THE INFLUENCE OF PRECIPITATION AND AIR TEMPERATURE ON PERENNIAL ICE ACCUMULATIONS IN SCĂRIŞOARA ICE CAVE

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ABSTRACT. - The influence of precipitation and air temperature on perennial ice accumulations in Scărişoara Ice cave. Recent increase of global air temperature has played an important role in the retreat of both mountain and polar glaciers and ice sheets. Perennial ice accumulations in caves also respond in a sensitive manner to changes in climatic parameters, especially air temperature and rainfall amount, but the role and importance of these two factors is still in debate. In this paper, we asses the dynamics of ice in Scărişoara Ice Cave (Romania) in relation to external climatic forcing. We show that there is an important difference between surface and cave glaciers in terms of response to the recent climate changes, *i.e.* (opposite to surface ice bodies), mild winters and rainy autumns are favorable for ice formation, while warm and dry summers determine the preservation of accumulated ice.

1. Introduction

Perennial ice accumulations, in forms of ice sheets, ice caps, ice shelves and mountain glaciers are a very sensitive recorders of climate change (Oerlemans, 1992, 2005, Lemke et al., 2007). Recent retreat of glaciers and melting of large ice sheets has been generally correlated with rising air temperatures (Lemke et al, 2007). However, there are also reports of present day glacier growth and advances, correlated with increased precipitation, *e.g.,* in Norway (Nesje et al., 2000), New Zeeland (Chinn et al., 2005) and Karakoram (Hewitt, 2005).

A peculiar case is that of subterranean glaciers, *i.e.*, perennial ice accumulations in caves, a typical feature for many low-altitude, low-latitude East-European caves (Racoviță & Onac, 2002, Holmlund et al, 2005, Luetscher, 2005, Kern et al., 2007, Tulis & Novotny, 2007). Cave ice responds in a sensitive manner to external climate changes (Ohata et al., 1994, Rachlewicz & Szczucinski, 2004, Luetscher et al., 2005, Trofimova, 2007, Kern et al, in press), although the main factor responsible for ice dynamics is still in debate. Most of the studies have emphasized the role of winter cooling (Racoviță et al, 1987, Racoviță, 1994, Luetscher et al., 2005) for ice accumulation, while other studies proposed the rate and timing of precipitation (Perşoiu, 2004) as the main factor in this process. Regarding the melting of ice, increase in summer air temperature (Racoviţă et al, 1987, Racoviţă, 1994), warming of rainwater (Holmlund et al., 2005) and increased summer precipitation (Perşoiu, 2004) have been proposed as the main triggers of the process.

In this paper, we reanalyze previously published (Racoviţă, 1994) and new data on ice dynamics, in correlation with external climatic factors - air temperature and rainfall amount, in order to asses the role played by each of them in the accumulation and ablation of ice, as well as the way in which cave ice responds to recent climatic changes.

2. Site description

Scărişoara Ice Cave (700 m long, 105 m deep) is located in the Apuseni Mountains, NW Romania, on the edge of the Scărişoara Plateau, at 1165 m asl (Fig. 1).

