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Seasonal, annual and decadal ice mass balance changes in the ice cave Jaskinia Lodowa w Ciemniaku, the Tatra Mountains, Poland

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Abstract

Jaskinia Lodowa w Ciemniaku (Ice Cave in Ciemniak) is located in the Western Tatra Mountains (Tatry Zachodnie) and it hosts the largest known subterranean block of perennial ice in Poland. Its entrance is situated at 1715 m a.s.l. and the cave climate is classified as dynamic type with seasonal and diurnal variations of air temperature. The mass balance of ice body was investigated on monthly, annual and decadal scale through a set of detailed measurements of ice geometry performed during 2000–2004 years and in comparison with existing older data. The nature of recent perennial ice changes was determined through temperature measurements and seasonal ice surface observations. In general the ice mass reveals negative mass balance, however melting is not continuous throughout the year. The largest lowering of ice surface was observed in summer, due to melting, and in winter (when temperatures were well below zero) on account of sublimation. The increase in ice volume was observed in springtime when percolating water was available and the temperature was slightly below zero. In the balance year 2000–2001, 37.8 m^3 of ice was lost and in 2001–2002 as much as 53.2 m^3. During the subsequent period, 2002–2004, the average negative mass balance was even of about 66.8 m^3. Comparison between the detail geodetic survey in 2002 and published data from 1986 reveals that the averaged annual ice volume lost was 36.6 $m^3 y^{-1}$, slightly less than recently. The confrontation of reported ice mass geometries in 1922, 1950 and 1986 allows to estimate averaged annual ice mass loss in the period 1922–1950 as 23.0 $m^3 y^{-1}$ and, during the time-period 1950–1986 as 24.8 $m^3 y^{-1}$. It clearly shows that ice mass losses were significantly higher in the last decade.

Keywords: perennial ice in caves; ice mass balance; sublimation; the Tatra Mountains; Poland.

Bilan saisonnier, annuel et décadaire des changements dans la grotte à glace Jaskinia Lodowa w Ciemniaku, Montagnes de Tatra, Pologne

Résumé

Jaskinia Lodowa w Ciemniaku (La Grotte à Glace de Ciemniak) est située dans les Montagnes du Tatra Occidental (Tatry Zachodnie) et abrite le plus grand bloc souterrain de glace pérenne de Pologne. Son entrée est située a 1715 m altitude et le climat de la grotte est considéré de type dynamique, avec des variations saisonnières et journalières de la température de l'air. Le bilan de la masse du corps de glace a été étudié aux échelles des mois, annuelles et décadaires parmi un set de mensurations de détail de la géométrie de la glace faites entre 2000 et 2004 et par des comparaisons avec les données les plus anciennes existantes. La nature des changements récents de la glace pérenne a été déterminé par des mensurations de température et par des observations saisonnières de la surface de la glace. En général, la masse de glace a révélé un bilan de masse négatif, même si la fonte n'est pas continuelle durant l'année. Le plus grand abaissement de la surface de la glace a été observé en été, dû à la fonte et en hiver (quand les températures baissent au-dessous de zéro) due à la sublimation. Une augmentation du volume de glace a été observé au printemps, en présence de l'eau de percolation et aux températures légèrement au-dessous de zéro. Durant l'an de bilan 2000–2001, on a perdu 37,8 m^3 *de glace, tandis que entre 2001–2002 la perte a été de 53,2* m^3*. Dans la période suivante, 2002–2004, le bilan de masse moyen négatif atteint même 66,8* m^3*. Une comparaison entre le lévé géodésique de détail de 2002 et les données publiées en 1986 a relevé que le volume de glace perdu annuellement a été de 36,6* $m^3 y^{-1}$*, un peu moins que récemment. Une comparaison entre les géométries des masses de glace de 1922, 1950 et 1986 permet une estimation de la perte annuelle moyenne de glace entre 1922 et 1950 de 23* $m^3 y^{-1}$ *et de 24,8* $m^3 y^{-1}$ *entre 1950 et 1986 démontrant que la perte de la masse de glace a été d'une manière significative plus grande dans la dernière décade.*

***Mots-clés**: glace pérenne dans le grottes, bilan de la masse de glace, sublimation, Montagnes de Tatra, Pologne.*

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Introduction

Ice caves (rock-hosted caves containing perennial ice) arouse an exceptional attention among caves of the temperate climate zone (RACOVIȚĂ, 2000). One of the fundamental questions concerns the genesis of perennial ice masses in caves and their stability under modern climatic conditions. Partly the answer can be given by mass balance studies. Net mass balance is a sum of gains and losses of mass over an entire ice mass during a given year. So it can show us if modern conditions are favorable for ice mass build up or degradation. Because recent global climate change has impacted almost all environments it is expected that also ice in caves has responded to it. However mass balance is a sum of several processes like: freezing, melting, sublimation, resublimation and their significance must be known before any further conclusions could be drawn. Consequently, the aims of this study are twofold:

- to estimate mass balance of perennial ice mass in Jaskinia Lodowa w Ciemniaku at seasonal, annual and decadal time scales, and
- to identify and quantify the processes, which dominate ice mass balance and their relation to external factors.

