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Rapid changes of the ice mass configuration in the dynamic Diablotins ice cave – Fribourg Prealps, Switzerland

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Abstract

The Gouffre des Diablotins is a deep cave system located in the Swiss Prealps. In 1991, the entrance zone of the cave was almost free of ice. Nevertheless ice volume sharply increased in 1994, plugging almost totally the gallery from the lower entrance. The ice cave have also experience flooded period between 1996 and 2007, and very heterogeneous ice surface morphology and textures have formed. Continuous cave climate measurements initiated in 2009 showed the predominant role of winter atmospheric air conditions to drive both the efficiency of chimney-effect circulation and seasonal modifications of the ice mass. Main part of the ice loss is currently due to sublimation in wintertime.

1 Introduction

Several recent studies have been oriented in the processes involved in the ice cave climate and mass balance (e.g. Luetscher et al., 2003; Luetscher 2005), showing that fluctuations of ice mass depend directly on the hydrological and thermal regimes experienced by the cave during wintertime. Moreover, processes involved in ice cave can be very complex, causing in certain cases a very heterogeneous distribution of ice and topoclimatic zones over short distances (Lauriol et al., 1988). Both in static and dynamic ice caves, ice mass is subject to strong seasonal modifications (Ohata et al., 1994a,b; Luetscher, 2004). Numerous recent studies showed that the ice volume has more or less continuously decreased during the last decades (Rachlewick and Szczucinski, 2004; Luetscher and al., 2005).

Several authors (Atkinson et al., 1983; Lauriol and Clark, 1993; Lismonde, 1993; Ohata et al., 1994a; Luetscher, 2005; Lauriol et al., 2006) pointed out the major role played by air circulation in the ice cave climate and ice mass modifications. In mountainous areas, Lismonde (2002a) and Luetscher and Jeannin (2004a) assumed that “chimney-effect” driven by the thermal gradient between the inside and outside air temperature is at the origin of most air circulation observed in alpine karst systems, due to the occurrence of several entrances located at different elevations. This ventilation system produces a negative thermal anomaly compared to the mean annual air temperature (MAAT) in the lower part of the system where cold air is aspirated in winter, and a positive thermal anomaly in the upper part of the system. The cooling effect of such a seasonal reversible air circulation is also reported from porous debris accumulation like talus slopes at low elevation where the MAAT is largely positive (Delaloye et al., 2003; Morard et al., 2008). This process is also currently used in embankments to preserve permafrost conditions under transportation infrastructures at high latitude or high altitude (e.g. Arenson and Sego, 2006).

This paper will present the particular case of a dynamic ice cave located in the Fribourg Prealps (Switzerland), in which the volume of ice has sharply increased in the middle of the 1990's. The goal of this paper is to determine which processes are currently involved in the ice cave climate and seasonal modifications of the ice mass, in order to explain this apparently surprising behavior.

2 Site description

The Gouffre des Diablotins is located in the Morteys Valley extending northeast of the highest summit of the Fribourg Prealps (Switzerland), the Vanil Noir (2389m) (46°32′09″ N, 07°09′43″ E) (Fig. 1a). Geologically, the valley corresponds to a synclinal valley formed in massive limestones from the Préalpes Médianes. The area is also an old glacial valley with high cliffs on both southeastern and northwestern slopes. More than 50 caves entrances are inventoried in the valley and the longest cave is the Réseau des Morteys with its 8900 m long and 550 m deep (SCPF, 2010). The MAAT recorded at the close meteorological station in Moléson summit (1974 m a.s.l.) is about +2.8 °C, and winters are characterized by cold (–2.2 °C±1.1 °C in average between 1983 and 2009) and snowy conditions.

The Gouffre des Diablotins is the deepest cave of the area with 652 m deep, and it is developed in the vertical massive limestones of the southeastern slope of the Vanil-Noir syncline (Fig. 1b). The cave has two entrances, the lower one at 2007 m a.s.l., 30 m high in a north oriented rockwall, and the upper one at 2092 m a.s.l., on the top of the Rochers des Tours (Fig. 1c). Both entrances are linked together by a 105 m vertical pit and a 50 m descending gallery. The deepest part of the cave can be reach from a gallery starting at the intersection between both entrances (“gallery junction” on Fig. 1c). The Diablotins ice cave is also the most important ice volume known in the Fribourg Prealps (estimated to about 100 m^3). Today, the ice extends discontinuously along the lower entrance gallery. The two lower thirds of the 105 m vertical pit are also permanently covered by ice (Fig. 1c) (Bovey, 1995). Due to its L-shaped configuration with two entrances located at different elevations, the cave could be attached to the dynamic type, with the occurrence of a ventilation system by “chimney effect”. Moreover, the importance of deep air circulation process is also pointed out by the name “Diablotins” (“little evil creatures”) which refers to the presence of permanent strange murmurs inside the cave system (Bovey, 1995).

2.1 Archives of speleological investigations

The particularity of this ice cave is founded in the rapid changes of the ice mass configuration observed during the last two decades and related in the archives of the Spéléo-Club des Préalpes fribourgeoises (SCPF) (Jutzet 1991, Bovey 1995). Main components of the Diablotins ice cave are presented in detail in Fig. 1c–e.

