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Thermal Regime of a Cold Air Trap in Central Pennsylvania, USA: the Trough Creek Ice Mine

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ABSTRACT

Air temperatures internal and external to a talus cave ('ice mine') in central Pennsylvania were measured hourly for three years. Despite its location near the base of a talus slope, the cave demonstrated the thermal characteristics of an apparently static cave, with limited connections to the external environment other than through the cave entrance. Congelation ice that lasted until late spring formed as drip or flowstone and ponded ice from the limited influx of infiltrating water during late winter/early spring. A closed period of thermal stratification and slow warming of cave air was followed by an open period in winter months during which the cave was cooled by the influx of cold dry air. Unlike the occasionally strong and localised cooling induced by the flow of cold air from vents at the base of talus slopes, static cold traps retain their cold air and have little apparent effect on surrounding biota, instead providing potential refugia for organisms that prefer colder temperatures. Published 2012. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS: cold air trap; thermal anomaly; talus cave; ice deposit; Pennsylvania

INTRODUCTION

In the 1890s, climatologist Edwin S. Balch visited 33 cold sites in eastern North America, including ravines and gorges, taluses and boulder heaps, as well as man-made wells, mines and tunnels where ice had been reported to persist into the summer months (Balch, 1900). He observed that specific geographic features facilitated the persistence of 'cold traps' (natural refrigerators or *glaciéres naturelles*) that maintained mean annual temperatures lower than those of their surroundings. Although many of these features were believed by local residents to contain perennial ice, Balch found little direct evidence to support these claims, even though cold air flowing from some talus slopes in summertime suggested the possible presence of inaccessible deposits of ice year-round. Deep and narrow rock crevices and gullies allowed the preservation of snow and ice where features such as topography, altitude, aspect and heavy vegetation minimised their exposure to direct sunlight, warmer temperatures and wind. Ice also formed within permeable talus slopes and in caves sharing these physical characteristics. The seasonal displacement of warm interstitial or void space air by heavier cold winter air cooled the surrounding rock, and infiltrating water from rainfall and thawed ice and snow formed subsurface ice deposits. Man-made tunnels and mines also occasionally mimicked the same natural conditions that were suitable for the formation and preservation of ice in talus and caves (Balch, 1900, 1921). Thermal stratification of air in summer at such locations prevented the mixing of warm air by convection and slowed the ice-melting process.

Historically, scientific studies of eastern North American cold air traps have been cursory, usually limited to the collection of random temperature measurements taken with mercury thermometers (Balch, 1900). The relatively recent development of small, accurate and inexpensive temperature data logging devices has allowed a better understanding of the temporal variability of temperatures in caves and cold environments. Their value has been demonstrated in studies of Jura Mountain karst caves containing perennial ice (Luetscher, 2005), Missouri cave bat hibernacula (Elliott and Clawson, 2001), the regional distribution of permafrost in Appalachian Highland soils (Walegur and Nelson, 2003) and numerous other examples.

Recent studies have demonstrated that cold air traps can harbour flora and fauna that are representative of

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climates colder than those of their surrounding environments (Lendemer *et al*., 2009; Zacharda *et al*., 2005). These localised temperature anomalies can result in the presence of 'biogeographical islands' or refugia for temperature-sensitive organisms, the function and fate of which may serve as valuable indicators of future global climate change (Whitehead, 1973). However, detailed information on the thermal characteristics of these unique habitats is lacking for sites in eastern North America.

In this study, we report the temperature regime of the Trough Creek ice mine, a cold air trap feature in central Pennsylvania. Air temperatures inside and outside the cold air trap were monitored for three years, establishing a thermal signature for the site that provides a scientific baseline upon which future studies of climate change and potential ecological perturbations can be based.

