entrance of Pure Imagination Cave on October 10, 2015. Light from Cerberus Moulin shows through the upper end of the cave.



Figure 9. The Cerberus Moulin, Pure Imagination Cave on September 19, 2013.



Figure 10. Cerberus Moulin, Pure Imagination Cave on June 20, 2015. The old moulin has increased in size dramatically.



Figure 11. Cerberus Moulin the day of discovery on November 9, 2011. View from the inside looking out the moulin.



Figure 12. Cerberus Moulin on June 22, 2015. View from the inside out the moulin.

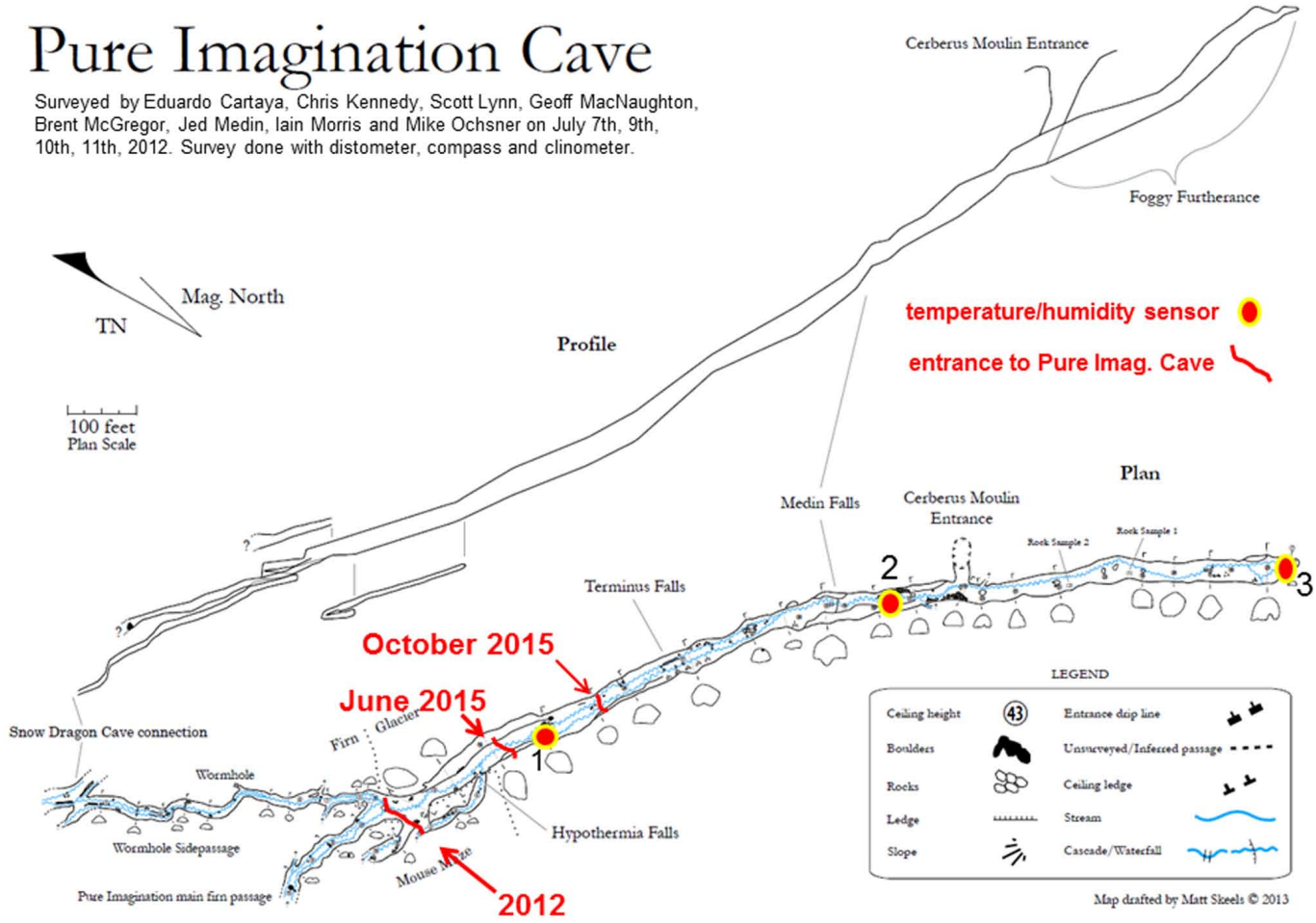


Figure 13. Map of Pure Imagination Cave showing changes of the cave entrance and the placement of the first data loggers in 2014.

be subdivided into the following stages: On October 10, 2014, we set up of a stationary installation of three sensors to measure air temperature and relative air moisture inside the glacier cave. From June 20–25, 2015, we undertook an intensive, short-term mobile measuring program to measure air, water, and surface temperatures throughout the entire area of the cave, as well as to measure air currents at two sites, above and below the moulin. For a clearer identification, we call the lower part of the cave Pure Imagination and the upper part beyond the moulin Hot Imagination Cave. On June 25, 2015, we expanded the measuring network by four additional measuring sensors to measure air and water temperatures inside Hot Imagination Cave.

Start of Long-Time Measurements

The first monitoring network was installed to gain a preliminary impression of the climatic conditions inside the glacier cave as a basis for following measurements in spring 2015. The goal was to install temperature and humidity sensors with data loggers for storing the data before the winter season to get an overview of the entire area of the cave. After the first visit, we decided to leave the sensors for at least three years or as long as the caves exist. Sensor 1 (GEOPRECISION M-Log5W-HUMIDITY data logger for air humidity and air temperature in white plastic housing; filter cap: HD-polyethylene, porous diameter 25 µm; sensor type: Sensirion SHT75; accuracy air humidity: ±1.8%; accuracy air temperature: ± −0.3 °C) was positioned at the lower entrance of the glacier close to the former exit. Sensor 2 was installed about 20 m below the large moulin at the end of Pure Imagination Cave, while sensor 3 was installed at the upper end of Hot Imagination Cave. Thus, two sensors were located in areas influenced by openings, while sensor 3 was located at the closed upper end. The sensors were positioned to be protected from falling rocks as well as from dripping water. The measuring frequency was 30 minutes.