In August 1983, the lower gallery was completely plugged by ice. However in summers 1991 and 1992, the ice disappeared almost completely from the lower entrance gallery, allowing intense explorations of the karstic network during these years. In August 1992, the speleologists reached −652 m in the Gouffre des Diablotins (Fig. 1b). In July 1993, ice plugged the bottom of the “ice slide” and a fixed rope was installed in the “chimney-room” to access the “gallery junction” trough the top of the room. Since 1994, the ice mass has sharply increased to finally plug completely the lower gallery in

1995 near the "gallery junction". Since them it has been impossible to reach the intersection with the vertical pit again from the lower entrance. In 1996, ice was founded in the "chimney-room". Between 1997 and 2001, important quantity of water mixed with ice was observed in the lower gallery at the current "ice plug" location and impeded the access to the "chimney-room". A pipe was installed in order to evacuate this unfrozen water, but the lower gallery was still flooded in 2005. Since 2007 cold airflow was again perceptible along the ice mass.

2.2 The Diablotins ice cave in 2009–2010

In order to better understand the processes occurring in the Diablotins ice cave, the lower gallery was visited more frequently in June, October, November 2009, March and May 2010 to observe the current state of the ice cave (cave climate, configuration of the ice mass, types of ice) and its evolution at a seasonal time scale. A fixed string was installed above the "ice plug" to measure the changes of the elevation of its surface. Some measurements were also taken with high precision portable weather station (Skywatch GEOS 11, JDC Electronics).

The spatial distribution of ice along the lower gallery is very heterogeneous, but the ice content is generally more important on the south-west side of the gallery than on the north-east side. Moreover, the ice mass configuration in the Diablotins ice cave, as the morphology of ice surface, has known important seasonal modifications in 2009–2010. The state of the ice cave in 2009 is presented in Figs. 1c, 2 and 3.

2.2.1 Seasonal modifications of the ice mass

14 June 2009: A snowfirn partially occupied the room at the lower entrance (Fig. 1c). Ice plugged the lower gallery at the "ice plug" location, but a strong outflow of cold air (–0.3 °C, 2.5–3 m/s) was blowing out of the cave from a small opening on the top of the ice mass. The walls were also covered by hoarfrost (Fig. 3e).

31 October 2009: An ice stalactite has also formed before the ice plug, illustrating exit

of percolating unfrozen water. At the ice plug location, airflow was always blowing out of the cave, but the gallery walls were at that time only covered by few hoarfrost crystals. The surface of the ice mass has diminished of about 4 cm where the fixed string was installed, and more at its extremity (Table 1). Thus it was possible to penetrate again the ice cave beyond about 20 m to the "chimney-room", where a particular flat ice ceiling – not observed in 1996 – has been formed. The rope installed in 1993 cross the ice ceiling and its extremity is caught in the ice (Fig. 2c). Walls at the end of the "chimney-room" were also covered by a thin layer of ice.

21 November 2009: Air was always blowing out of the lower gallery and the surface of the ice plug has again diminished of about 2 cm since 31 October. In the back of the "chimney-room", water was seeping along the ice stalactites and the walls, and airflow was blowing out from the ice ceiling. The gallery was plugged by ice in the "ice well" and the "gallery junction" was not reached (Fig. 2d). Nevertheless, the bottom of ice mass was pierced by a decimeter conducts where airflow was blowing out (Fig. 3o), maybe connected farther to the vertical pit.

9 March 2010: The lower entrance was partially blocked by snow. Weak inflow of air was perceptible and the surface of the ice plug was 10 cm lower than in June (Table 1). In many places along the gallery section, the ice volume has obviously diminished since November 2009. The ice surface was dirty and covered by a thin layer of dust, originating from the rock ceiling of the gallery. In the "chimney-room", the walls were dryer than in November and no percolating water was perceptible. The airflow rushed in the ice slide trough small holes newly formed in the ice (Table 1).

22 May 2010: New clear transparent ice has formed in the floor of the ice cave from the ice plug (6 cm higher than in March) until the "chimney-room" (Table 1 and Fig. 3h). The walls of the lower gallery were covered by hoarfrost, but no strong airflow was perceptible at the ice plug. In contrast in the "chimney-room", air flow was blowing out from holes in the bottom of the ice slide. Thus, a sharp ice mass increase is recorded during the snowmelt period as normally reported for ice cave (Rachlewicz and Szczucinski, 2004; Luetscher, 2005).

2.2.2 Types of ice and morphology of ice surface

Observations of ice type as well as the morphology of ice surface could be used to assess both the origin of ice (Ford and Williams, 1989; Luetscher and Jeannin, 2004b) and the processes involved in its accumulation and ablation (Bella, 2006).

Ice observed in the Diablotins ice cave is mainly opaque to clear, sometimes with rock debris incorporated in the ice mass (Figs. 2a and 3f). Under the ice plug, coarse polycrystalline ice surface structures were observed in early winter (Fig. 3k), but have disappeared in March (Fig. 3i). At some places, ice is extremely transparent and smooth, and contains sometimes some bubbles (under the ice plug and in intermediate corridor) or undefined internal structures (ice ceiling) (Fig. 3i–j–n). Floor ice carpets the intermediate corridor (Fig. 3l). Finally, seasonal forms of ice accumulation develop as ice stalactites, fine layers of ice in the cave walls, ice flowstone (Fig. 3f–h) and hoarfrost (Fig. 3e). Hoarfrost is preferentially found in the largest sections of the lower gallery, where a decompression of the air flow occurred. According to the classification of Ford and Williams (1989), the origin of ice mass observed in the Diablotins ice cave can be attributed to congelation process, mainly to freezing of infiltrating water and also partially to freezing of ponded, static water.