SITE DESCRIPTION

The Trough Creek ice mine is a geologic feature located in Trough Creek State Park in Huntingdon County, Pennsylvania (40°19'56'' N, -78°07'24'' W; Figure 1A). Although located in the Appalachian Mountain Section of the Ridge and Valley physiographic province (Way, 1999; Sevon, 2000), the site location is associated with nearly horizontal sedimentary bedrock, steep topography and narrow valleys more typical of the Allegheny Mountain Section of the Appalachian Plateau province. Great Trough Creek has entrenched a 150–250 m deep gorge into nearly horizontally bedded, yellow-brown sandstones, siltstones and conglomerates of the Mississippian-age Pocono Formation (Wilshusen, 1969; Berg *et al*., 1980).

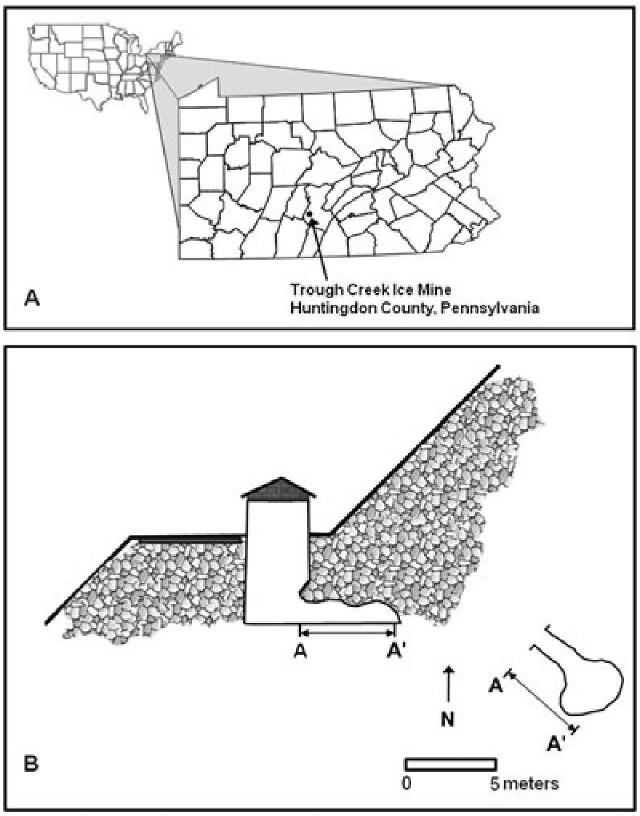

Figure 1 (A) Location of the Trough Creek ice mine in Huntingdon County, Pennsylvania, USA. (B) Cross-section of the talus slope, ice mine and shaft, including plan view of the ice mine talus cave.

The ice mine consists of a shaft and stairway leading to a small talus cave located near the base of a west-facing (270° aspect) talus slope on the side of Terrace Mountain (Figure 1B; White and White, 1999). Although we refer to the talus cave and its associated shaft and structure by its common name of Trough Creek ice mine throughout this paper, little evidence exists to suggest that the cave ever served as a mine, as discussed below.

Trough Creek ice mine lies at an elevation of 257 m above sea level, *ca*. 15 m above Great Trough Creek and *ca*. 138 m below thickly bedded quartz sandstone outcrops at the canyon rim near the top of Terrace Mountain. Access to the opening of the talus cave, which lies *ca*. 5 m below ground level, has been facilitated by the construction of a protective shelter and stone stairway (Figure 2A and B). This construction creates an artificial vertical shaft below ground level with a volume of *ca*. 112 m^3, excluding the talus cave itself. The walls of the shaft are mortared with cement, largely preventing the influx of air and water from the surrounding talus. The cave opening at the base of the shaft is 1.4 m wide x 1.2 m high; the cave itself extends 4.9 m horizontally, with a maximum height and width of 1.3 m and 2.9 m, respectively, and a total volume of *ca*. 9 m^3 (Figure 1B). Public access to the talus cave is not restricted, but most visitors limit their exploration to the bottom of the shaft, where the extreme temperature differences between surface and cave temperatures can be best experienced in the summer months.