Study site

In the Polish part of the Tatra Mountains (Tatry, Fig. 1) which constitute a part of the Western Carpathians, 26 ice caves are reported (SIARZEWSKI, 1994). The largest perennial ice body is in Jaskinia Lodowa w Ciemniaku (Ice Cave in Ciemniak, Fig. 2). The entrance in the cave is located at 1715 m a.s.l., about 600 m above the floor of Kościeliska Valley (one of main valleys on the northern slopes of the Tatra Mountains), in the western slope of the Ciemniak Mountain.

The cave was described for the first time in the 19th century by OSSOWSKI (1883) and PAWLIKOWSKI (1887). Detailed measurements and research started when the cave was rediscovered by T. and S. Zwoliński, in 1922 (ZWOLIŃSKI, 1923). First notes on the ice mass extent are from ZWOLIŃSKI (1961). More systematic studies were conducted in 1960s and particularly in the 1980s by numerous researchers (GRADZIŃSKI & WÓJCIK, 1961; RYGIELSKI & WIELICZKO, 1988; RYGIELSKI *et al.*, 1988; RYGIELSKI *et al.*, 1995; and various unpublished materials in archives of the Tatra National Park in Zakopane and in Institute of Quaternary Research in Poznań). The published studies were concentrated mostly on the cave description, climate, the ice-body genesis, morphology and some aspects of ice surface dynamics.

The cave has one entrance exposed to the west. The total length of its passages is about 390 m, and *c.* 100 m of the main passage developed in W–E direction is covered by perennial ice (Fig. 2). The elevation range between utmost parts of the cave is 42 m (with reference to the entrance: –11 m and +31 m). The ice-covered part is composed of two segments. The first one consists of a corridor, which goes up from the entrance through two steps and connects their flatter parts to the *Upper Platform*. From the latter, ice surface descends to the second segment, which is separated from it by a narrow vertical passage which is temporary blocked by ice. It continues with a steep *Icefall*, which goes down to the flat *End Chamber* (this part is not accessible since the end of the 1990s). The present study is concentrated on the first, upper segment. The chimneys located above the *Upper Platform* and the *End*

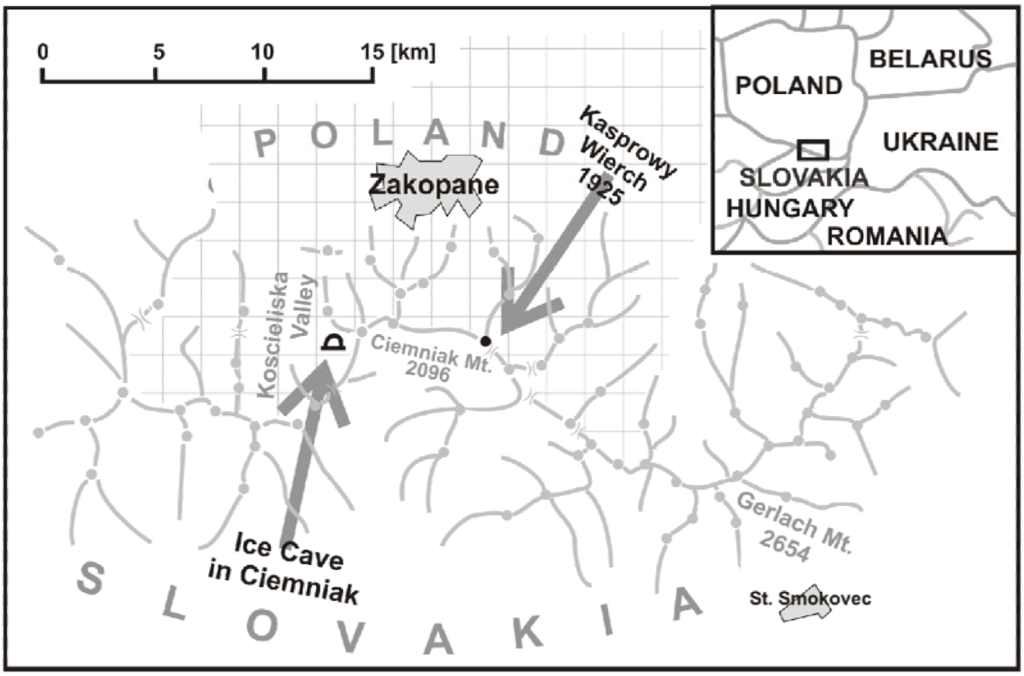

Fig. 1. Location of Tatra Mountains and location of Ice Cave in Ciemniak and the meteorological observatory on the top of Kasprowy Wierch (1925 m a.s.l.) on a simplified map of mountain ridges in the study area.