According to Bella (2006), several ice ablation forms observed in the ice cave are attributed to air circulation, such mound-shape depressions sculpted in the ice plug on the leeward side of a stone caught in the ice mass (Fig. 2a), huge U-shape hollow (Fig. 2b), scallops and oval mound-shaped elevations (Fig. 3g), and quasi-spherical depressions in the flat ice ceiling (Fig. 3m). Ablation channel build in the ice mass at the bottom of the “ice well” can originated from runoff of unfrozen water (Fig. 3o).

3 Continuous measurements of the Diablotins ice cave climate

3.1 Devices

An autonomous temperature data logger (UTL-1, Geotest AG, accuracy: ±0.25 °C) recorded the air temperature at the iceplug since 16 June 2009. Moreover, the lower entrance was equipped on 31 October 2009 with several devices connected to a meteorological station (MADD Technologies) to measure the airflow characteristics (temperature, humidity, velocity and direction), the rock temperature at 5cm depth and external air temperature. Accuracy is ±0.1 °C for the temperature sensors and ±1% for the relative humidity. The windmill anemometer had an accuracy of ±0.1 m/s and a sensitivity of about ±0.2 m/s. A measure was programmed every hour. Unfortunately, between 21 November 2009 and 22 May 2010, the station recorded only every 10 h due to a calendar problem. Two others autonomous temperature and relative humidity loggers (i-button, resolution: 0.5 °C and 1%, time interval: 3 h) were placed in the intermediate corridor and at the end of the chimney-room in 21 November 2009. Devices locations are shown in Fig. 1c–d.

In addition to these direct observations and measurements, data from two close meteorological stations of the Meteoswiss network are used to determine the external atmospheric conditions (Fig. 1a). Air temperature and relative humidity provide from the Moléson summit (1974 m a.s.l.). As snow records were not available from Moléson summit, data from Château d'Oex (985 m a.s.l) were used to estimate the inter-annual variability of snowfall.

3.2 Cave climate seasonal evolution

3.2.1 Stable and continuous blowing regime during summer

During summertime, the cave air temperatures are stable at −0.3 to 0 °C (Fig. 4) and run most of time independently from the external air temperatures, except during short periods of colder weather (external air temperature between 0 °C and +2 °C) when warmest cave air temperatures are recorded (arrows "a" on Fig. 4). During this constant period of blowing airflow, the air is also saturated (rH=100%) at the ice plug (Fig. 5b). Rachlewick and Szczucinski (2004) attributed this stable thermal state to the latent heat consumption for melting.

3.2.2 Reversibility periods of the airflow direction

In autumn, airflow direction reverses in the lower entrance when the external air temperature crosses a threshold of about +2 °C (Fig. 4). When the external air temperature becomes smaller than +2 °C, the external air temperature is thus sucked inside the cave, as shown by the synchronous behavior between the cave air temperature and the atmospheric conditions (Lismonde, 2001; Luetscher, 2005) (Figs. 4 and 5). The crossing of this thermal threshold is also well expressed by the changes in relative humidity from saturated (outflow) to unsaturated state (aspiration), and by the rapid reverse of the airflow direction, agreeing well with theory (Lismonde, 1993). Moreover, the airflow velocity increases when the temperature gradient increases on both sides of the inversion threshold. Velocities of about 1 m/s are recorded in autumn but remained zero in most part of winter. These values were lower than those recorded with handy anemometer (Fig. 1c and Table 1). As the fluctuations of the cave air temperature indicated air circulation effect, the anemometer has probably not worked properly during winter or the airflow velocity was under its level of sensitivity.

An interesting behavior can be notice for the cave air temperature. At the beginning of an aspiration phase, cave air temperature follows immediately the external air temperature variations. In the other hand, at the end of an aspiration phase – like in autumn and at the end of winter – air temperature inside the cave reacts more slowly and need a few days to reach again 0 °C (arrows "b" in Fig. 4). Rock temperatures also experienced such varying behavior (Fig. 5d).

3.2.3 Cooling and drying of the ice cave in wintertime

During the winter aspiration phases, cave air temperature warms from the lower entrance to the end of the "chimney-room", with increasing differences during strong atmospheric cold waves ("c" on Fig. 4). Nevertheless, even if an attenuation of air temperature fluctuations is observed (Table 2), all parts of the lower gallery are affected by the winter cooling.

A significant part of the cold aspirated inside the ice cave is transmitted and stored by thermal conduction in the rockwall of the cave. The cooling of the rock during winter is also more important close to the lower entrance, where the air temperature is the coldest, than at the ice plug location (Fig. 4d).

While warming an air mass should theoretically cause a reduction in its relative humidity (Forbes, 1998), the reverse phenomenon is registered in the Diablotins ice cave during aspiration phases (Fig. 5b and Table 2). In general, air temperature and relative humidity curves at the ice plug also track each other. Thus, the aspirated air humidifies itself when it penetrates deeper inside the ice cave, but shows a similar relative behavior between the outside and the inside of the cave. It means that variations of relative humidity inside the lower gallery are mainly driven by the evolution of relative humidity of the atmospheric air mass as those measured at Moléson summit, when the ventilation system is in aspiration mode ("double-arrows" in Fig. 5a–b). In contrast, when the external air temperature reached again the airflow inversion threshold in winter, the relative humidity of the ice cave increased rapidly to 100% and does not follow the relative humidity evolution of the atmospheric air ("x" events on Fig. 5b).