The roof of the talus cave is spanned by large tabular sandstone blocks, oriented in nearly horizontal position, with some pervasive active tension cracks (Figure 2C). The nearly level floor slopes gently upwards towards the rear of the cave and is composed of breakdown in the form of small boulders, cobbles and finer sediments. The natural rock walls of the cave are composed of breakdown or bouldery diamicton interpreted as either colluvium or crushed material inter-layered between slumped blocks. Sandstone clasts in the ice mine are finer-grained, less quartz-rich, more iron-stained and less thickly bedded than the quartz sandstones that dominate the talus or crop out along the canyon rim, suggesting that the materials in the cave are derived from lower in the Pocono stratigraphic interval. It is likely that the large volume and great depth of loose sandstone blocks and boulders above the ice mine provide the architectural framework for the cold air trap (Wilshusen, 1969).

The talus slope above the ice mine is *ca*. 37.5°, composed of angular to sub-angular, quartz-rich boulders and cobbles of Pocono sandstone and conglomerate and bounded by a large (200 m by 300 m) arcuate landslide that extends from

Figure 2 The Trough Creek ice mine. (A) Shelter covering the shaft opening and stairway to the talus cave entrance. (B) Stairway leading down to the talus cave entrance. (C) View looking into talus cave entrance, 16 March 2010, showing representative drip/flowstone and ponded congelation ice deposits. This figure is available in colour online at wileyonlinelibrary.com/journal/ppp

the valley floor to a resistant Pocono sandstone layer cropping out along the canyon rim. The hollow left by the landslide appears to be significantly larger than the volume of talus material, indicating that Great Trough Creek has transported most of the landslide material downstream from the site. Two thick conical portions of the lower talus may be derived from relatively recent slope failures, but the overall geomorphology suggests that most of the talus postdates the large landslide. Open boulder surfaces comprise up to 58 per cent of the talus slope above the ice mine; the rest of the talus is dominated by a mixed oak forest consisting of chestnut oak (*Quercus prinus*), red oak (*Q. rubra*), eastern hemlock (*Tsuga canadensis*), black birch (*Betula lenta*), sassafras (*Sassafras albidum*), basswood (*Tilia americana*), blackberry (*Rubus*) and grasses.

The internal composition of the landslide deposit is only exposed in the talus cave, where no datable materials have been obtained. An absolute age chronology for the slope can be inferred from research throughout the region (Mills, 1987; Ciolkosz *et al*., 1990; Clark *et al*., 1992; Braun, 1994; Sevon, 1999; Grote and Kite, 2010), which reveals that unconsolidated Appalachian slope deposits developed in response to a complex history of climate-related events. The most intensive colluvium deposition phases were associated with periglacial activity during extremely cold episodes. Although some sites record multiple colluvial episodes extending back more than 100 000 years (Hoover and Ciolkosz, 1988; Braun, 1994), most of the sandstone-dominated colluvium on the surface of extremely steep slopes like the west side of Terrace Mountain were produced by accelerated physical weathering under cold climates coeval with Late Wisconsin (MIS 2) glaciation, the terminus of which reached within 140 km of the Trough Creek ice mine (Sevon and Braun, 1997) *ca*. 20 000 years ago. However, talus in the central Appalachians remains active under modern conditions and significant portions of it may date to the Holocene (Hack, 1965; Hupp, 1983).

Debate exists over the origin of the term ice mine for this talus cave, but it has been proposed in popular literature to have been a prospect adit made in the search for ore to support the nearby (3 km) Paradise charcoal iron furnace, which operated between *ca*. 1827 and 1865 (Wilshusen, 1969; Patrick, 2004). Balch himself was apparently unaware of the site and did not mention it in his list of cold traps in Pennsylvania (Balch, 1900), nor in a follow-up publication about the similarly named Coudersport ice mine, located 150 km to the north in Potter County, Pennsylvania (Balch, 1921). The site was also unmentioned in *The Geology of Huntingdon County* (White, 1885), a publication unlikely to overlook such a regional geologic oddity at the time. It appears more likely that the talus cave was discovered during the construction of a logging railroad *ca*. 1910 (Rainey and Kyper, 1982). This railroad was abandoned in 1917, and the former right of way now serves as the paved park road that passes directly in front of the ice mine (Figure 2A). It is likely that the enlargement of the entry to the talus cave and the completion of its associated stonework shaft and stairway took place during the development of the state park in 1936.