Mobile Measurements and Short-Time Measurements Program

The mobile measuring program from June 20 to June 25, 2015 covered two priority areas. Both flow conditions at two selected sites in a vertical profile and thermal conditions in a high spatial resolution were obtained.

Repeated mobile measurements of air temperature, as well as of flow velocity and direction every 20 m throughout



Figure 14. Sensors of the sensor chain of 28 sensors measuring the air and water temperature in Hot Imagination Cave.

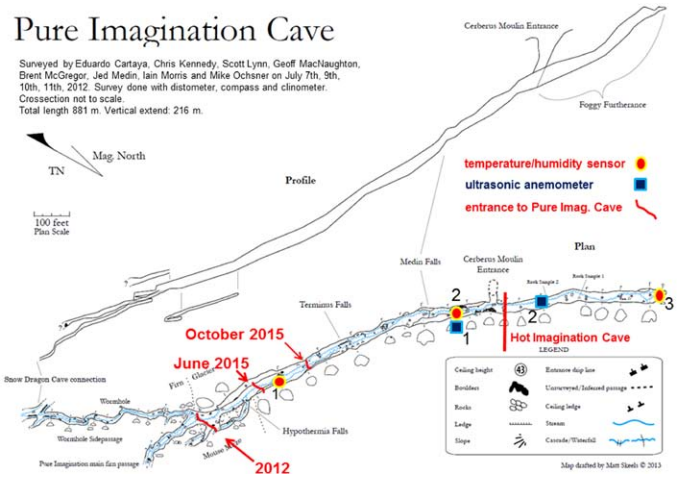


Figure 15. Pure Imagination Cave showing the location of the ultrasonic anemometers in comparison of the location of the data loggers.

the entire cave, were taken at 0.05 m above ground and 2.0 m above ground with a Testo 925.

Repeated mobile measurements of surface temperature with a thermal camera (InfraTec VarioCAM) in the entire cave at intervals of 10 to 20 m over the entire length of the cave each up- and down-glacier. Consistent intervals were not possible due to the complex topography of the cave.

Measurements of air and water temperature at selected sites were obtained using a sensor chain (GEOPRECISION digital thermistor string; resolution: 0.065 °C; accuracy (typical): ± 0.25 °C for the range –10 °C to +30 °C; string cable in PUR quality; the string is absolutely waterproof / IP69; diameter: cable 5mm /sensor: 8 mm) of 30 m length with 28 temperature sensors at intervals of 1 m (Fig. 14), from June 21 9:45 p.m. to June 23 00:00 midnight. The sensor chains were installed in the higher part of the cave, starting from the warmest spring known so far. Three further warm spring areas (so-called hotspots), mixing areas, and cold-water runoffs were also recognized. Unfortunately, meltwater leaving the ice could not be surveyed due to distance.

Stationary measurement of air temperature, as well as horizontal and vertical air currents, were collected at heights of 0.6 and 4 m above ground at two sites (Figs. 15 to 17) using ultrasonic anemometers (METEK USA 1). Site 1 is located in Hot Imagination Cave about 20 m behind the opening to the moulin. In this area, the slope gradient is low, about 5 degrees. The lower measuring instrument was placed in the meltwaters flowing out about 0.6 m above ground ,and therefore, was located about 6 m lower than the measuring instrument close to the ceiling. Site 2 was located in Pure Imagination Cave about 20 m behind the opening to the moulin at a steep slope of about 25 degrees. The measuring instrument close to the ground was placed in the lower part of the slope directly above the meltwater stream, and the higher measuring instrument was located in the central area of the slope, about 4 m above the ground and 8 m above the lower measuring instrument. The upper anemometer malfunctioned after 12:47 hours.

Long-Term Measurements

Based on the mobile measuring program, four additional temperature sensors with data loggers were installed (GEOPRECISION M-Log5W-CABLE temperature data logger with sensor cable in waterproof plastic housing; sensor type: PT1000 in stainless steel cap; accuracy: ± 0.1 °C (at 0° C); resolution: 0.01 °C.) on June 25, 2015 (Fig. 18). This campaign focused on water temperatures in the hottest known spring in Hot Imagination Cave, as well as in the outlet area about 20 m from the large moulin. In addition, temperature sensors were placed 1 m above ground in the central hall at the latter site and at the same height directly next to the ice wall. The investigations focused on thermal dynamics between the lower end close to the opening of the cave and the closed upper end. These measurements are scheduled at least for 3 more years or until collapse of the cave.

Summary of First Results

The first expedition focusing on the climatology of glacier caves revealed numerous unexpected results.

Stationary Measurements of Air Temperature Using Data Loggers

Preliminary measurements in 2014 showed an unusually high air temperature of up to 7 °C; especially in areas up-glacier from the Cerberus Moulin of the glacier cave. In general, we expect air temperatures around the freezing point, as the air temperature inside glacier caves is influenced by the surrounding ice masses, meltwater flow, and potentially



Figure 16. Location of the ultrasonic anemometers in Pure Imagination Cave. Left: view to the lower entrance of the cave. Right: view to the upper entrance (Cerebus Moulin) cave



Figure 17. Location of the ultrasonic anemometers in Hot Imagination Cave. View out of the cave in upper picture, view inside cave in lower picture.

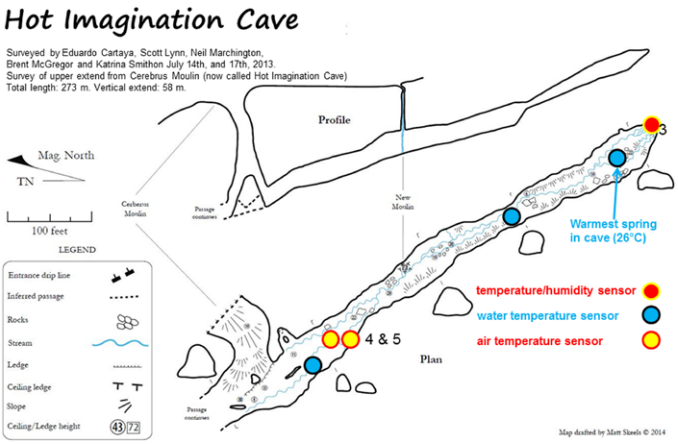


Figure 18. Pure Imagination Cave placement of additional data loggers.