4 Discussion

4.1 Heat exchange between cave air, rock and ice

The cooling of rock temperature in winter as the thermal gradient of the cave air measured between the lower entrance and the “chimney-room” can be attributed to the heat exchange between the cave air with the rockwall and the ice mass (Lismonde, 2002b). After Luetscher (2005), much more energy is stored in the form of ice (latent heat) than in the rock (sensible heat). These heat fluxes could also explain the thermal damping of the fluctuations of cave air temperatures at the end of an aspiration phase and the inertia of the system due to thermal state of rock and ice (Lismonde, 2002b).

In consequence an important cold reservoir can form during winter in the lower gallery of the Diablotins ice cave. After Saar (1955), winters with long low temperatures weather are more favorable situations for the presence of dynamic ice cave with chimney-effect ventilation system. In addition to this exogenic factor, the cooling effect could also be increased by endogenic factors (Luetscher, 2005) particularly by absorption of latent heat due to evaporation/sublimation process. On the other hand, the condensation warming effect from ice formation during snowmelt period or from hoarfrost during blowing phase of saturated air seems to be weak, as showed by the gradual and slow warming of the cave in April–May.

4.2 Part of sublimation and melting in the ice mass loss

A significant loose of ice mass has been observed in wintertime, despite the air temperature keeps always under the freezing point. The entire lower gallery is thus subject to sublimation process, as evidenced in March by the disappearance of ice layers on the walls in the “chimney-room”, the “polishing” of the ice stalactites and ice walls in the intermediate corridor (Fig. 3h), or by the presence of fine dust on the floor. Law and vanDijk (1994) attributed the existence of this thin layer of sediments as a result of the sublimation of the frozen surface of the cave walls. The apparently counterintuitive relationship between cave air temperature and relative humidity in the different parts of the ice cave could also be interpreted as an evidence of very efficient sublimation phases in winter. By warming, air becomes dryer and increases the rate of sublimation. But simultaneously, the rock and ice will transfer their moisture to the cave air (Lauriol et al., 1988; Lismonde, 2002b), explaining the increase of relative humidity between the "ice plug" and the "intermediate corridor". The drying of cave consecutive to the aspiration of external air in winter is more intense near the entrance (Forbes, 1998), but its effect can exceed a kilometer, as reported by Lismonde (2002a) for the Trou qui Souffle (Isère, France). Ohata et al. (1994) considered the aspiration of dry and cold air as the main element of heat balance in ice cave. By seasonal measurements of the ice mass balance, Rachlewicz and Szczucinski (2004) also considered that sublimation process causes the most intensive rate of ice mass loss, even if in their case the ice is primarily lost by melting.

The ice mass will also decreased in summer due to melting by warm percolating water (consecutive to thunderstorms for instance) (Luetscher, 2005) and by the penetration of warmer air from the upper entrance. A part of the ice melting could also be caused by heat supply from the walls, the north-east side of the ice plug being indeed distant of about 10 cm from the lateral wall. In the Diablotins ice cave, only a loss of 4 cm was measured between June and October 2009 on the elevation of the ice plug. Moreover, the measurements were made after a 10 days period of aspiration in mid-October, when sublimation probably occurred. Thus, summer melting seems to be a process of less importance in regard to winter sublimation in the Diablotins ice cave.

4.3 Relative importance of variables controlling the sublimation rate

In the Diablotins ice cave, sublimation could thus be considered as the main process controlling the rate of ice loss. But which variables could best explain this process observed in winter in the Diablotins ice cave? Law and Dijk (1994) made a review of sublimation as a geomorphic process on frozen sediments, ice and snow, and discussed the relative importance of changes in relative humidity, air temperature and wind velocity.

Some experiments showed that a decrease in relative humidity from 90% to 80% had double the rate of sublimation (Law and Dijk, 1994). Moreover, sublimation seems to be more efficient between −1 and −4 °C. Under −4° C, the rate will decrease to become very low at −12 °C. A more intense airflow velocity (depending on the thermal gradient between the external air and cave air temperatures) will also increased the rate of sublimation, by increasing the rate of heat exchange of water molecules between the rock and ice surface, and the air. Nevertheless, the magnitude of these effects is widely discussed (Law and Dijk, 1994). Anyway, all experiments showed that the rate of sublimation increase by (1) decreasing relative humidity of air, (2) rising in air temperature until the freezing point and (3) increasing wind velocity.

Thus, dry air conditions in winter and important temperature contrast (by increasing the airflow velocity) could favour the sublimation rate and could be seen as unfavourable conditions for the ice mass balance. Nevertheless, in the current state of knowledge, it is not possible to determine more precisely the relative importance of these three factors in the sublimation rate observed in the Diablotins ice cave during the winter.

4.4 Possible causes of decadal evolution of the Diablotins ice mass

Based on the analysis of one year of measurements in the Diablotins ice cave – which showed that the climate of the ice cave is mainly influenced by winter conditions and that air circulation plays a major role in its behavior – we try to determine which meteorological parameters have changed for the last 20 years. A reconstruction of the atmospheric winter conditions (relative humidity of air, daily sum of negative air temperature (air freezing Index) and quantity of snow) was carried out since 1983 (Fig. 6). Daily meteorological data were taken from the two closest stations of the Meteoswiss network (Fig. 1a).