MATERIALS AND METHODS

Ambient air temperature measurements in the talus cave and on the associated talus slope were collected using waterproof HOBO® temperature/light Pendant data loggers (UA-002-64; Onset Computer Corp., Bourne, Massachusetts) over a period of 36 months beginning in February 2007. These loggers have a stated accuracy of ± 0.54 °C between 0 °C and 50 °C, with a resolution of 0.10 °C at 25 °C. This accuracy rises to *ca*. ± 0.75 °C at −20 °C, the lower end of its operating range. The ice mine data logger was placed at the rear of the talus cave under rock cover to prevent discovery by animals or visitors to the site. The talus slope data logger was placed 1.5 m above ground level, *ca*. 35 m uphill from the ice mine, within a grove of eastern hemlock (*T. canadensis*) trees, which provided year-round partial shade (Lundquist and Huggett, 2008). Temperature measurements were initially collected every 15 min for 10 months; subsequently they were collected on an hourly basis. A light sensor on the talus slope data logger confirmed that it only received indirect exposure to sunlight during the study period (data not shown). For the final 26 months of the study, a HOBO® Pro v2 temperature/relative humidity data logger (U23-001; Onset Computer Corp.) was also placed in the talus cave within 1 m of the other temperature logger. The stated accuracy of the humidity sensor is given as ± 2.5 per cent between 10 per cent and 90 per cent relative humidity, to a maximum of ± 3.5 per cent, with a resolution of 0.03 per cent; temperature accuracy is given as *ca*. 0.2–0.3 °C, with a resolution of *ca*. 0.02–0.04 °C over the temperature range found in the ice mine. Dew point estimates were automatically calculated and recorded based on collected temperature and relative humidity measurements. The software program HOBOware® Pro (version 2.3.0; Onset Computer Corp.) was used to download and further process collected data logger information.

On each visit to the site, the surface temperatures of the rock walls near the rear of the ice mine were measured prior to entry using an infrared thermometer (model FI40L; FLW, Costa Mesa, California), with a stated accuracy at temperatures > 0 °C = ± 1 °C (resolution 0.1 °C) and at < 0 °C = ± 1 °C ± 1 °C per degree. Air flow velocity was measured at the ice mine entrance with an anemometer (Kestrel 2000 pocket weather meter; Nielsen-Kellerman, Boothwyn, Pennsylvania; minimum detectable velocity = 0.3 m/s). Congelation ice volume in the talus cave was estimated by measuring the depth and area of ponded ice.

RESULTS

Hourly ambient air temperatures collected for three years from the interior of the ice mine talus cave and from a constantly shaded location on the talus slope above it are shown in Figure 3. Monthly temperature averages, maxima, minima and ranges for both locations are listed in Supplementary Information Table S-1. Mean annual air temperatures (MAAT) for the talus cave and talus slope were 2.6 °C and 12.2 °C, respectively, during this study, compared to a longer-term MAAT (1975–2009) of *ca*. 10.2 °C for a weather station 14 km away (Raystown Lake 2; National Climatic Data Center, 2012). Talus surface air temperatures showed the extreme diurnal variation expected with such measurements. Sustained periods of time (> 24 h) when talus surface air temperatures remained below 0 °C at this site were infrequent and limited to the months of November through March. In contrast, the air temperature in the talus cave remained below 0 °C continuously from late November or early December through early to late April. The air temperature in the talus cave attained

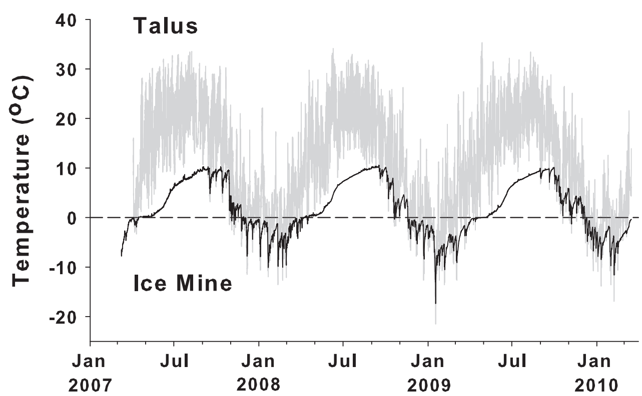

Figure 3 Ambient air temperatures recorded hourly in the ice mine talus cave and on the talus slope above it over a three-year period of time.