Situation des Montagnes de Tatra, de la Grotte à Glace de Ciemniak et de la station météorologique du sommet Kasprowy Wierch (1925 m altitude) sur la carte simplifiée des crêtes montagneuses de la région étudiée.

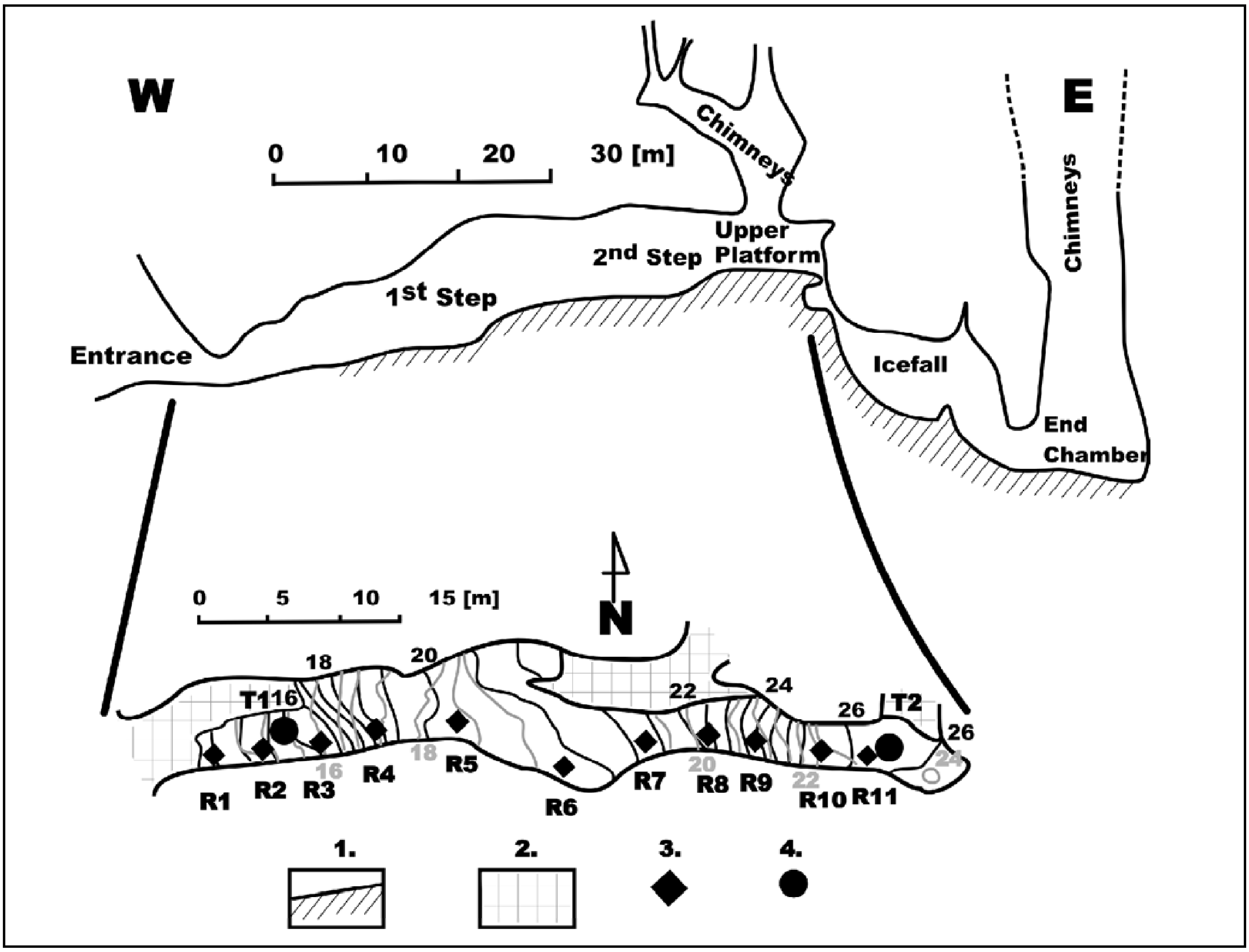

Fig. 2. Long profile of cave's main passage and map of its upper, glaciated part, compiled on the base of data from Zwoliński (1961), Rygielski *et al.* (1995) and own measurements from 2002. Black contour-lines show the ice surface in 1986, gray contour-lines in 2002. Contour interval: 0.5 m. Key: 1: ice surface; 2: ice free areas in the cave; 3: reference points for mass balance survey (R1–R11); 4: points of temperature measurements (T1–T2).

Profil longitudinal de la galerie principale de la grotte et carte de la partie supérieure, à glace compilés à partir des données de Zwoliński (1961), Rygielski et al. *(1995) et des mesures des auteurs faites en 2002. Les courbes de niveau en noir montrent la surface de la glace en 1986, celles en gris la surface en 2002. L'intervalle des courbes de niveau est 0,5 m. Légende: 1: surface de la glace; 2: zones non-glacées de la grotte; 3: points de référence pour le relevé du bilan de masse (R1–R11); 4: points de mesure des températures (T1–T2).*

Chamber are more than 30 m high and serve as main pathways of water supply from cracks and fissure systems connecting the cave with the surface.