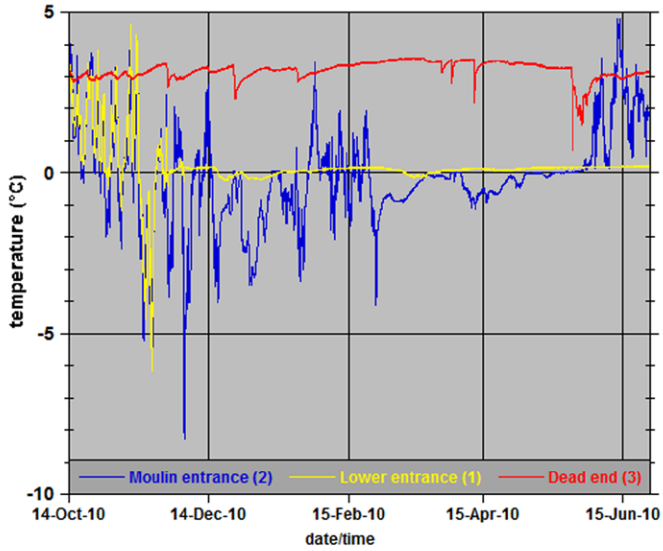


Figure 19. Air temperature at three different locations in Pure and Hot Imagination Caves from October 2014 to June 2015. Numbers represent the sensor numbers in Figure 13.



Figure 20. Upper part of Hot Imagination Cave is usually very foggy.

the exposed bedrock and boulders. Generally, considerably higher or lower air temperatures can only occur in the entrance area of the cave or open moulins due to inflowing warm or cold air from the outside atmosphere. The first measurements, however, also showed surprisingly high air temperatures at the closed upper end of the cave, even in winter (Fig. 19, sensor 3). Additionally, dense fog already indicated special conditions in this area (Fig. 20).

Comparing the data from three temperature sensors reveals substantial differences between the sites. The air temperature at both sites inside Pure Imagination Cave (Fig. 19, sensors 1 and 2) are more or less similar until November 2014. They are clearly influenced by atmospheric air, showing drops in temperature, along with warmer periods. In contrast, the sites that were located up-glacier inside the conduit were slightly cooler. This may be due to higher elevation up-glacier or cold inflowing air from the moulin only 20 m away. Later, the higher site (Fig. 19, sensor 2) still showed substantial temperature fluctuations, while the temperature at site 1 had little to no fluctuations. The sensor may have been covered in snow starting in November, which it shielded from the atmospheric influences. This, however, is not visible till February for the higher site close to the moulin (Fig. 19, sensor 2) due to its more sheltered position in the cave. Here some snow blown inside might have damped the temperature from the middle of February to the beginning of June. Even in June, sensor 1 was still covered in snow and fallen ice and could not be found. Due to the remote sensor we could download the data, but the data are not representative of air temperature (Fig. 19).

Air temperature at sensor 3 at the upper end of Hot Imagination Cave (i.e., the sensor farthest from the entrance) shows a completely different pattern. Due to its position at the very end of the cave in the area of outflowing meltwater discharge between glacial ice and bedrock and its large distance from the cave's openings, stable air temperatures around freezing point are expected. In addition, no incoming warm air masses are expected, at least during the winter months. Against these expectations, air temperature do not drop below freezing at any time, but varies between 2.8 and 3.5 °C. Remarkably, a wave structure characterized by abrupt drops in air temperature and slow temperature increases was found; its frequency decreased from 6 to 17 days in fall 2014 up to 2 months in spring 2015. One possible reason is outbreaks of cold meltwater from the upper part of the glacier, which are more likely in fall than in winter and early spring. This could explain the temperature drop and the changing frequency.

The highest temperature of 3.6 °C was reached on March 15, 2015 and steadily decreased afterward, followed by some intense temperature drops. Even during the most intense drop in air temperature, it only drops once below 1 °C for a short time. Those high air temperatures can be considered as an anomaly.

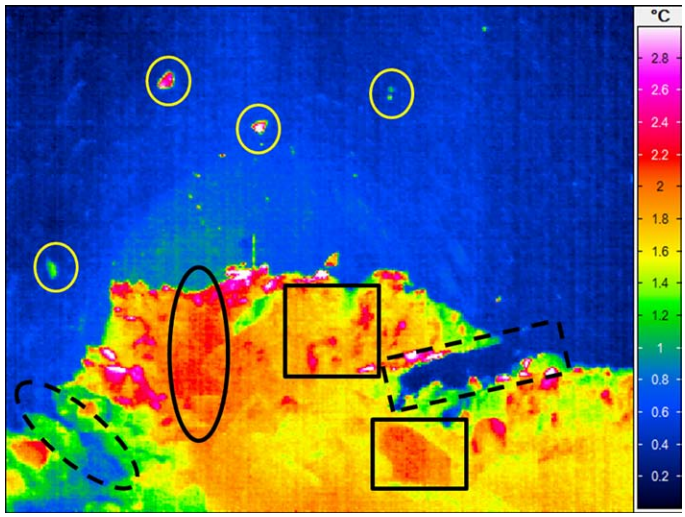


Figure 21. Thermal picture in Pure Imagination Cave in June 2015, facing upslope. The straight line in the back is the post of the ultrasonic anemometer. The warm spots in the blue ceiling and walls are rocks melting out the ice (yellow circles). White spots on the ground are mostly exposed and dry rocks. Purple and red spots on the ground are flowing water (black oval) or exposed rocks (black rectangle). The colder structures on the ground are cold meltwater (lighter blue with a dashed black oval) or solid ice (darker blue with a dashed black rectangle).