its maximum value just above 10 °C in mid-September to early October of each year (10.3 °C, 10.5 °C and 10.1 °C in 2007–09, respectively). The coldest temperatures measured in the talus cave and on the associated talus slope occurred in January and February of each year. The lowest temperatures (−17.4 °C and −21.5 °C in the mine and on the talus slope, respectively) were measured on 17 January 2009 and corresponded to a 78-year low temperature recorded for this date at a National Weather Service station in nearby Huntingdon, Pennsylvania (−27 °C). Estimates of maximum congelation ice volume on the floor of the talus cave and immediately outside its entrance ranged from 0.21 to 0.36 m^3, present from March until May. Hoar frost was observed on the walls of the talus cave in March but it did not accumulate. No ice was detected within the talus cave after the end of May during each year of the study period.

The annual repeating cycle of the air temperature profile for the ice mine talus cave over three years consisted of the following five distinct periods, which varied slightly from year to year, and are shown for one annual cycle (2007–08) in Figure 4:

1) From mid-April to mid-May, air temperatures were very stable near freezing, gradually rising from 0 °C to 1 °C. During this period of time, ice was generally present in the mine. The beginning of this period corresponded to the rise of ambient outside temperatures above freezing, the absence of sub-freezing temperatures in the talus cave and the beginning of thermal stratification of the air mass within the ice mine shaft (‘closed period’), when external temperatures were always higher than those in the ice mine.
2) Mid-May to late June marked a period of steady, but relatively rapid warming of cave air. The temperature rose *ca.* 1 °C per week, from 1 °C to 7 °C. This corresponded to the complete melting of congelation ice, the warming of any residual meltwater and the most rapid seasonal rise in the external air temperature. The external temperature rise corresponded to the increasing length of the solar day and the localised heating of air above the associated talus slope.
3) From late June until mid-September, the air temperature in the talus cave rose more slowly and thermal stratification was maintained. Throughout this period, air temperatures outside the ice mine remained higher than inside the talus cave, where the annual maximum (ca. 10 °C) was reached at the period’s end.
4) Mid- to late September marked the onset of the open period, when thermal stratification ceased and cooler external air began to exchange with that in the mine. Each cooling event was followed by a rapid warming of the talus cave air, as the warmer rock walls conducted heat to the cooler air mass.
5) Late November marked the establishment of average daily sub-freezing air temperatures within the mine. The cave remained at or below 0 °C from then until early to mid-April, when the outside air temperature minima once again rose above the freezing point and period 1 began again. During the latter portion of this time frame (ca. March; Figure 4), the greatest accumulation of ice inside the mine was observed, mainly from the infiltration of small volumes of water via snowmelt and early spring rains. Cooling events during this latter phase were episodic and limited to times when cold air drainage coming down the mountainside was colder than the cave air.

The measured relative humidity within the ice mine talus cave over a 26-month period is shown in Figure 5. Deep cooling events in the talus cave during winter were marked by the introduction of cold and dry air. Once the ambient air temperatures in the cave rose above 0 °C, relative humidity remained close to 100 per cent, reflecting the presence of