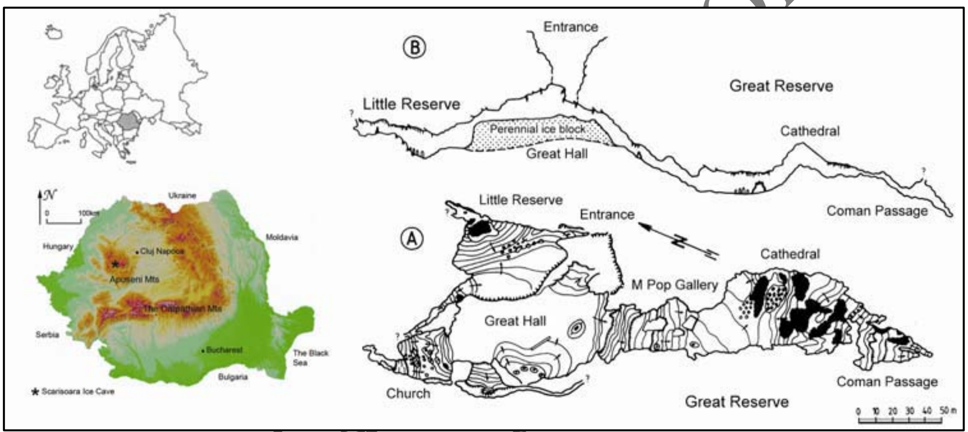

Fig. 1. Location, map and cross-section of Scărişoara Ice Cave

The cave is carved in thickly bedded Upper-Jurassic limestones (Bucur & Onac, 2000), its entrance being located on the western wall of a circular shaft 60 m in diameter and 47 m deep, the bottom of which is covered by a perennial layer of snow. A conical shaped ice block, with a volume of ~ 100.000 m^3 lies in the first chamber of the cave (Great Hall), forming its floor. This block delimitates three distinct sectors of the cave: The Church, Little Reservation and Great Reservation (Fig. 1); in all these rooms surrounding the ice block, fields with ice stalagmites being developed. The cave also contains a variety of calcite speleothemes, which mostly decorate the inner, non-glaciated parts of the cave.

The climate of the area surrounding Scărişoara Ice Cave is continental temperate, showing a strong influence of the westerlies. The mean annual temperature near the cave is ~6.5°C, with the temperature of the coldest month (January), and warmest (July) being around -9ºC, and 17ºC, respectively (Perşoiu et al., 2007). The prevailingly western circulation of the air in the Apuseni Mountains causes very large precipitation amounts (over 1600 mm per year at Stâna de Vale, some 30 km to the NW) to fall on their western slopes, whereas on the eastern slopes the annual amounts are reduced by half (below 850 mm at Băişoara, ca. 35 km to the NE). In the area surrounding the cave, the mean annual precipitation varies around 1200 mm, with the highest values in spring and early summer months and the lowest values in October. The mean duration of the interval with snow cover is estimated to 150-180 days per year, with mean values ranging between 1 cm and 1 m. Maximum values can exceed 1 m at the bottom of dolines, and 3-4 m at the bottom of the Scărişora Ice Cave's entrance shaft.

The climate of Scărişoara Ice Cave is the direct consequence of the external climatic variations and underground ventilation caused by the presence of a single entrance and mainly descendent passages (Racoviță, 1927, Şerban et al., 1948, Viehmann et al., 1965, Racoviță, 1994). This peculiar morphology leads to cold air inflow inside the cave during winter months, triggered by the higher density of the cold external air masses compared to the warmer ones inside; while in summer, the same density difference prevents the exchange of air masses between the two environments.

Within the cave, Racoviță (1984) distinguished four climatic zones: a transitional zone in the entrance shaft, a glacial zone comprising the area occupied by the ice block (Great Hall, The Church), a periglacial zone (Little and Great Reservation), and a warm climate zone in the non-glaciated parts of the cave (Coman Passage and Sânziana's Palace). The spatial repartition of these climatic zones is reflected by the thermal pattern of the cave: while in Great Hall the mean annual temperature is around –0.9ºC, it increases to –0.2ºC in the Great Reservation and 4.4ºC in the Coman Passage.

The air temperature has the greatest variations in the glacial meroclimate. During the periods with cold air inflow in winter (extending from late October to early April), the temperature follows closely the external climate evolution and may decrease below -15°C. During summer, when aerodynamic exchanges with the surface cease, the underground temperature is independent from external variations, being influenced only by the thermal inertia of the ice block and the overcooled walls of the cave, rarely increasing above +0.5°C (Racoviță, 1994; Onac et al., 2007).