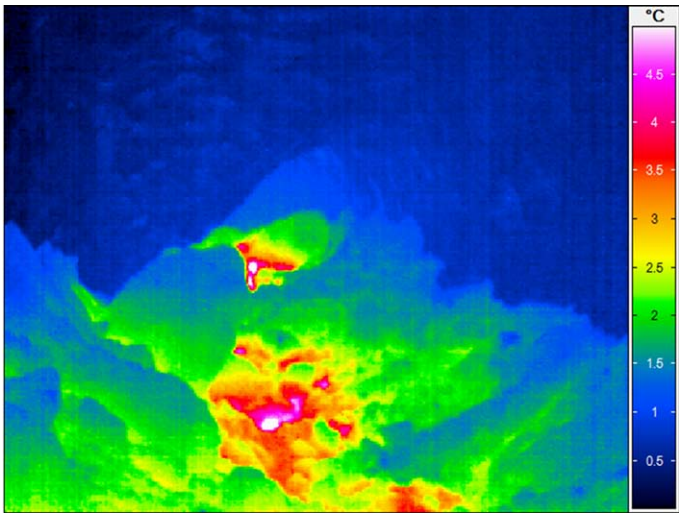


Figure 22. Thermal picture in Hot Imagination Cave in June 2015, facing upslope. The white and purple spots show clearly the warm water from the warm springs.

Short-Term Measurements of Meltwater Using Sensor Chains and Thermal Cameras

The first thermal images clearly indicated surprisingly high temperatures of out-flowing meltwater at the base of the glacier. While we found water temperatures of 1.6 °C at the outlet at the lower entrance of the glacier at Pure Imagination Cave, those water temperatures increased to 7.7 °C at the outlet in the higher area of Hot Imagination Cave to the moulin (Fig. 21).

However, at the outlet between ice mass and bedrock at the upper end of Hot Imagination Cave we found the expected meltwater temperature of exactly 0.0 °C. Because the sensor chain did not reach that far up and we were more interested in the temperature of the warm springs, these measurements were made a few times by hand-held devices.

A total of 46 warm springs in the out-flowing meltwater of the higher parts of the cave were identified by measurements using a thermal camera followed by direct measurements of water temperature using a temperature sensor (Figs. 22 to 24). Figure 22 shows an example of warm spots in the down-flowing meltwater streams. Figure 23, the series of four pictures shows the mixing of already warmed up meltwater with some warm, thermally-affected groundwater. These mixing areas can be found all over in Hot Imagination Cave. In the lower parts of the cave, only two warm springs were found (Fig. 24). Despite a continuous warming of the total meltwater flow, those springs could be clearly differentiated from surrounding water.

Figure 25 outlines the high variation range of water temperatures by showing data from twelve selected temperature sensors of the sensor chain. The largely unaffected meltwater shows stable temperatures slightly above freezing point. These water temperatures increase to 1.5 to 2.2 °C only 20 meters after leaving the glacier. Several thermal images indicated that these temperatures correspond to those of the ice-free ground. Either the ground is warmed up by a deeper heat source, or there are unknown slightly effective warm springs upgradient.

In comparison to the meltwater leaving the glacier, temperature sensors in the water measured higher temperatures to a greater or lesser extent. The temperatures of the unaffected water were just above the freezing point; the warmest hot spots were up to 26 °C. In the mixing areas of warm and cold water, as well as the air, the temperature was above 3 °C.

Three additional hot spots showed water temperatures of 17.7 to 19.2 °C. For all mentioned measuring sites, the course of the temperature is very stable, and slight variations can only be found at the warmest point. The measurement period, however, was only 44 hours. The sites in the mixing area between cold meltwater and warm springs showed much higher variations, with warmer and cooler periods without any temperature changes in meltwater and spring water (Fig. 25). As these periods last for several minutes or hours, they cannot be explained by short-term turbulences, but can be due to changes in flow conditions or diurnal meltwater water level changes.

So-called hot spots only occur in connection with water, but higher bedrock temperatures could be identified by using