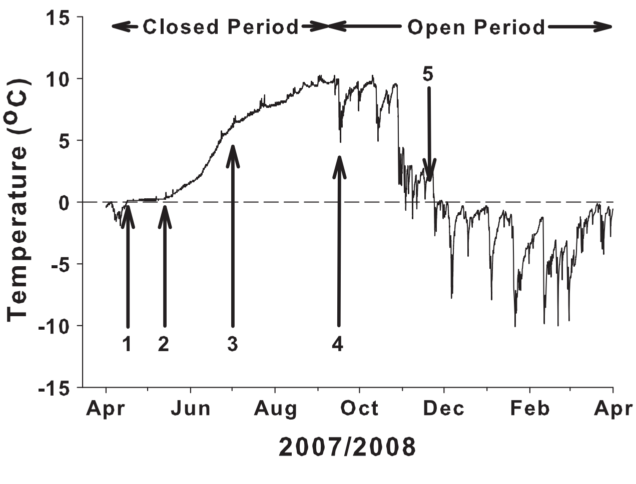

Figure 4 One annual thermal cycle within the ice mine talus cave showing open and closed periods, which are characterised by the exchange of outside air and thermal stratification, respectively. Numbers shown represent the onset of distinct periods in the thermal cycle, which are discussed in detail in the text.

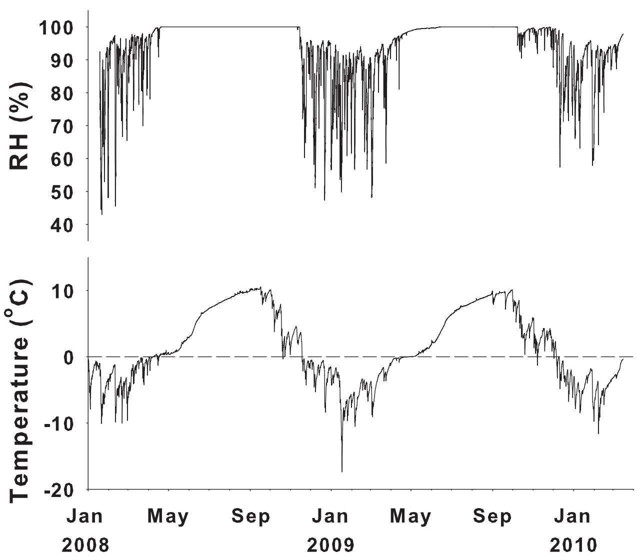

Figure 5 Per cent relative humidity (RH) and ambient air temperature measured hourly in the ice mine talus cave over a two-year period of time.

Table 1 Internal air temperature, dew point, relative humidity and rock wall surface temperature in the Trough Creek ice mine on selected dates between 2008 and 2010.

Date	Air temp, °C	Dew point, °C	Rel. humidity, %	Wall temp, °C
18 Jan 2008	−1.0	−2.6	89.0	−4.0
May 01, 2008	0.4	0.4	100.0	−4.0
May 21, 2008	2.1	2.1	100.0	1.0
Oct 31, 2008	0.7	0.7	100.0	−2.0
Nov 14, 2008	3.3	3.3	100.0	2.0
Mar 18, 2009	−2.0	−2.8	93.9	−9.1
Jul 21, 2009	7.7	7.7	100.0	2.5
Oct 08, 2009	7.6	7.6	100.0	7.0
Oct 29, 2009	5.0	4.9	99.5	3.0
Dec 16, 2009	−2.1	−6.5	71.2	−6.0
Mar 16, 2010	−0.4	−0.7	97.8	−5.3

moisture in the cave in the form of free water or ice and the general lack of air circulation. No air flow was ever detectable by anemometer (min. detection of 0.3 m/s) at the cave entrance during site visits.

Calculated dew and frost point temperatures were compared to temperature measurements made directly on rock wall surfaces in the talus cave. These data (Table 1) showed that surface temperatures were consistently at or below calculated dew/frost point temperatures for air in the cave. This is consistent with the frequent observation of moisture condensation or hoar frost crystallisation on the cave wall surfaces. The warmest cave wall surface temperature measured during this study was 7.8 °C in September 2007, when the corresponding ambient air temperature was 10.4 °C.