This analysis has to be considered as a rough "qualitative" approach to understand the potential main causes of the modifications observed in the Diablotins ice cave since 1983. It is based on three main hypothesis: (1) the level of relative humidity of air would play an important role on the rate of ice sublimation when external air is aspirated in the lower entrance, (2) colder winters would favor the recharging of the cave in coldness and the freezing of percolation water, (3) snowy winters would provide more percolation water for the formation of congelation ice during the period of snowmelt. The results of the reconstruction showed that winters 1989, 1990, 1992 and 1993 were mild, less snow-covered and with dry air conditions (Fig. 6). These years correspond with the low ice content period of the ice cave. In contrast opposite meteorological conditions were encountered during winters 1994 and 1995, when the strong increase of the ice mass was observed.

Jutzet (1991) and Bovey (1995) also proposed the hypothesis of compression/decompression of the airflow as an explanation for facilitating the freezing of percolation water in some part of the lower gallery. Indeed airflow velocity will depend both on the thermal gradient between the inside and the outside of the cave, but also on the diameter of the gallery. The airflow will accelerate in the narrow sections of the gallery, and will thus be compressed. At the exit of narrow sections, the pressure of the airflow will theoretically decrease and favor the freezing of percolating water and/or the vapor of the air (hoarfrost). Such process, in addition with the changes in meteorological variables, could thus explain the rapidity of ice mass changes observed in the Diablotins ice cave.

It is more difficult to explain the evolution of the ice mass between 1997 and 2005, when the lower gallery was almost entirely flooded and no strong airflow was perceptible by the speleologists. It is possible to that consecutive of the cold, wet and snowy winter 1994 and 1995, ice almost totally filled cracks and the narrow sections at the "gallery junction" and at the "ice slide", preventing water from draining and creating a "water-pocket" at least during a certain time in summer during the following years. Air circulation could have been stopped or seriously reduced during such event.

Nevertheless, observations of airflow in 2009–2010 have illustrated the complex pattern in its direction and origin in the "chimney-room" (Fig. 1c). Since 2007, the water pocket totally disappeared and the return of a strong airflow explains the current morphology of ice surface (Figs. 2 and 3), originated by air circulation and ice sublimation (Bella, 2006).

4.5 Origin of the flat ice ceiling in the chimney-room

One of the most spectacular parts of the Diablotins ice cave is found in the "chimney-room", where an important ice mass and a particular flat ice ceiling have formed between 1997 and today. Several hypotheses could be advanced to explain its formation.

Firstly, the origin of ice could be attached to freezing of stagnant water. A cycle of water filling – formation of "lake-ice" – draining when an opening is drilled in the ice mass has been reported by Turri et al. (2003) in the Moncodena ice cave (Lombardy). In their case, the congelation starts at the air – water interface and spreads down until the exhaustion of the unfrozen water. Such similar event could have occurred in the Diablotins ice cave, when a part of the stagnant water found in the lower gallery between 1996 and 2005 had frozen in contact with the overcooled rockwall. This could explain the flat morphology of the ice-ceiling in the chimney-room and the occurrence of very transparent ice with some bubbles in the lateral ice on the intermediate corridor (Ford and Williams, 1989).

The second hypothesis is link to the freezing of humidity from the airflow. Lauriol and Clark (1993) reported the occurrence of ice ceiling in the subhorizontal gallery of Grande Caverne Glacée (northern Yukon) and attributed their origin as an accumulation of hexagonal ice (hoarfrost) growing down from the roof of the cave. Lauriol and Clark (1993) also explained that the initial hoarfrost accumulation could have evolved by cycles of sublimation and regelation of ice, changing their initial crystallographic structures. Thus the ice ceiling encountered in Grande Caverne Glacée presented an irregular crystal growth arrangement and a high porosity formed by both occluded and interconnected bubbles. Such crystals structure seems to be very similar to those observed in the ice ceiling of the Diablotins ice cave. This process could be also relatively rapid, since the ceiling ice accumulation in the Grand Caverne Glacée is about 1.5 m thick and age of this structure is quite young (50–70 years). In the Diablotins ice cave, the rate of ice formation by freezing of air humidity from the airflow could also have been accelerated by the supply of humidity from the unfrozen water pocket.

Both theories could also be mixed to explain the rapid ice mass increase and the type of ice founded today in the Diablotins ice cave, which could have a mixed origin of freezing of infiltrating water and also probably of more static water, and from freezing of condensation of saturated air inside the cave when the ventilation system is in blowing phase. After the whole draining of the water pocket in the lower gallery (since 2006–2007), the return of a strong airflow has then carved the current morphologies of ice surface. Nevertheless ice drilling and more detailed ice analysis will be necessary in the future to validate or disprove these hypotheses.

5 Conclusions

The main conclusion of our study is that an efficient air circulation process by chimney-effect currently determined both the cave climate and the seasonal ice mass evolution. Airflow seasonally reverses when a thermal threshold of +2 °C is crossed. During winter, drying and strong cooling occurred in the ice cave, directly link with the evolution of atmospheric air temperature and relative humidity. The main loss of ice is recorded during winter by sublimation. Melting in summertime is of secondary effect. During snowmelt period, congelation ice formed in the ice cave.

The a priori surprising increase of the ice mass since 1994, which plugged almost entirely the lower gallery in 1995 seems to be link to a transition from dryer, warmer and less snow covered winters between 1989 and 1993, to wetter, colder and snowy winters in 1994 and 1995. Due to the plugging of the narrow sections of the gallery by ice, a temporary water pocket have then occurred until 2005, explaining partially the origin and morphology of ice encountered in the Diablotins ice cave.