3. Methods

Ice dynamics was recorded since 1947, by measuring the distance between the ice surface and the rock wall above it. The monitoring was being performed monthly during three distinct periods: September 1964 - June 1968, April 1982 - December 1992 and since October 2004 onwards. Between these intervals, sporadic measurements were performed, so that, especially for the period after 1963, a good record of ice dynamics exists.

Air temperature and rainfall amount data for two meteorological stations (Vlădeasa (1836 m asl) and Băişoara (1400 m asl)) were provided by the National Meteorological Administration. Hourly values were converted in monthly and seasonal (winter: D-J-F; spring: M-A-M; summer: J-J-A; autumn: S-O-N) averages for both stations, and simple linear trends were calculated. The data used in this study spans the interval January 1961- December 2003, so that meteorological data for the last 3 years when ice dynamics data exists is not available.

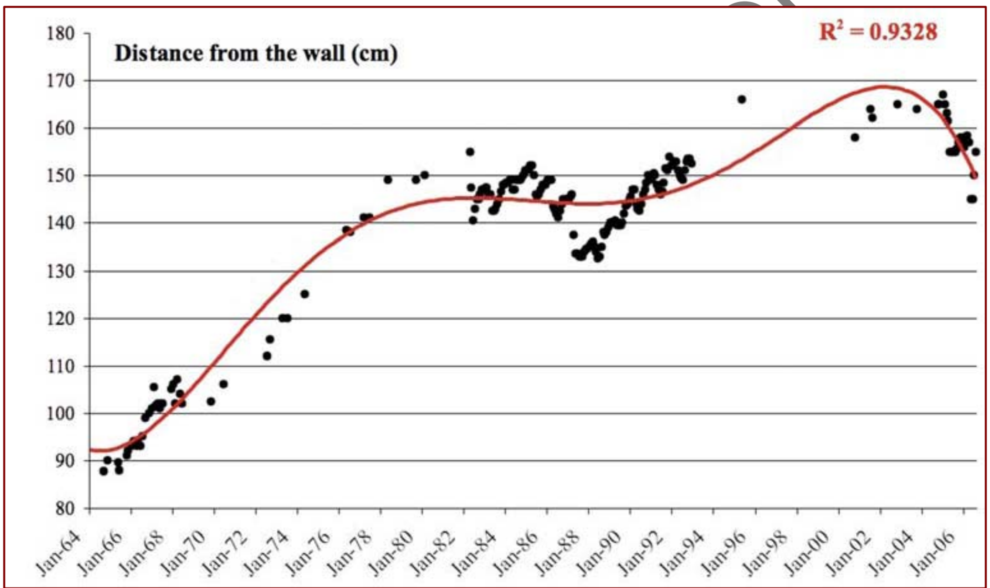

Fig. 2. Long-term dynamics of the ice block

4. Results

Measurements of ice level dynamics spanning the last 40 years show alternation of melting intervals with intervals of ice accumulation (Fig. 2). A period of intense melting extended from 1947 until the late '70s, followed by two decades of fluctuating ice level (1980-2000). Starting with 2000, the ice volume steadily increased, net annual accumulation exceeding ablation.