DISCUSSION

The Trough Creek ice mine talus cave can be considered a simple cold air trap, or more precisely, an apparently static cave in the terminology of Balch (1900). Luetscher and Jeannin (2004) and Luetscher (2005) distinguish between alpine ice caves that are static, statodynamic or dynamic, based on the degree of forced air convection within the cave, although this terminology is meant to pertain to caves that receive an annual input of snow and ice sufficient to maintain perennial ice deposits. Like most of the documented eastern North American cold traps (Balch, 1900), the Trough Creek ice mine contains a seasonal ice deposit that is formed in late winter/early spring and the persistence of which into late spring promotes thermal stratification and maintains a cooler temperature within the mine throughout the summer months. The term apparently static is justified in the case of the ice mine, for while air circulation measured at the cave mouth was negligible and suggested a lack of air circulation, the entry of water into the mine to form ice suggests that air flow may be periodic or was simply undetectable during site visits.

Air exchanges in the ice mine appear to be largely limited to a classic open period (Luetscher, 2005) in winter when dense cold air drainage sinks into the void space of the shaft and talus cave, further cooling the interior rock surfaces. This cooling hypothesis is contrary to the mechanism proposed by others for the Trough Creek ice mine (Wilshusen, 1969; Patrick, 2004), which presumed that cold air trapped within the associated talus slope above the mine exited the downslope cave during summer months, creating a cold air vent. Although cold air vents at the base of talus slopes are somewhat better known regionally (Hayden, 1843; Balch, 1900, 1921; Lendemer *et al.*, 2009), the lack of measureable air flow and the minimal introduction of water into the Trough Creek ice mine suggest that the talus cave remains largely segregated from air flow in the talus slope. Instead, air circulation is dominated by dense cold air drainage that moves downslope and enters the shaft and talus cave.

Ice accumulation in the Trough Creek ice mine consisted solely of endogenous congelation ice that formed as drip or flowstone ice and as ponded ice on the floor of the talus cave from the freezing of infiltration water (Figure 2C). In contrast, exogenous firn ice generated from snow diagenesis plays an important role in the maintenance of ice deposits in most ice caves containing perennial ice, and few are reported to be maintained by congelation ice alone (Luetscher, 2005). It seems likely that ice may have persisted longer and the talus cave may have remained colder for longer periods of time prior to structural modifications made to its entrance. The maintenance of a protective roof over the open shaft prevents the accumulation of snow and the formation of firn ice at the cave entrance. The average annual snowfall in the region varies widely from year to year and place to place. Annual snowfall recorded locally between 2001 and 2011 ranged from 25.4 cm in 2008–09 to 190.5 cm in 2002–03 (Raystown Lake 2; National Weather Service Forecast Office, 2012). Assuming an over-simplified maximum 10:1 conversion of snow volume to ice mass during snow diagenesis, this would equal the potential addition of 0.55 to 4.15 m^3 of ice to the ice mine complex, increasing the potential total volume of accumulated ice by two to 20 times. In the absence of an artificial cover over the shaft, period 1 of the annual cycle (Figure 4), incorporating the melting period of the existing ice mass, would vary in duration on an annual basis. Winters with exceptionally high annual snowfall might even generate enough firn and congelation ice to persist throughout the entire year. In contrast, the protection of the open shaft from direct solar radiation and rainfall prevents the additional input of heat that would accelerate ice melting in late spring and early summer in a similarly unknown way.

Other human-influenced effects may also modify the volume and behaviour of accumulated ice in the talus cave. Previous protective roofs over the ice mine only covered a portion of the upper shaft (Ostertag and Ostertag, 2002), allowing greater introduction of rain and snow precipitation. Visitors to the ice mine have observed that prior to *ca*. 1960 snow was ploughed directly from the park road into the open shaft to prolong the cold temperatures in the mine into the summer (H. M. Edenborn, personal communication, 2010). Additionally, it has been observed that the rock walls of the shaft prior to that time were not joined with mortar and had been covered with mosses and ferns. This sealing of open gaps in the rock walls may have eliminated additional sources of cooling air and water into the shaft and cave.