Finally, the current re-opening of the lower gallery will enjoy the speleologists of the SCPF, who waited for 20 years to reach again the deepest parts of the Gouffre des Diablotins.

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Table 1. Changes of elevation of the ice surface at the ice plug, and airflow direction and velocity measured with portable anemometer (GEOS 11).

	Changes of elevation (cm) of the ice surface at the ice plug			Airflow		
Date	Rock ceiling – ice surface distance (cm)	from 14 Jun 2009	from previous date	Location	Direction	Velocity (m/s)
14 Jun 2009	114	–	–	Ice plug	Outflow	2.5–3.0
31 Oct 2009	118	−4	−4	Ice plug	Outflow	1.5
21 Nov 2009	120	−6	−2	Top of the chimney-room	Outflow	not measured
9 Mar 2010	124	−10	−4	Ice slide (chimney-room)	Inflow	0.8–1.9
22 May 2010	118	−4	+6	Ice slide chimney-(chimney-room)	Outflow	not measured

Table 2. Average and standard deviations of air temperature and relative humidity in the Diablotins ice cave, when the external air temperature is lower than +2 °C (aspiration phases).

		External air	Lower entrance	Ice plug	Intermediate corridor	Chimney-room
Air temperature (°C)	Mean	−4.7	−3.3	−2.7	−2.5	−1.3
	Stdev	4.4	2.1	1.5	1.2	0.6
Air relative humidity (%)	Mean	79.3	–	84.9	91.0	–
	Stdev	22.6	–	12.4	9.5	–

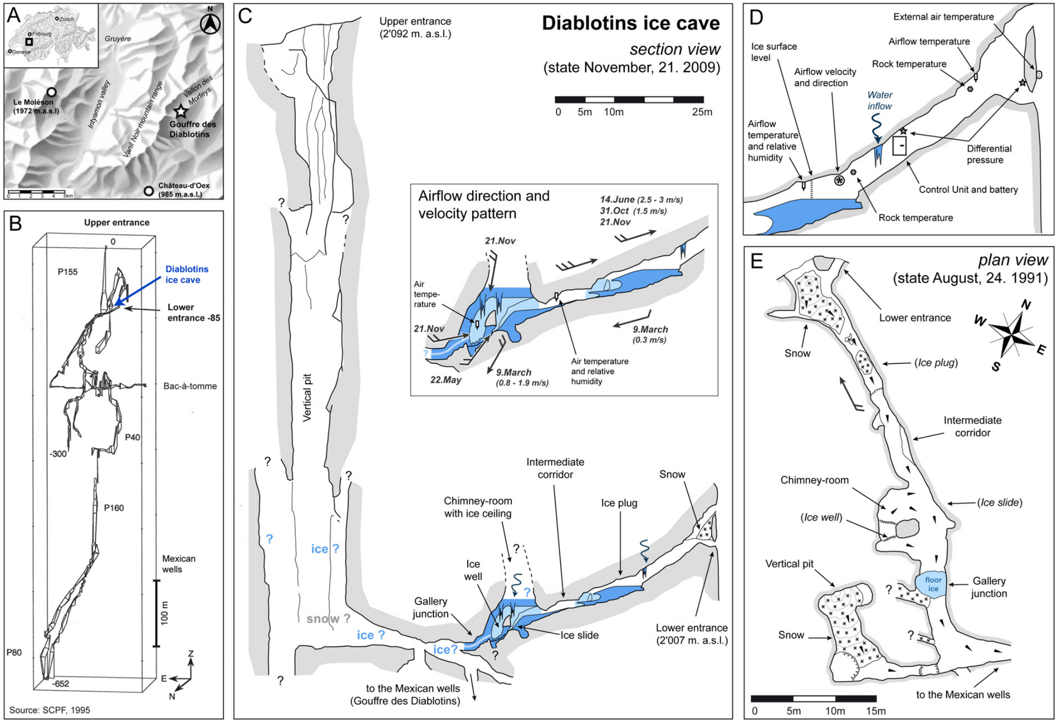

Fig. 1. **(A)**: Location of the Gouffre des Diablotins; **(B)**: Map of the Gouffre des Diablotins karstic system; **(C)**: Section view of the entrances zone of the Gouffre des Diablotins with ice mass configuration encountered in 21 November 2009 and the pattern of airflow direction observed in 2009–2010; **(D)**: Location of the devices; **(E)**: Plan view of the entrances zone of the Gouffre des Diablotins, the gallery was almost free of ice on 24 August 1991 (cave mapping by Laurent Dechanez and Pascal Schenker, SCPF).

Fig. 2. Pictures of the main parts of the ice cave. **(A)**: the ice plug (31 October 2009); **(B)**: U-shaped hollow under the ice plug (31 Ocotober 2009); **(C)**: the chimney-room with the flat ice ceiling (9 March 2010); **(D)**: Ice well at the end of the chimney-room (9 March 2010).