The cave climate is classified as dynamic and is characterized by strong air circulation (Rygielski *et al.,* 1995). It is supposed however, that the *End Chamber* might hold glacial meroclimate (temperatures below 0 °C) as a result of the complete ice blocking of the lower corridors during the last decade. The cave entrance can be seasonally blocked by snow, which substantially changes the air circulation inside the cave.

The perennial ice body has a stratified structure consisting of alternating layers of clean ice and ice with different types of impurities (dust, rock debris, minerals crystallized during ice formation (as mentioned by Pulina & Pulinowa, 1972) and organic detritus — *e.g.*, bat remnants such as bones or entire frozen bodies). The volume of the ice was given by Gradziński & Wójcik (1961) at 1500 m^3, but this value seems to be significantly underestimated. Seasonal forms of ice accumulation develop as ice stalactites and stalagmites as well as in form of icefalls on cave walls. On the surface of perennial ice block thermo-erosive channels of more than 0.5 m of depth are seasonally formed.

Methods

The observations and measurements were performed between the March 3, 2000 and May 18, 2002. Complementary measurements were made on August 30, 2004. The temperature was measured every 1.5 hour with self-registering thermometers, between 09.11.2001 and 18.05.2002, at two locations (T1 and T2 on Fig. 2) at a height of about 2 m above the ice. For air temperature analysis data from meteorological observatory on Kasprowy Wierch (1925 m a.s.l., about 9 km to the E from the cave entrance, Fig. 1) were also used. The ice surface elevation changes were measured in relation to eleven fixed marks along the cave (Fig. 2). Additionally, lateral extension of the main ice body and seasonal ice features were measured. In the spring of 2002 a detailed theodolite survey was conducted. Mass balance was calculated on the basis of water equivalent using fixed date system, on seasonal – annual scale based on the marked points survey. The ice density used for computation was 0.917 g·cm^{-3}. Decadal mass balance changes were calculated on basis of our own geodetic survey of 2002, published plans and profiles from 1986 (Rygielski *et al.,* 1995), 1950 and 1922 (Zwoliński, 1961).

Results

Temperature record

Cave air temperatures were measured for six months (November to May – Fig. 3). During the whole time-period the temperature has never been higher than °C. The amplitude was much bigger close to the entrance (T1 – over 17°) than at the end of the cave (T2 – 6.7°). Amplitudes were the highest when the temperatures were the lowest. Fluctuations of air temperature were simultaneous at both measuring locations (Fig. 3) so delay in temperature change between them was not bigger than measurement interval (1.5 hour). When approaching 0 °C the temperatures at both locations are equal (slightly below 0 °C) and do not change for longer periods (weeks).

Cave air exchange

Comparative analysis of air temperature records in the cave and on Kasprowy Wierch (Fig. 3) reveals three kinds of relationships. In winter, when air temperatures outside and inside the cave were below 0 °C, their fluctuations were almost simultaneous. The temperatures of cave air were higher but they well reflected changes observed on the surface. Good ventilation of the cave was characteristic for this period, accidentally measured using a pressure-pipe control sensor in the range between 0.5 and 1.5 ms^{-1}. During late winter and spring the situation changed. The temperatures outside the cave fluctuated around 0 °C, and one time were higher, and another lower than cave air temperature. The variations were still well-recorded in air cave temperature but only for temperatures below 0 °C. For periods when temperatures outside the cave were positive, the cave air temperature was stable at few degrees below 0 °C. In late spring and summer the temperatures