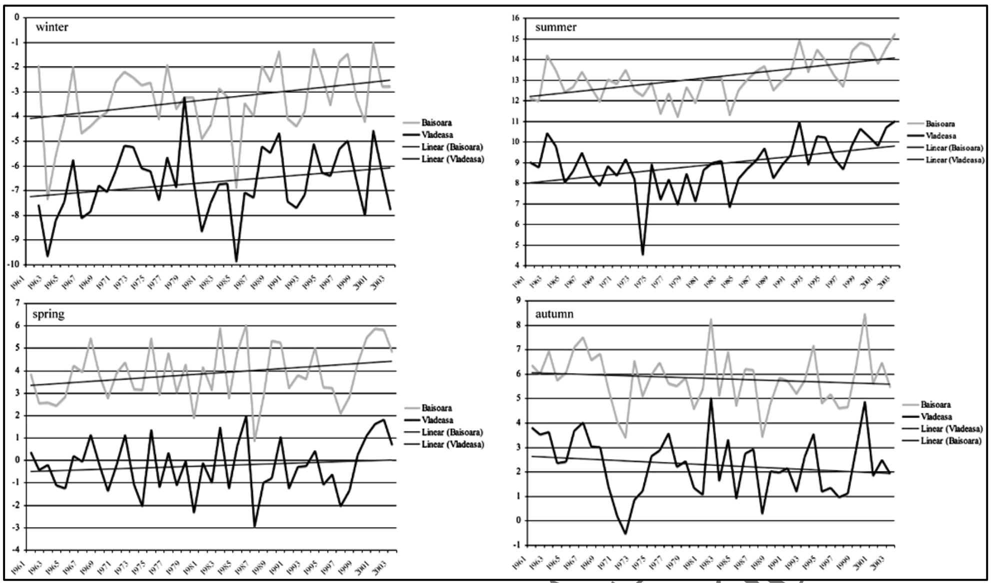

Fig. 3. Seasonal changes of air temperature at Vlădeasa (dark blue) and Băişoara (light blue) meteo stations. Linear trend is indicated by the red lines (upper – Băişoara, lower – Vlădeasa)

Over the past ~40 years (between 1961 and 2003), the mean annual air temperature has increased by more than 0.6°C at Vlădeasa station and 1°C at Băişoara; whereas annual rainfall amount has strongly (>150 mm) decreased at Vlădeasa, and only moderately (~50 mm) at Băişoara. Spring, winter and summer air temperature (Fig. 3) has increased by more than 1°C, whereas autumn values have slightly decreased (~0.5°C). This discrepancy between seasons is valid in case of rainfall amount too, all seasons except the autumn, which experienced a moderate increase, recording a decreasing trend of precipitation, the strongest being over the winter and the less pronounced in summer (Fig. 4).

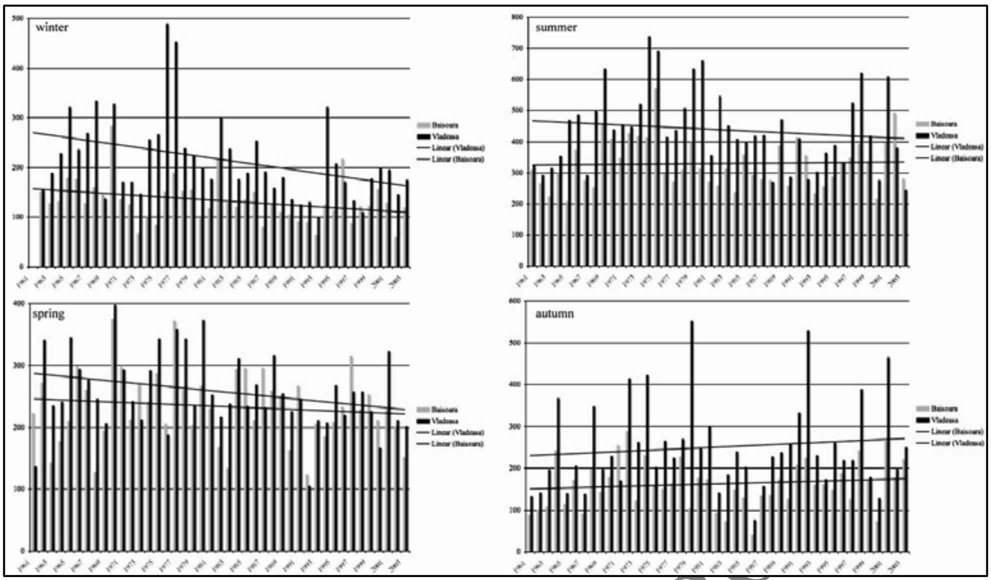

Fig. 4. Seasonal changes of rainfall amount at Vlădeasa (dark blue) and Băişoara (light blue) meteo stations. Linear trend is indicated by the red lines (upper – Vlădeasa, lower – Băişoara)