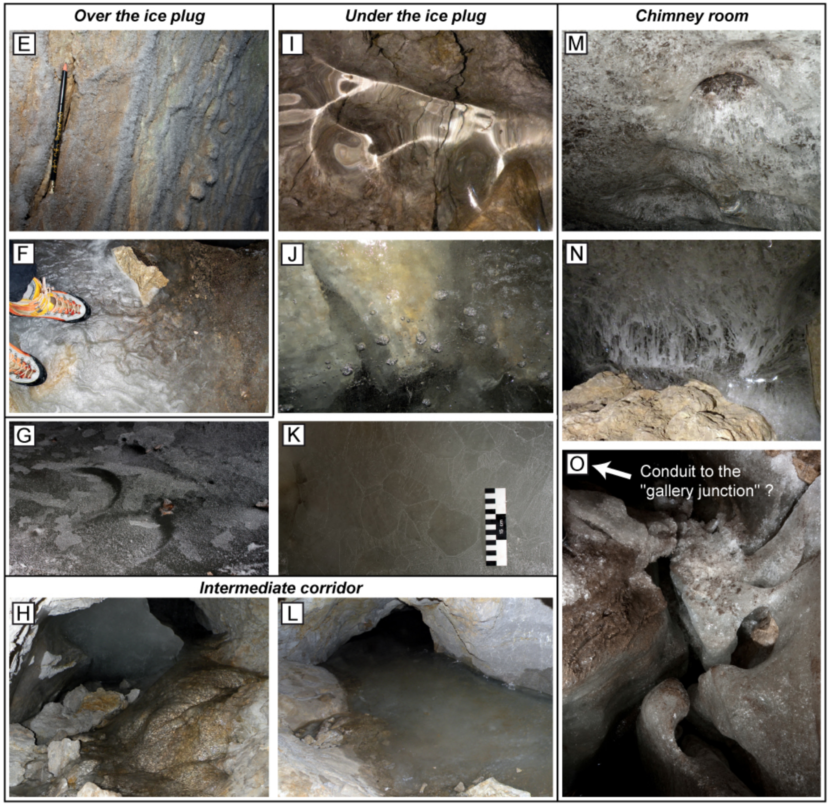

Fig. 3. Different types of ice morphology. **(E)**: Hoarfrost on the wall at the iceplug (16 June 2009); **(F)**: Ice flowstone over the iceplug (31 October 2009); **(G)**: Oval mound-shaped elevations in the intermediate corridor (21 November 2009); **(H)**: Ice flowstone before the intermediate corridor (22 May 2010); **(I):** Transparent ice under the ice plug (9 March 2010); **(J)**: Bubbles in clear ice (31 October 2009); **(K)**: Large polycrystalline structures at the ice surface under the ice plug (21 November 2009); **(L)**: Floor ice in the intermediate corridor (22 May 2010); **(M)**: Quasi-spherical depressions in the flat ice ceiling (22 May 2010); **(N)**: Transparent ice with internal structure inside the flat ice-ceiling (9 March 2010); **(O)**: Ablation channel and conduct build by waterflow in the ice mass at the end of the "ice well" (21 November 2009).

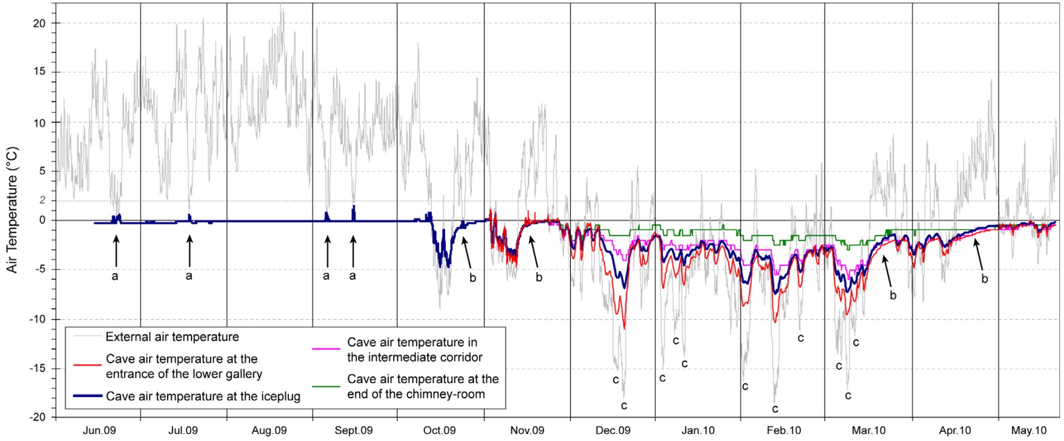

Fig. 4. Evolution from June 2009 to May 2010 of external air temperature, cave air at the entrance of the lower gallery, at the ice plug, in the intermediate corridor and at the end of the chimney-room. **(a)**: inversion of airflow direction in summertime; **(b)**: thermal rebalancing of the cave air temperature after strong aspiration phase in early and late winter. **(c)**: cold atmospheric waves in wintertime.