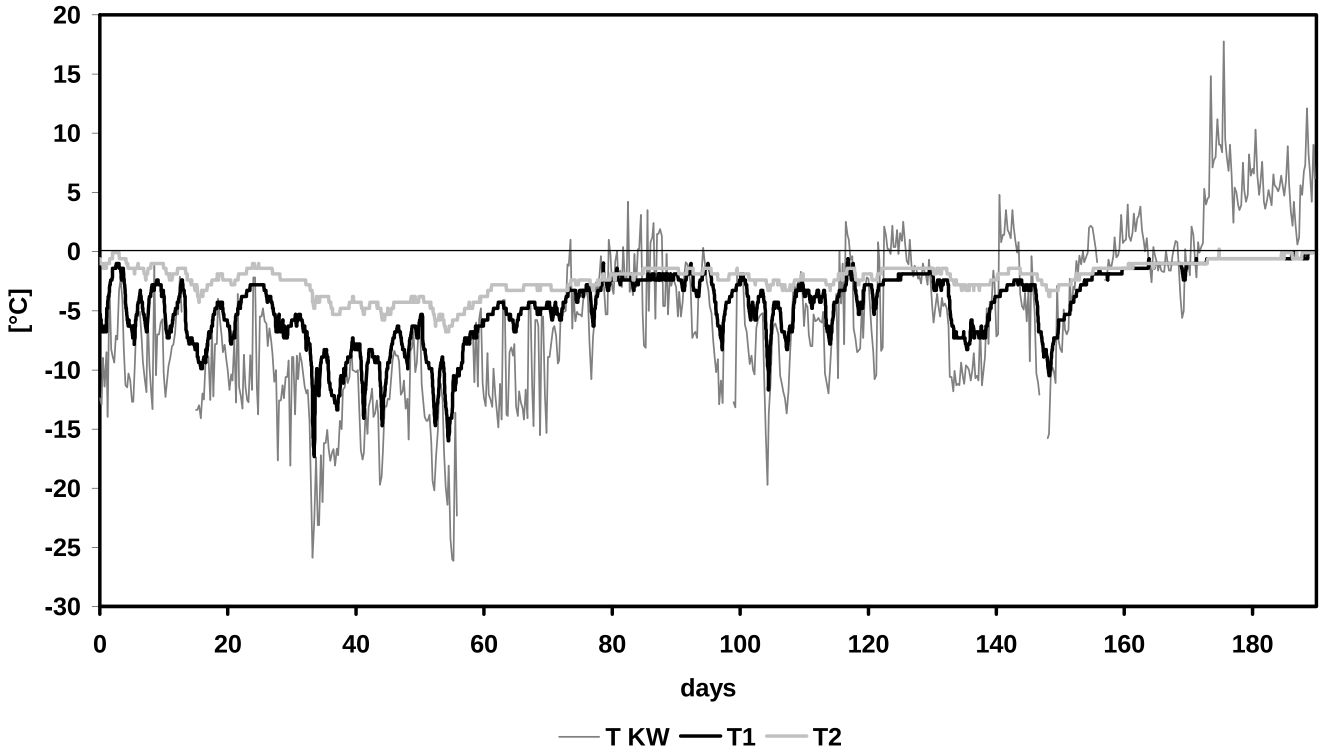

Fig. 3. Air temperature record for the period 09.11.2001 to 18.05.2002. T1 and T2 represent cave air temperature close to the entrance and at the end of the cave respectively (see Fig. 2). TKW – temperature recorded at Kasprowy Wierch meteorological station (1925 m a.s.l. — for location see Fig. 1).

Enregistrement de la température de l'air entre 09.11.2001 et 18.05.2002. T1 et T2 représentent les températures de l'air dans la grotte près de l'entrée et, respectivement, près du terminus (voir Fig. 2). TKW est la température enregistrée à la station météorologique de Kasprowy Wierch (1925 m; voir Fig. 1 pour sa situation).

outside the cave were positive. They were accompanied by a stable temperature of about –0.1 °C inside the cave. The changes in the surface temperature had no reply in cave air temperature, which was controlled by latent heat balance driven by melting process. The cave air exchange rate was the lowest during this period. During direct observations no sensible air movement was observed. Summer circulation conditions starting in late June or July were described by (RYGIELSKI *et al*. (1995). They conclude that cold cave air is gravitationally drained out through the entrance, whereas the warmer external air is sucked from the surface by the presumed fissure-chimney system.

Seasonal changes in ice mass balance

According to the sequence of ice surface elevation measurements carried on in average once every three months between March 2000 and May 2002, seasonal averaged mass balance (Fig. 4) was calculated for the main perennial ice body filling the cave. Seasonal ice formations (stalagmites, etc.) are small in volume (maximum volume is estimated to be about 2 m^3) and were not in focus of the present study.

Positive averaged seasonal mass balance was observed only in transient period between late winter and spring. In the same season temporal ice forms were the best developed. Through the rest of a year the mass balance was negative. The highest values of negative mass balance were noticed in winter, when on average as much as 0.66 m^3 of water equivalent per day was lost. Although generally the same trend was observed along the entire cave, the biggest changes were observed on steep steps and the smallest on flat ice surface.

Annual mass balance changes

Annual mass balance was calculated using fixed date system with the beginning of March as a reference. The mass balance was calculated for two years: 2000 (03.2000 – 03.2001) and for 2001 (03.2001– 03.2002). In both years the ice mass balance was negative –34.66 m^3 and –48.83 m^3 of water equivalent for 2000 and 2001 respectively. The ice surface lowering in these periods was in order of 15 and 30 cm in successive years. The average mass balance for subsequent period (05.2002–08.2004) was also negative: –61.25 m^3 of water equivalent per year, and the surface lowered by about 60 cm.

Processes participating in ice mass balance

The ice mass balance (B) in the cave can be represented by following equation:

$$B = (F + S_R) - (M_S + S + M_B) \qquad (1)$$

where: F – increase of ice mass by freezing; S_R – resublimation; M_S – surface melting; S – sublimation; M_B - basal melting.

Basal melting, although previously reported (RYGIELSKI *et al.*, 1995), is difficult to be estimated but it is expected to be equal everywhere under the ice mass and insignificant in comparison with other mass balance factors (at least one order of magnitude smaller). Reprecipitation of sublimation vapour was observed in form of small ice crystals on the cave walls. However no evidence was found on participation of this process in growing of main ice body. So quantitavely the process is believed to be unimportant.