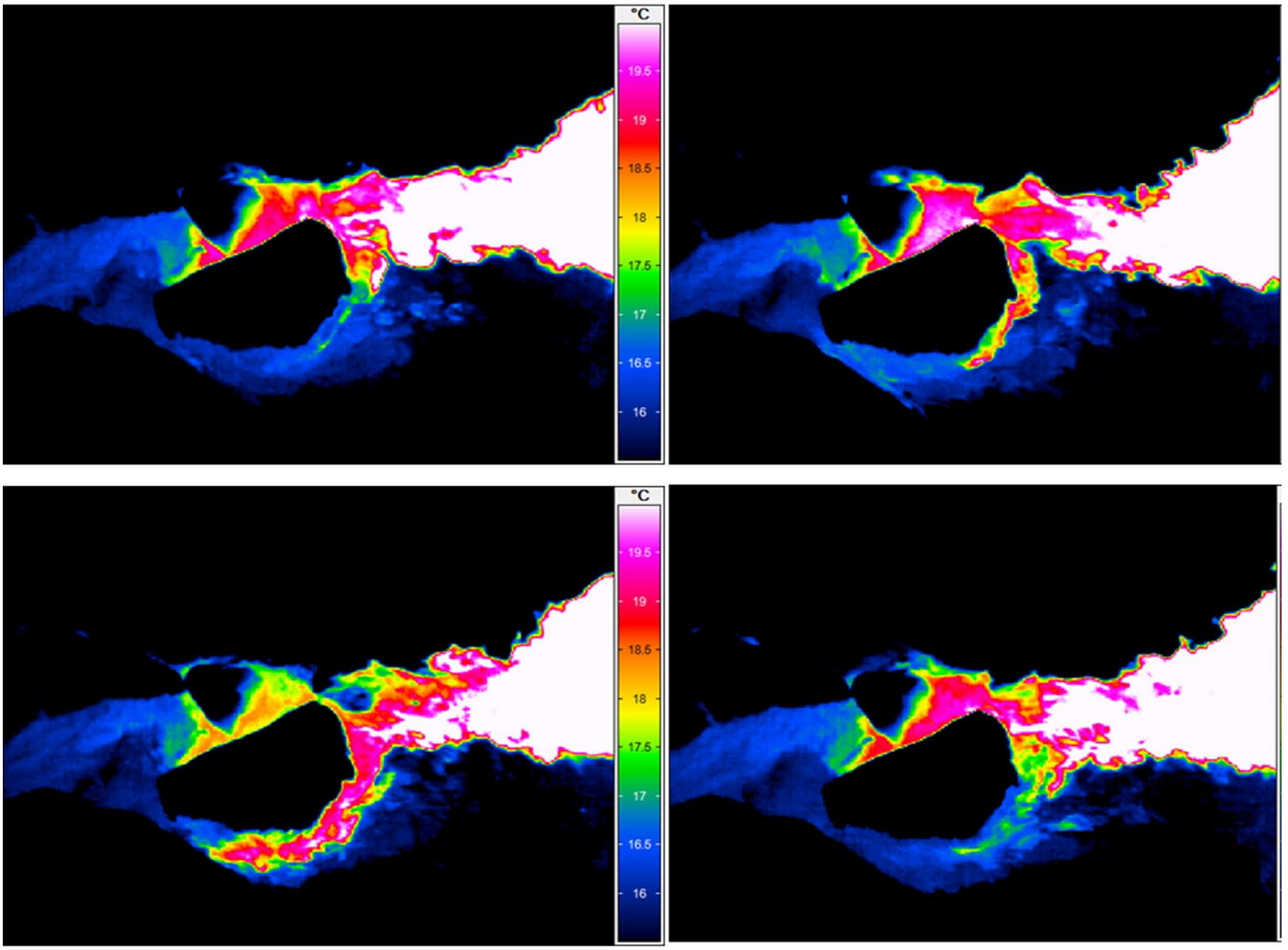


Figure 23. Series of thermal pictures documenting the mixing of already warm meltwater (blue) and warmer spring water (white) around a rock.

thermal cameras. However, those temperature changes of 1 to 3 K are relatively small and seem to be connected to warm springs below the surface (Figure 25). No fumaroles of hot steam could be identified.

Short-Term Measurements of Air Temperature Using Sensor Chains

With values of 4 °C to 5 °C, both sensors of the sensors chain measuring the air temperature in the upper part of Hot Imagination Cave, as well as the stationary data logger, found clearly increased temperature values. Those can be explained by the proximity of 0.2 to 0.5 m to warm springs. Although the consistently high air temperature is not expected inside a glacier cave, it can be explained by the thermal activity of the volcano.

Short-Term Measurements of Surface Temperature Using Thermal Cameras

The entire surface of the cave was surveyed twice each in the mornings of June 22, 2015 and June 24, 2015, using a thermal camera. The repeated survey reflected different external conditions characterized by steadily

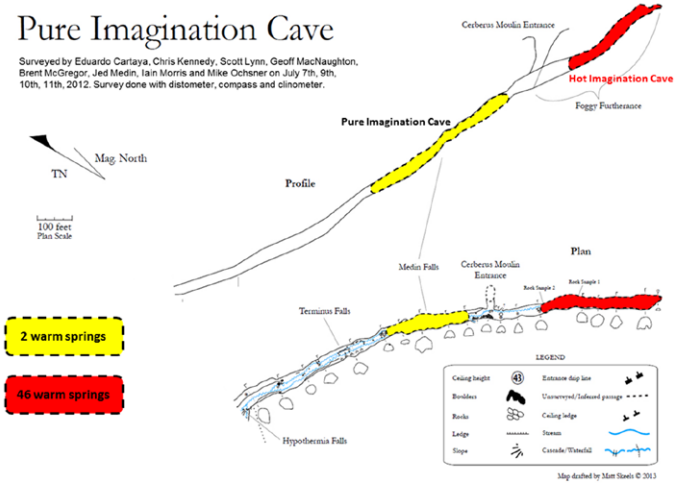


Figure 24. Areas with the numbers of proven warm springs in Pure and Hot Imagination Caves.

increasing air temperatures. While the most important results in terms of warm spring areas have already been discussed in detail, further results will be presented below.

In general, the surface of the ice was covered with a thin film of water. Temperatures were around freezing point, with only temperatures of the transparent clear ice being lower. Those appeared as cold spots or bands in the thermal images.

Another important aspect regarding climatology of glacier caves is strongly warmed sediments of all grain sizes trapped in the ice (Fig. 26). Various sediments including long bands of clay, pebbles, and boulders with diameters of 1 m were identified, leading to numerous thermal patterns. An initial review of the thermal images shows a clear relation between sediment size and surface temperature, with larger sediment diameters being connected with stronger heating. Other important factors

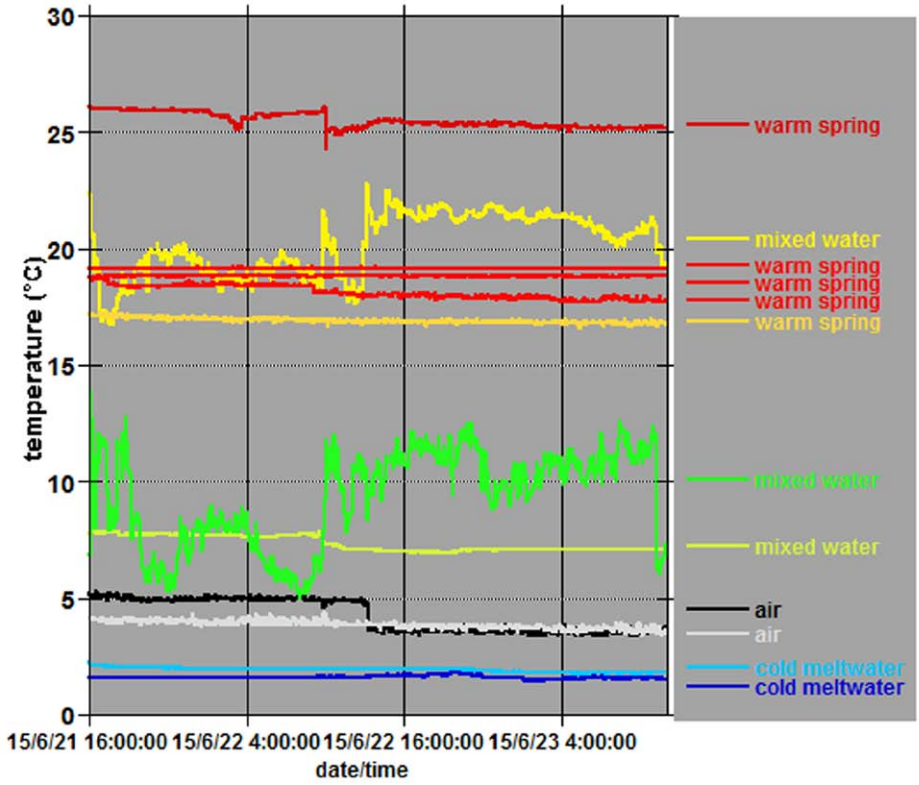


Figure 25. Air and water temperature at selected sensors of the sensor chain in Hot Imagination Cave from June 23 to June 25, 2015.