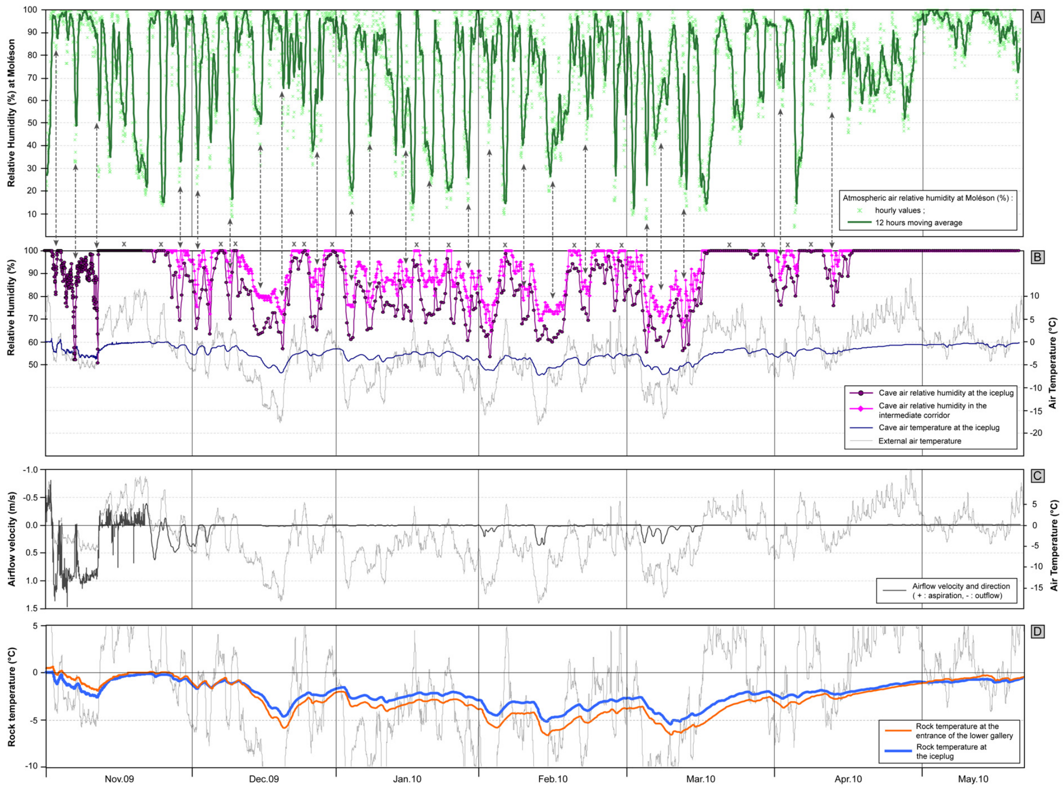

Fig. 5. Climate of the lower gallery from November 2009 to May 2010. **(A)**: Atmospheric air relative humidity measured at Moléson station; **(B)**: Air temperature and relative humidity at the iceplug (x: period of mild weather in wintertime, causing a weakening or an inversion of the air circulation in the lower gallery); **(C)**: Airflow velocity and direction at the iceplug; **(D)**: Rock temperature at the entrance of the lower gallery and at the ice plug. The gray curve corresponds to the external air temperature.

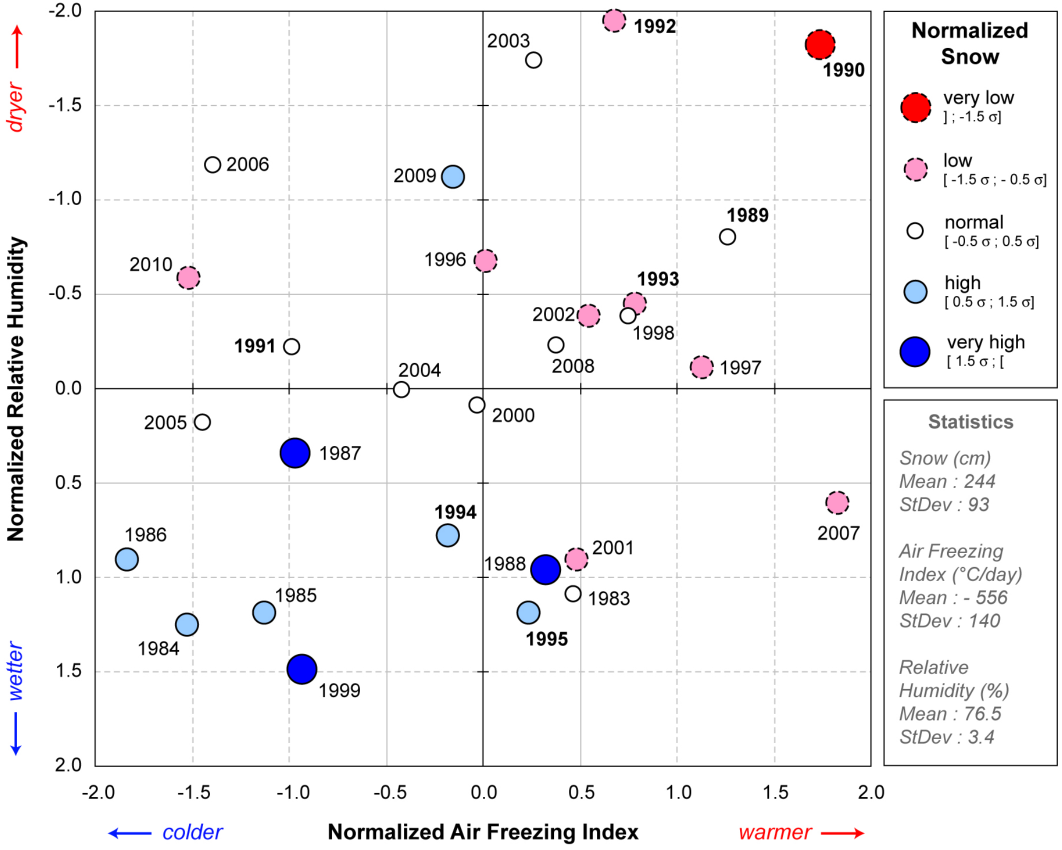

Fig. 6. Reconstruction of winter meteorological conditions (air temperature and relative humidity, snow) from 1983 (October 1982–April 1983) to 2010. Normalized values are based on the average and standard deviation from the period 1983–2009.