The remains of a metal hasp at the entrance to the Trough Creek talus cave indicate that a door was once used to further seal the cave portion of the ice mine. Although this may have been used to regulate visitor entry, such an approach has also been used to prolong the survival of ice formations in summer at other regional cold traps, such as Sam's Point ice caves in the Shawangunk Mountains, New York (Dirig, 1994) and the Coudersport ice mine in Sweden Valley, Pennsylvania (Balch, 1921; Patrick, 2004). The Coudersport ice mine is a vertical exploratory mine shaft located at the base of a talus slope comprising broken Devonian Lock Haven Formation shale (Patrick, 2004). Located approximately 150 km to the north of the Trough Creek ice mine, the Coudersport ice mine was a popular tourist attraction from *ca*. 1901 to 1990 due to the persistence of ice within a small (3 m x 3.7 m x 9.8 m) shaft from *ca*. April to October. At this site, the connectivity between the shaft and adjacent talus allows greater influx of percolating water and cold air (Balch, 1921), resulting in a much greater initial mass of ice relative to the volume of the shaft than is formed at the Trough Creek site. Continuous hourly temperature measurements made in 2009 and 2010 at the Coudersport ice mine showed a much longer persistence of cold air consistent with the presence of ice, remaining below 1 °C until mid-August and reaching an annual maximum of only 4.3 °C in October (data not shown). In contrast, the Trough Creek ice mine air temperature typically rose above 1 °C in mid- to late May and achieved an annual maximum temperature greater than 10 °C (Figure 3).

Cold air traps are often of particular ecological interest since they can provide climatically variant niches and act as local refugia or habitat islands for disjunct populations of plants and animals normally found in colder climates (e.g. Core, 1968; Whitehead, 1973; Dirig, 1994; Zacharda *et al*., 2005; Lendemer *et al*., 2009). Such sites are frequently characterised by cold air flow out of a cold trap that results in a significant suppression of the local mean annual air temperature. It appears likely that cold air stratification within the Trough Creek ice mine system effectively retains cold air during warm months and does not have a major influence on the surrounding ecosystem. The Trough Creek ice mine and its associated talus slope are recognised as preferred habitats of the Allegheny woodrat (*Neotoma magister*), an endangered mammal species in Pennsylvania that prefers rocky habitat and caves, but little is known about how temperature influences this preference. Other regional cold trap sites with cold air drainage harbour visible boreal lichens and plants indicative of the cold air flow (Lendemer *et al*., 2009). Less easily observed species, such as boreal mites, have been shown to be indicators of periglacial climates on cold European scree slopes (Zacharda *et al*., 2005). At the Trough Creek ice mine, cold-loving psychrophilic bacteria with an optimal growth temperature $< 10\,°C$ (Russell and Cowan, 2006) have been found to be relatively more abundant in the cave itself than in exterior soils (H. M. Edenborn and A. Hartsock, unpublished data), consistent with the relatively cool temperatures maintained within the cave year-round. The temperature ranges within such cold trap environments selectively limit the ability of various forms of life to live or thrive. Detailed knowledge of the influence of these limitations on regional biological distribution and diversity is essential to our comprehension of the potential impacts of future climate change.

CONCLUSIONS

This study represents the first long-term continuous monitoring of ambient temperature in an eastern North American cold trap environment, a talus cave in central Pennsylvania, USA. The Trough Creek ice mine talus cave can be considered an apparently static cave that behaves seasonally in a manner consistent with other simple cold air traps having open and closed periods of cave air circulation and stratification. The presence of a relatively impermeable vertical shaft and a protective roof at this site deflects snow and ice that might otherwise maintain colder annual average temperatures within the talus cave. The stratification of cold air in summer within the talus cave limits its influence on the surrounding ecosystem but creates habitat with an average annual temperature much colder than that of the surrounding landscape and more ordinary subterranean habitats at similar depth. This site provides a local refugium for organisms best adapted to survival in dark and colder environments, including psychrophilic bacteria and possibly fungi and other life forms. Better understanding of the thermal characteristics of these environments will allow a more realistic assessment of their role as habitats and the potential impacts of future climate change on biological diversity and distribution.

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Supporting Information

Supplementary Information Table S-1. Monthly average, maximum, minimum, and range for air temperature data collected: A) in the Trough Creek ice mine talus cave; and B) at the talus slope location between April 2007 and February 2010.

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