Figure 26. A boulder hanging in the ice ceiling of the cave and melting out.

are the sediment's shape and the degree of melting around it. Rough boulders with exposed peaks and ridges warm more strongly than even and smooth surfaces. Rocks already melted from the ice and thus exposed to air currents also reached noticeably higher temperatures than rocks still mainly embedded in ice. Therefore, the melting of rocks out of ice is an accelerating process. Both the progressive warming of the rock, as well as its decreasing adhesion to the ice mass, lead to a fast detachment of the rock. Rocks in the ceiling detach faster than those in the wall, which experience some degree of support from underlying ice masses. The melting effect of large rocks also causes melting rings surrounding those boulders (Figs. 21 and 26).

Furthermore, the temperature of sediments largely depends on the temperature of air entering the glacier cave. During the first measurements on June 21, we found rock temperatures of larger rocks (> 5 cm) to be about 2.5 to 3.5 °C, with maximum temperatures of the largest rocks of 4.1 °C, whereas some days later those values increased to 4.0 to 5.0 °C with maximum of 6.0 °C (Fig. 21). Unfortunately, we don't have enough measurements to give an exact correlation coefficient for the causal relationship between incoming air temperature, rock size, and rock temperature. Measurements to answer this important question are planned for future visits.

It can be assumed that the warming of ice up to freezing point continues, especially from exposed sediments. Consequently, ice close to warm rocks will melt faster than uninfluenced ice. However, it has to be considered that those results only reflect the situation during the summer months. In winter, rocks exposed from the ice may have the opposite effect: Atmospheric air below freezing entering the cave will first cool down those sediments, which conduct cold temperatures into the glacial ice body, leading to the formation of colder spots where the melting process of the glacier ice stops first.

Measurements of Air Currents Using Ultrasonic Anemometers

In addition to measurements of thermal events inside the glacier cave, investigations also focused on air currents.

Pure Imagination Cave (Figs. 27 and 28).

Unfortunately, the upper anemometer malfunctioned after 12:47 hours. But even the over the short period, the two instruments that measured the airflow simultaneously shows us remarkable result (Figs. 27 and 28). Some of us who have been inside a cave know strong winds caused by convection or barometric pressure effects very well (Pflitsch et al., 2010). But a combination of high airflow velocities and high temperatures inside a glacier cave as a mostly frozen environment had not been observed or measured yet.

In accordance with the high temperatures of the external atmosphere, which exceed the temperatures inside the tunnel for the entire measuring period, our measurements show a pronounced downward air current over the entire vertical distance of the tunnel for the entire measuring period. Warm air enters through the moulin, cools down, flows downward due to gravity, and leaves the tunnel through the lower opening. This result is consistent with investigations during the individual measurements.

The flow velocities reached 4.04 m s^{-1} close to the ground and 6.68 m s^{-1} close to the ceiling at the same time. Even the mean values of the horizontal component of 1.55 m s^{-1} at ground-level and 3.14 m s^{-1} at the ceiling show relatively high values, with an increase of velocity with increasing height above ground. This effect might be caused by the higher roughness of the ground and is typical for the outside atmosphere as well. Similarly, on average, the vertical components of 0.72 m s^{-1} and –1.28 m s^{-1} indicate a clear downward movement. Further values are included in Tables 1 and

Table 1. Statistical overview about the measurements of the ultrasonic anemometer in Pure Imagination Cave (v = horizontal air velocity (m s^{-1}), z = vertical air velocity (m s^{-1}), t = air temperature (°C)).

Statistic	v-ground	v-ceiling	z-ground	z-ceiling	t-ground	t-ceiling
min	0	0	−0.32	−0.38	2.32	2.34
max	0.88	1.24	0.52	0.41	4.87	5.99
average	0.3	0.48	0.04	0.03	3.57	3.6
median	0.3	0.48	0.4	0.03	3.59	3.62
variance	8.64	24.02	2.42	3.8	12.78	20.95

Table 2. Statistical overview about the measurements of the ultrasonic anemometer in Hot Imagination Cave (v = horizontal air velocity (m s^{-1}), z = vertical air velocity (m s^{-1}), t = air temperature (°C)).

Statistic	v-ground, short	v-ground, long	v-ceiling	z-ground, short	z-ground, long	z-ceiling	t-ground, short	t-ground, long	t-ceiling
min	0.22	0.22	0.4	−2.07	−3.08	-3.02	4.26	4.26	6.32
max	4.04	4.75	6.68	0.34	1.12	0.87	11.19	12.77	13.23
average	1.55	1.9	3.14	−0.72	−0.85	-1.28	8.06	8.73	9.61
median	1.71	1.85	3.1	−0.71	−0.83	-1.26	8.03	8.77	9.51
variance	17.96	26.89	48.49	6.7	9.71	14.46	78.17	126.49	80.09

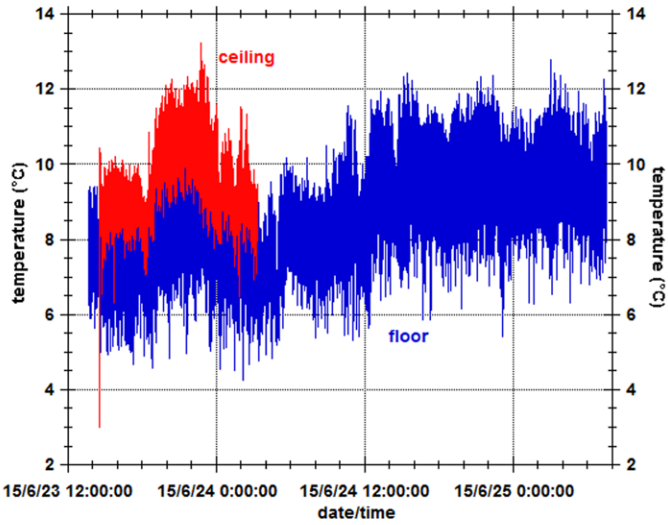


Figure 27. Air temperature (°C) of airflow at 0.6 m and 4.5 m above ground in Pure Imagination Cave from June 23, 2015 to June 25, 2015.