The quantification of freezing, ice melting and sublimation participation in the ice volume changes is presented on basis of results from 05.2001–05.2002 balance year. Seasonal changes in mass balance show good correlation with cave air temperature changes (Fig. 5) and cave ventilation. It defines periods of domination of each of the three main processes. The increase in ice mass in spring time was attributed to the freezing process (the period is characterized by temporarily positive

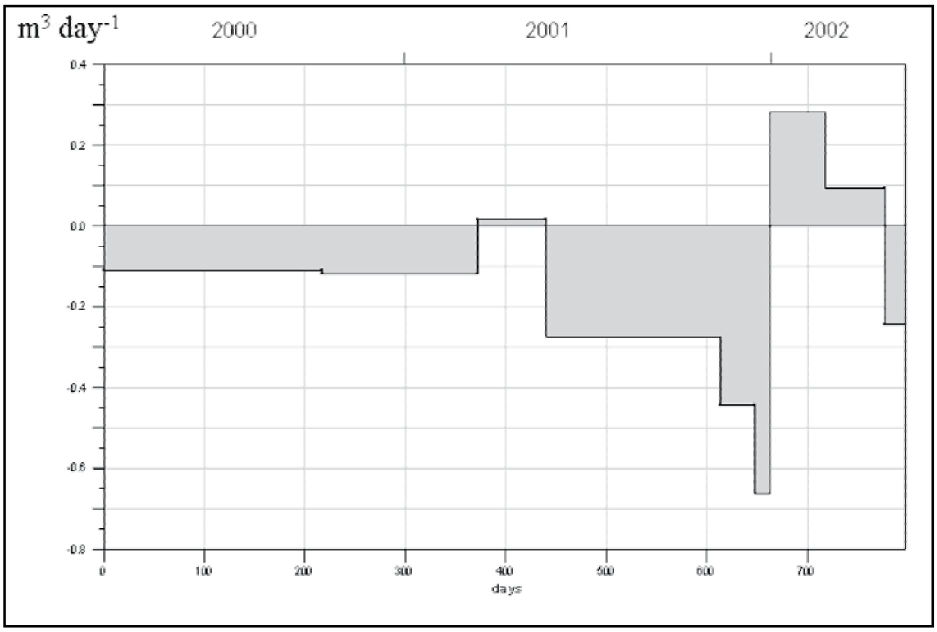

Fig. 4. Averaged seasonal mass balance in m^3/day of water equivalent for the period from 04.03.2000 to 18.05.2002. Every change of the mass balance chart represents subsequent measurements date. The variations between years are partly due to differences in intervals between surveys. Positive averaged seasonal mass balances are observed in late winter – spring periods, and maximum negative in winter.

Bilan de masse saisonnier moyen en m^3/jour de l'équivalent en eau pour la période de 04.03.2000 à 18.05.2002. Chaque changement du graphe représente une date de mesure. Les variations entre les années sont partiellement dues aux différents intervalles entre les relevés. Des bilans de masse positif ont été observés à la fin de l'hiver – printemps, tandis que le minimum a été enregistré en hiver.