5. Discussions and conclusions

Previous studies (Racoviță, 1927; Racoviță, 1994; Rachlewicz & Szczucinski, 2004; Luetscher, 2005) have emphasized the role played by the strength of cooling during winters in the dynamics of ice, suggesting that the volume of ice that accumulates in a cave is directly influenced by winter air temperature. However, recent studies (Perşoiu, 2004; Perşoiu, 2006, Kern et al., in press) have shown that the availability of water inside iced caves and the timing of this availability are the main factors that control the rate of ice accumulation. Due to the peculiar morphology of most of the caves that host ice (single entrance, descendent shafts), air circulation is restricted to those periods when the external air temperature is bellow the internal one (between mid-autumn and late spring), when cold air sinks and accumulates inside the caves, whereas during periods with (generally) positive outside air temperatures, no dynamic exchanges occur between the two environments. There is, however, an extremely limited input of energy from the exterior to the cave, by conductive heat transfer through the air column inside the entrance shaft (Fig. 1).

As cold air exists inside the cave between mid-autumn and late spring, ice can form in this interval only when there is available water to be frozen. As shown by Perşoiu (2004) and Kern et al. (in press), the largest amounts of such water exist inside the cave at the end of the melting period in autumn, when a shallow (~15 cm deep) lake stands on top of the ice. As a consequence of cold air inflow inside the cave, the water of this lake freezes downward from the top, to form a layer of stratified ice up to 15 cm thick ("lake ice"). This period extends approximately from late September until mid-November, the onset of the freezing process and its duration being influenced by the peculiarities of the external air temperature variations.

A second period of rapid and consistent ice formation occurs in spring, when negative temperatures are still preserved in the cave, while outside, rising air temperatures and increased precipitation cause the melting of snow and the infiltration of larger amounts of water into the cave. The dripping water arrives in a cool cave environment, and rapidly freezes in thin ice layers ("floor ice"), superimposed on the autumn ice. In periods of mild winter, melted snow can reach the cave, where it freezes rapidly, adding a thin layer of ice to the existing one.

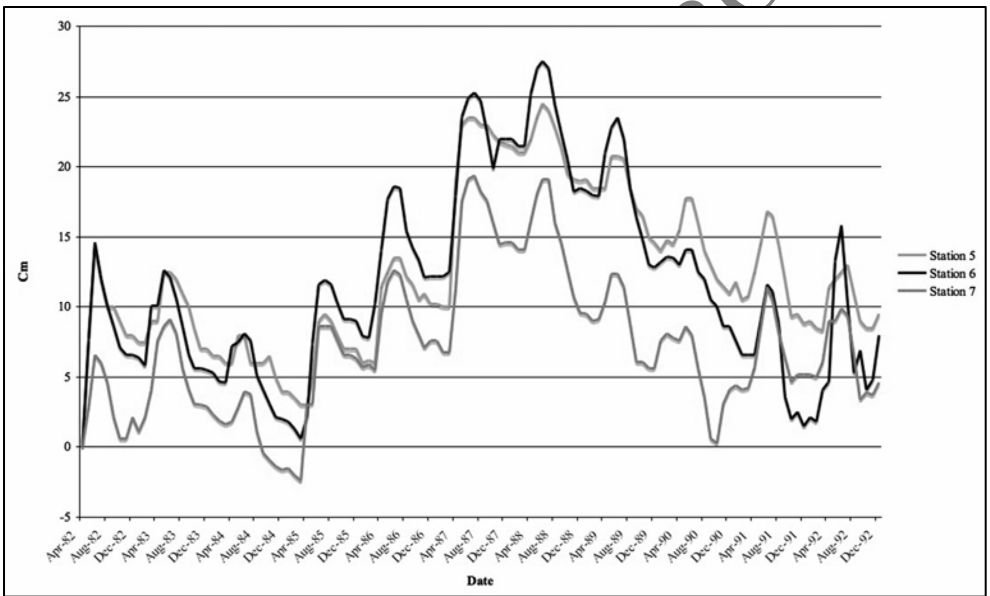

Fig. 5. Annual cycles of ice dynamics. The ice level is measured with reference to the 1982 ice level (0) in three different points in the Great Hall, Scărişoara Ice Cave