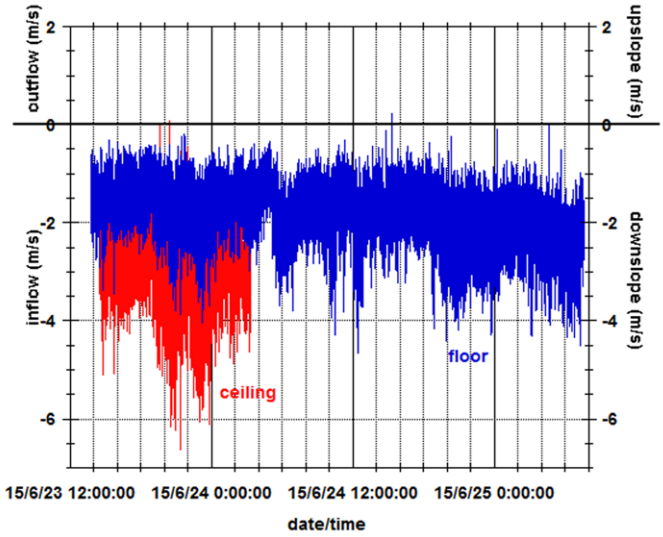


Figure 28. Direction and velocity (m s^{-1}) of airflow at 0.6 m and 4.5 m above ground in Pure Imagination Cave from June 23 to June 25, 2015.

2.

The temperatures of the cave air are quite surprising as well, reaching 4.3 °C to 11.2 °C at ground level just above the glacier water and 6.3 °C to 13.2 °C close to the ceiling for the corresponding12 hour time period. Also, the mean values of 8.1 °C close to the ground and 9.6 °C close to the ceiling show a clear temperature increase with height in the glacier tunnel. Those high air temperatures inside the ice tunnel are no snapshots, as proven by a further increase in temperature measured at ground level over the entire measurement period.

Hot Imagination Cave (Figs. 29 and 30)

Completely different flow conditions were found above the moulin in Hot Imagination Cave, the upper end of which, is closed (Fig. 15). Both horizontal and vertical flow velocities are lower. Thus for the area close to the ceiling, the maximum of the horizontal component was only 1.24 m s^{-1} with a mean value of 0.48 m s^{-1}, whereas for the area close to the ground maximum and mean values of only 0.88 m s^{-1} and 0.3 m s^{-1} respectively were found. The vertical component, with mean values of 0.03 and 0.04 m s^{-1} and maximum values of less than ± 0.5 m s^{-1}, was very weak compared to the dynamic part of the glacier tunnel. The flow rates inside the upper closed part of the glacier cave seem inconsiderable compared to the lower part with openings on both sites. These flow rates, however, are still higher than those of many other known static and even dynamic caves. (Pflitsch et al., 2010) The flow direction reveals a clearly pronounced vertically structured flow system in this part of the glacier cave. Thus for the area close to the ground, a clear and steady outflow was found, while air was flowing in upwards along the ceiling.

Taking the temperature information measured by sonics into account, it can be summarized that at least temporarily, ground-level cold air flows out of the cave while warm air flows in at the ceiling. During warm periods, the air temperatures close to the ceiling are higher than those close to the ground, while during cooler periods, the air close to the ceiling is cooler than at ground level. Thus on average, both areas appear equally tempered, with mean values of around 3.6 °C. However, the maximum temperatures of 4.9 °C close to the ground and 6.0 °C close to the ceiling differ clearly.

The origin of warm air currents close to the ceiling could not be determined yet. During warmer periods, warm air from the outside might accumulate underneath the ceiling, while during colder periods “waste heat” from the water might have an effect and heat layers of air close to the ground. The former is rather unlikely, as air masses from the outside of the tunnel cannot enter this part of the cave easily due to the moulin’s shape and the relatively small opening to the upper area. In addition, there is no dynamic drive by the suction effect as found in the lower part of the cave. The relatively small temperature difference between the air close to the ground and close to the ceiling and the rather turbulent vertical and horizontal air movements suggest convective mixing of air. It might be caused by the warm water. This is also supported by sections with weak air movements where temperature peaks in the higher air layers correspond with temperature decreases close to the ground and vice versa.

In addition, a recently developing Drooling Moulin 10 m up-glacier away from the measurement site at least temporarily influences the vertical component of the flow regime. This moulin, which had already been observed in the previous year, but closed during the winter months, generates waterfall-like dripping meltwater. The rate of meltwater

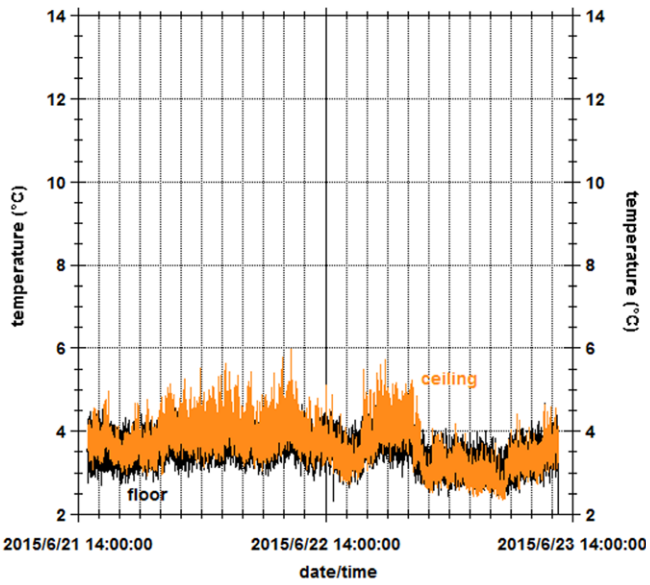


Figure 29. Air temperature (°C) in Hot Imagination Cave at 0.6 m and 4.5 m above ground from June 23, 2015 to June 25, 2015.