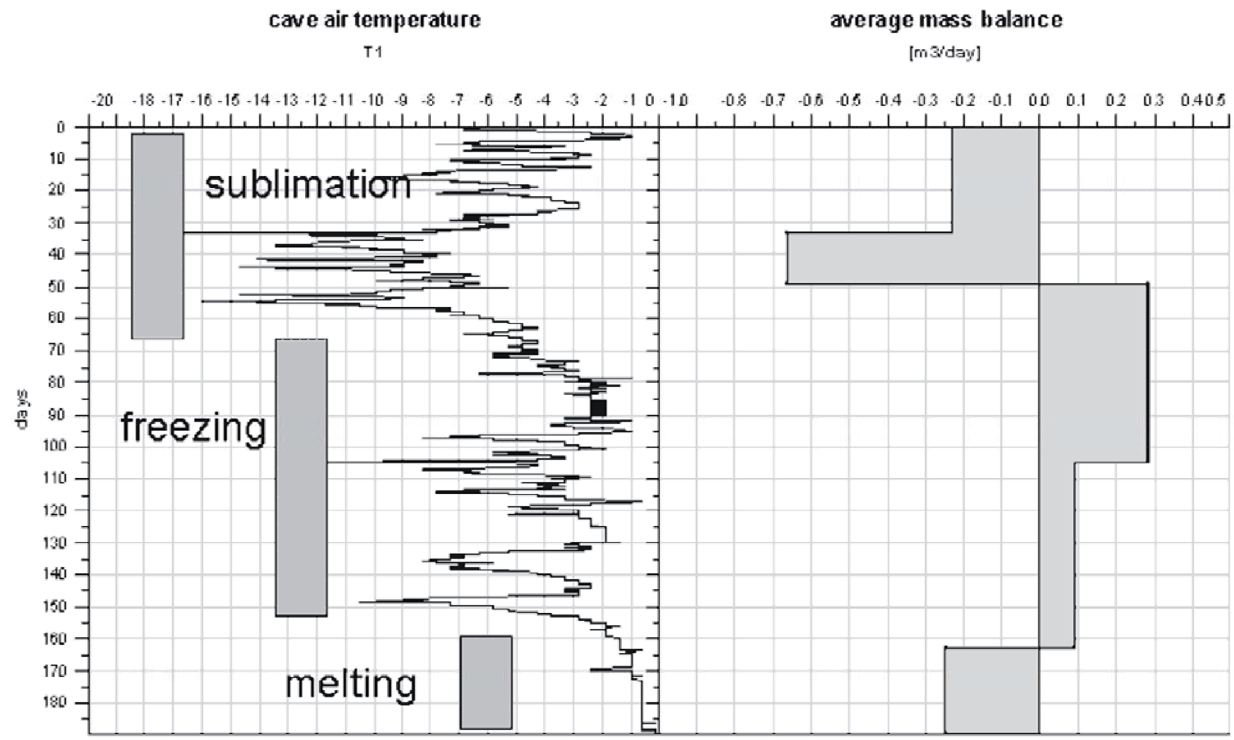

Fig. 5. Cave air temperature at site T1 (close to the cave entrance) and seasonal ice mass balance (m^3/day of water equivalent) for the time-period 09.11.2001–18.05.2002. Grey bars on the left diagram represent dominating process of mass balance.

La température de l'air dans le point de mesure T1 (près de l'entrée de la grotte) et le bilan de masse saisonnier (en m3/jour équivalent d'eau) pour la période 09.11.2001–18.05.2002. Les barres grises de la diagramme de gauche représentent les processus dominants du bilan de masse.

temperatures outside the cave which making the percolating water available and negative inside; the cave air exchange is slowed in comparison to winter time). The loss of ice mass in winter time, when temperatures inside and outside the cave are well below zero is tied to the sublimation process (the period of good ventilation of the cave). During the rest of the year temperatures outside the cave are mostly positive and those inside the cave run independently. The temperature inside the cave is relatively stable (about 0 °C) and possibly controlled by latent heat consumption for melting. With the assumptions presented above a simplified equation with regard to the mass balance factors for studied year is:

$$B = F - (M_S + S) \tag{2}$$

Substituting measured values, the balance is:

$$B_{2001/2002} = 19.5 - (50.2 + 23.2) = -53.9 \text{ [m}^3\text{ w.e.]}$$

From the solution of this equation several conclusions can be drawn. The spring increase in the mass volume equals about 26% of total ice mass loss during the year ($M_S + S$). The ice is lost primarily by melting, which accounts for about 69%. However the most intensive loss of ice mass is during winter when in less than two months about 31% of total annual ice is lost due to sublimation. It suggests that milder and longer winters are more favorable for ice growth. Very severe winters are not expected to increase ice volume, on contrary, the ice volume decreases substantially due to sublimation.

Decadal changes in ice mass balance

Comparing the ice body morphology and longitudinal profiles along the upper parts of the cave between years 1922 – 1950 – 1986 – 2002 and 2004 (Fig. 6) reveals a continuous lowering of the ice surface. Distinct changes in ice geometry are expressed through a disappearance of the step in the middle part of the ice body, smoothing of near entrance ice front and apparent backward movement of the ice steps. The ice surface in the whole period of existing records lowered on average more than 6 m.

In terms of mass balance units, the mass loss varied for particular time intervals (Fig. 7). The decades from the 1920s until the 1980 are characterized by moderate negative ice mass balance in the range of 20–30 $m^3\ y^{-1}$ which could be balanced in particular years through ice accumulation in profitable conditions. Last two decades of the 20th century reveal accelerated ablation exceeding 30 $m^3\ y^{-1}$ and, as shown above by the annual values, incidentally doubling this value in the most recent times.

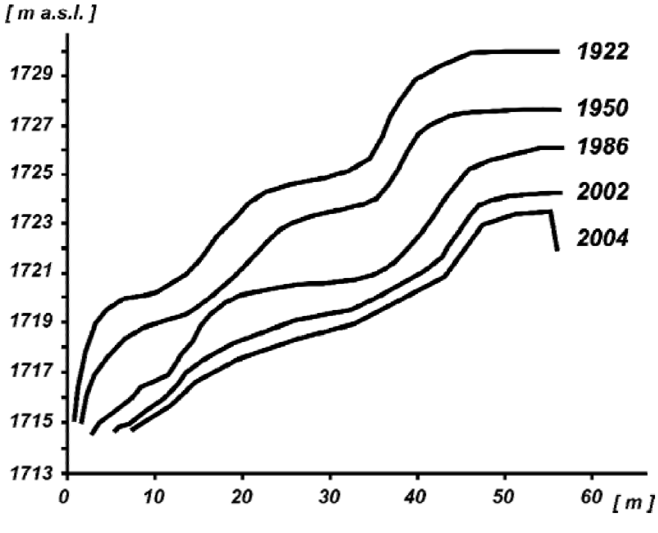

Fig. 6. Longitudinal profiles along the ice surface in the upper part of the cave based on cartographic materials from years 1922 and 1950 (Zwoliński, 1961), 1986 (Rygielski *et al.* 1995) and the authors' survey in 2002 and 2004. Profiles from years 1986 and 2002 are drawn according to contour maps (Fig. 2) acquired from theodolite measurements.