Melting of ice could occur when 1) the temperature inside the cave is above 0°C, and 2) the temperature inside the cave is bellow 0°C, but there is a large amount of dripping water, the energy brought inside the cave in this way offsetting the influence of cold air. In the absence of warm dripping water, the inertia of the ice block is sufficient to preserve negative air temperatures inside the cave during summer months and thus the ice that formed during the previous autumn through spring interval is being preserved. Heavy or long lasting summer rains transport large amounts of warm waters inside the cave and melting of ice begins. A shallow lake develops on top of the ice block, its warm waters contributing to the melting of ice. Thus, the level of ice in the cave reaches a maximum in late spring and a minimum in late summer/autumn (Fig. 5).

In order to establish a link between external climatic control and ice dynamics, we must thus consider both air temperature and precipitation amount and timing. The most favorable conditions for ice accumulations are being met during 1) cold and wet autumns; 2) mild winters; 3) moderately spring (with low temperatures and weak precipitations); and 4) dry summers. Wet summers and spring are periods of intense ice ablation, whereas warm and dry autumns are leading to reduced ice formation.

Racoviță et al. (1987) have shown that there is a good correlation between the air temperature inside the cave and the dynamics of ice, with rapid accumulation of ice during periods with low air temperatures and melting during periods with positive temperatures. However, they did not take into consideration the combined role played by external air temperature and precipitation. Figures 3 and 4 show how these two parameters had varied between January 1961 and December 2003, whereas in Figure 2 the dynamics of ice in Scărişoara Ice Cave is shown. It is evident that neither air temperature, nor rainfall amount can explain the changes in ice volume (represented as the distance between the rock wall and the surface of ice, *i.e.*, high values – increased distance between the rock and the ice - indicate melting of ice, whereas low values indicate accumulation of ice). The period prior to the 9th decade of the last century is being characterized by increased precipitations, especially in summer and winter, and low winter air temperatures, while autumns were generally drier and warmer than in present. Thus, conditions were met for ice to melt at a high rate, whereas accumulation was reduced.

The two decades following this interval were characterized by variable climatic conditions, that have led to rapid shifts between intervals (2-3 years) of higher than normal accumulation of ice (and reduced ablation), alternating with intervals of increased melting and reduced accumulation. The 1998/1999 and 1999/2000 winters were milder than usual and the preceding autumns were colder and wetter, and thus the accumulation of ice was greatly enhanced. Following these two years, a combination of cold and wet autumns, dry summers and mild winter occurred that have led to a steady increase of the ice volume inside the cave, a process that continues in present.

As a general observation for the 1961-2003 period, the area around the cave has experienced an increase in winter through summer air temperature and decrease in autumn air temperature, whereas rainfall amount decreased for winter, spring and summer seasons and increased for the autumn. The general trend towards colder and wetter autumns was favorable for ice accumulation, whereas drying and warming of the other seasons have led to reduced ablation during drier summers months and increased accumulation during the mild winters. Thus, our observations are contrasting those of Holmlund et al. (2005), who were expecting a fast melting of ice as a response to recent increase in air temperature.

Our results suggest that ice in caves responds in a sensitive manner to external climate changes, although in a different way than surface glaciers, *i.e.*, mild winters and rainy autumns are favorable for ice formation, while warm and dry summers determine the preservation of accumulated ice.

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