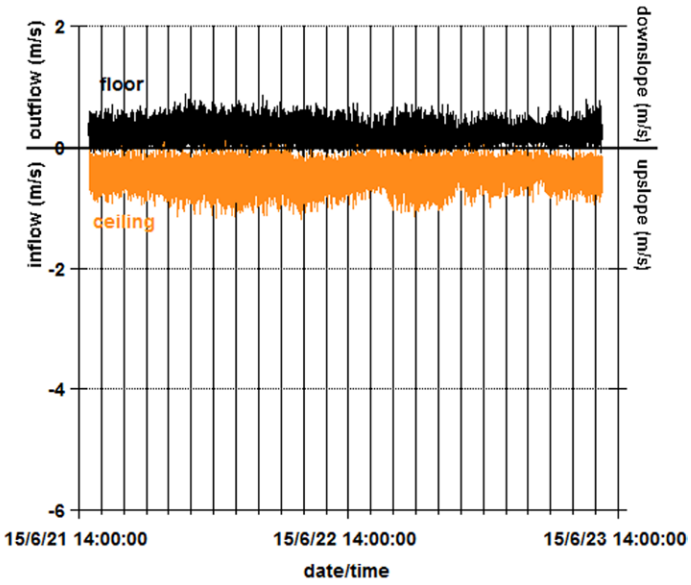


Figure 30. Direction and velocity (m s^{-1}) of airflow in Hot Imagination Cave at 0.6 m and 4.5 m above ground from June 23, 2015 to June 25, 2015.

dripping reached its maximum in the afternoon, while being weaker at night. Measurements by smoke tubes (Draeger Air Current tubes) show that in the area of dripping meltwater ,cold air is carried downwards before rising to the sides like a reverse mushroom shape similar to a downburst. Here impulses of air movement were induced by both falling water masses dragging the air downwards as well as the gravitational descent of air cooled by the water. At the edge of this "micro downburst," turbulence leading to mixing of air layers close to the ground with those close to the ceiling could be repeatedly observed. This observation could not be confirmed by measurements.

Additional Observations

In the area of centrally out-flowing water, and especially above warm springs, the lower layers of air show a higher air temperature than that in other areas. The warmed air rises in the center of the cave and collects immediately below the ceiling. Afterwards, it cools down and sinks at the cave walls. This was proven using smoke tubes. However, we found an asymmetry of both halves of the cave. In the upper end of the cave, the right half showed a general tendency of air rising toward the upper end, whereas air in the left half of the cave tended to sink toward the lower entrance of the cave. We think this is a spiral or corkscrew-like convection process caused by the downslope-flowing cold air, upslope-flowing warm air, and down-flowing cold air from the ceiling disturbed by the relatively warm meltwater and springs.

Summary of Measuring Results

The first expedition to Mt. Hood with a focus on investigating the climatological condition inside Sandy Glacier brought us an enormous amount of new results for understanding the glacier. The results are summarized as follows.

Substantially increased air temperatures measured during previous expeditions were confirmed both by stationary long-term and mobile short-term measurements. By using thermal cameras, we could also find reasons for those unusually high air temperatures. High air temperatures in the upper part of the cave are caused by numerous warm springs with water temperatures up to 26 °C. The water, however, is not only heated at those specific spots, but lastingly. Warm springs cause a constant warming of the water up to 7.7 °C up to the Cerebus Moulin and 1.6 °C to the lower entrance. Consequently, increased water temperatures lead to an increase of air temperature.

Another phenomenon of the central and upper areas of Hot Imagination Cave is the constant formation of fog, which forms by the mixing of rising warm and humid air masses from the warm meltwater areas and the cooler air masses from the ice walls of the cave.

In the lower part of the cave, warm water that cools due to in flowing meltwater and is warmed to a lesser extent by two warm springs, plays a tangential role enlarging the cave. In this part, the cave's large cross-sectional area and the large upper opening of the moulin and the lower entrance are more important for melting processes inside the cave. Both openings lead to strong chimney-effect currents between the external atmosphere and the air inside the cave, causing warm air masses from the outside to enter the cave. This was proven using ultrasonic measurements.

Warm air causes both, direct melting of the ice walls and a strong warming of rocks and sediments that are embed-

ded in the ice. Heating of those rocks accelerates the melting of surrounding ice masses, with large boulders causing additional heat flow into the first few meters of glacial ice.

Formation of glacier caves over an area of geothermal heat is a self-reinforcing process. Warm springs cause the formation of caves, leading to unusually large glacier caves with large openings that allow warm atmospheric air to enter the cave and accelerate further melting.

Important Activities for Future Research

It is clear that Sandy Glacier is located above an active volcano, with warm springs below the glacier. But even without the power of geothermal processes, inside glacial conduits or caves with a chimney effect, especially in regions with summer temperatures above the freezing point, the cave's climate is important to take into account for glacier melting. We have to take into account that these caves can play a substantial role in the mass balance and energy balance of a glacier. Especially at the lower part of the glacier, the ablation zone, glacier caves with a rocky floor (contact caves) can have a large effect to interior melting. In these parts, the rocky floor does warm up by direct and indirect sunlight and inflowing warm air masses. Convective upslope warm air and longwave radiation from the rocky floor and walls move energy though the interior of the glacier or ice pack and intensify melting processes. The thinning of the glacier cave ceilings can lead to unexpected collapses of up to hundred meters of cave in one summer and accelerate the glacier retreat enormously. An example is Worthington Glacier in Alaska near Valdez. We visited the glacier for about six years and the south-facing tongue showed always a glacier cave at the morning-sun-facing side, at least when the sun was high enough. The opposite side gets most of the year no sun. At the sun-facing side the glacier is for about 10 to 30 m (depends on the season, not attached to the open bedrock, and the cave, building between the glacier and the bedrock, has an unstable ceiling with many collapses. Thermal investigations showed already the warmer bedrock in comparison to the colder ice. Unfortunately, no further investigations have been done yet.

We know that these are the first results of a new field of research and there is a lot more work to do. Further expeditions are in preparation to observe the glacier and its caves, intensify and expand the measurements as a good base for necessary calculations. Future expeditions to Mt. Hood, Mt. St. Helens, and Mount Rainier are planned. Additionally, we have to expand this research to glaciers that are not affected by thermal heat sources, but with some good summer heat and a strong retreat like in Alaska, the Alps, or southern Greenland, to confirm our theories.

Acknowledgements

We acknowledge the help of the numerous porters who carried all the equipment and instrumentation, as well as food, up to base camp and then helped pack our gear back down the mountain to the trail head. Also the cavers who surveyed and mapped the cave and the photographers that documented the expedition. Without the multiple skills of the team members, the work could not have progressed.

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