Profils longitudinaux le long de la surface de glace dans la partie supérieure de la grotte à partir des matériaux cartographiques réalisés en 1922 et 1955 (Zwoliński, 1961), 1986 (Rygielski et al. *1995) et les relevés des auteurs de 2002 et 2004. Les profils de 1986 et 2002 sont réalisés à partir des courbes de niveau des topographies à théodolite de la Figure 2 .*

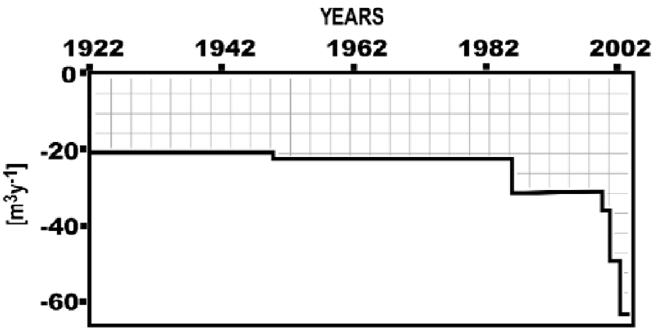

Fig. 7. Averaged ice mass balance for 80 years period (1922–2004) presented in water equivalent [m^3y^{-1}]. In total about 2250 m^3 of ice was lost in this time span.

Le bilan de masse moyen pour la période de 80 ans (1922–2004) en équivalent d'eau [m^3y^{-1}]. En total quelque 2250 m^3 de glace ont été perdus dans ce temps.

Discussion and conclusions

Mass balance studies of perennial ice masses in caves of temperate zone were published only for a few caves in the Carpathians (Silvestru, 1999; Racoviță & Onac, 2000), Ural Mountains (Andreichuk & Dorofeev, 1994), Japan (Ohata *et al.*, 1994) and North America (Marshall & Brown, 1974). For several others some notes exist, which mostly just notify whether the ice mass is in degradation or not. Most of the above mentioned studies, and as documented by their authors, were done for static ice caves. Stagnant cold air layer at the bottom of deep karstic shaft and negative mass balance is observed there in recent period. However in those cases the amount of ice loss (or ice surface lowering) was usually much lower than for Jaskinia Lodowa w Ciemniaku — a cave with a dynamic climate, primarily with strongly induced winter air circulation (Rygielski *et al,* 1995).

The contemporary climatic conditions are indicative for the degradation of the ice body in Jaskinia Lodowa w Ciemniaku. The increasingly negative mass balance in the last 80 years corresponds with global (Houghton *et al.,* 2001) and local climate warming trends. If the modeled future warming would occur the total loss of the ice body would be expected in 30 - 40 years. Similar or even more rapid changes are expected for some other dynamic ice caves, e.g., in the Italian Alps (Borsato *et al*., 2004).

Our continuous measurements of the cave air temperature shows that the circulation in Jaskinia Lodowa w Ciemniaku is not blocked in late winter and spring as was suggested by previous authors (Rygielski *et al.*, 1995). On the contrary these periods are the most dynamic with the ice growth and also with the biggest ice losses due to sublimation. The latter process was discussed by Mavludov (1989, 1992). He postulated that there is a strong relationship between ice evaporation (sublimation) intensity, air humidity deficit and airflow velocity in the cave. This agrees with the data we have presented – the sublimation occurred during the period with rapid temperature changes in the cave in response to the temperature fluctuations outside the cave (so with relatively high air flow rate).

The seasonal characteristic of ice mass balance also have important implications for interpretation of the stratigraphic record of the ice body. There can be significant differences between years in ice accumulation and degradation. Moreover they do not need to be simultaneous across the cave. It clearly shows that ice body layering can not be simple taken as annual stratification.

Summarizing the following conclusions can be drawn:

- the ice mass loss is due to melting (about 70% during the period of observations) in summer and autumn, and in effect of sublimation (about 30%) in winter. Increase in ice mass is observed only at the end of winter and beginning of spring period;

- the most favorable conditions for ice mass growth are when temperature outside the cave is fluctuating around 0 °C, and cave air temperature is below freezing point;
- during the last 80 years average ice mass balance was negative and over 2200 m^3 of ice was lost in this period;
- ice mass losses were significantly higher in the last decade in comparison to earlier periods, so the perennial ice mass is not stable in modern climatic conditions.

Acknowledgements

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