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ICE LEVEL CHANGES FROM SEASONAL TO DECADAL TIME-SCALES OBSERVED IN LAVA TUBES, LAVA BEDS NATIONAL MONUMENT, NE CALIFORNIA, USA

ABSTRACT: KERN Z. & THOMAS S., *Ice level changes from seasonal to decadal time-scales observed in lava tubes, Lava Beds National Monument, NE California, USA.* (IT ISSN 0391-9838, 2014).

Numerous lava tubes host seasonal or perennial ice accumulation in the Lava Beds region. Systematic ice level monitoring has been conducted for eight ice caves since 1990, and four other ice caves were added to the monitoring program during recent years. Cave names are used for publically advertised ice caves, and cave codes are used to help protect ice resources of the other eight monitored ice caves. Monitoring data has revealed that the seasonal cave ice phenology can be characterized by autumnal ice level low-stands of ice floors in the lava tubes. Regarding the multiannual evolution, both positive and negative ice mass balance periods were detected during the past 23 years. Balanced glaciation characterized the lava tubes over the early 1990s. Positive mass balances were reported for many caves from the late 1990s. Ice levels are still stable in Skull Ice Cave and U-200. Severe ice loss, however, has characterized the evolution of ice deposits in the other monitored caves. Major ice loss started in 1999 in Merrill, C-270, and M-470 ice caves, while not until 2003 in L-800. The recent rapid ice melt resulted in total ice loss for some caves. The perennial ice disappeared, for instance from M-470 and M-475 by 2005 and from Merrill Ice Cave by 2006.

KEY WORDS: Lava tube, Cave glaciation, Cave ice phenology, Decadal ice level trends.

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INTRODUCTION

Shrinking glaciers, decreasing sea ice extent, and thawing of permafrost are well known and frequently quoted examples of the recent retreating trend of the global cryosphere (Lemke & *alii*, 2007; UNEP, 2007; Zemp & *alii*, 2008); however, information regarding the status of cave glaciations worldwide is relatively scarce (Kern & Perşoiu, 2013). In this respect, multiannual, systematic volumetric and/or ice level monitoring data are definitely invaluable records for revealing cave glaciation trends. Such monitoring, however, is extremely rare in ice caves (Rajman & *alii*, 1985; Ohata & *alii*, 1994b; Luetscher & *alii*, 2008; Strug & Zelinka, 2008; Kern & *alii*, 2007), and perhaps the Romanian Scărişoara IC (Ice Cave hitherto abbreviated as IC) (Racoviţa, 1994; Perşoiu & Pazdur, 2011) and the German Schellenberg IC (Ringeis & *alii*, 2008) are the best examples so far of published multidecadal ice level monitoring data. Reconstructed ice level histories based on historic or stratigraphic evidence are also available in limited numbers (e.g., Luetscher & *alii*, 2005; Spötl & *alii*, 2014).

It has long been known that numerous lava tubes host seasonal or perennial ice accumulation in the Lava Beds region (Balch, 1900; Swartzlow, 1935; Halliday, 1954; Knox & Gale, 1959). However, the observation records obtained from systematic ice level monitoring conducted for 12 ice caves in the Lava Beds region were practically unknown to the ice cave research community until recently. Fuhrmann (2007) published 16 years of mean ice level changes from Merrill IC, while a recent study showed ice volume change estimates using five additional records in a global overview (Kern & Perşoiu, 2013). In this paper we publish the full ice level monitoring record of the 12 lava tubes covering the period from 1990 to 2012.

Although the dominant role of winter cooling is a consensus view in the community regarding the link between cave glaciations and aboveground weather (e.g., Ohata & *alii*, 1994a; Racoviţa, 1994; Rachlewicz & Szczucinski, 2004; Luetscher, 2005, Morard & *alii*, 2010) there are some alternative theories to explain the ice level fluctuations in the glaciated lava tubes of the Lava Beds region (Swartzlow, 1935; Fuhrmann, 2007). To test, verify, or refute these theories for the cave ice level fluctuations, instrumental records from a local weather station are used and discussed briefly in this paper.

SITE DESCRIPTION

Lava Beds National Monument (hitherto LBNM) is located on the lower north flank of the Medicine Lake Volcano (fig. 1). In postglacial time, 17 eruptions have added approximately 7.5 km^3 to its total estimated volume of 600 km^3, and it is considered to be the largest by volume among volcanoes of the Cascades arc (Donnelly-Nolan & *alii*, 2008; Donnelly-Nolan, 2011).

The flows produced by the Medicine Lake Volcano contained lava «rivers» that drained down gradient according to topography, forming channels and distributaries that slowly cooled, forming overlying crusts that acted as insulation for lava that continued to flow beneath. As the flows subsided, lava drained from the channels, leaving solidified casts that are the lava tubes known today. The region hosts hundreds of caves making for the highest concentration of lava tubes in the contiguous United States (Waters & *alii*, 1990). The majority of these formed within the so-called Mammoth Basalt, whereas additional caves are found in mostly younger basalts and igneous formations in the monument (Larson, 1992).

Deep caves are often characterized by stable topoclimatic conditions that reflect the mean annual surface temperatures in the region, as usual (Wigley & Brown, 1976; Badino, 2010); however, in some caves with suitable entrance and passage geometry, cold air sinks and becomes trapped in deep passages, allowing perennial ice floors to be maintained (e.g., Halliday, 1954). These lava tubes are characterized by active circulation of air in winter but comparatively little circulation in the summer months (Knox & Gale, 1959). According to the process-based classification of alpine and subalpine ice caves (Luetscher and Jeannin, 2004), they belong to the group of static caves with congelation ice.

MATERIALS AND METHODS

ICE LEVEL MONITORING

A long-term program has been conducted by the Cave Research Foundation, in conjunction with the Resource Management Division of LBNM, annually since 1990 to monitor ice levels in eight lava tubes to track the fluctuation of the ice from season to season and year to year (Fuhrmann, 2007, Smith, 2014). Additional caves were added to the monitoring network in 1991, 1999, 2005, and 2009. Basic attributes of the monitored lava tubes are given in table 1 and their profile views are displayed in figure 2. Four of the 12 monitored caves are publically advertised as ice caves and are therefore referred to in this paper by their given names (Crystal Ice Cave, Heppe Ice Cave, Merrill Ice Cave, Skull Ice Cave). The other eight caves are not generally visited by the public, so in accordance with NPS policies meant to protect their identities and sensitive ice resources, these caves are referred to by codes (C-270, L-215, L-800, M-310, M-340, M-470, M-475, U-200).

TABLE 1 - Attributes of selected ice caves, Lava Beds National Monument. All units in meters

Cave Name	Elevation	Length[1]	Depth[2]	# of entrances	Distance from weather station
C-270	1396	627.0	23.2	7	3466
Crystal Ice Cave	1524	808.9	29.6	1	1079
Heppe Ice Cave	1609	51.8	29.0	2	3658
L-215	1548	90.5	21.3	1	1735
L-800	1390	45.1	22.9	1	708
M-310	1412	81.1	20.1	1	2560
M-340	1400	196.6	21.9	2	2119
M-470	1349	122.2	25.0	1	3400
M-475	1342	44.5	21.9	1	3963
Merrill Ice Cave	1487	198.1	18.3	1	3944
Skull Ice Cave	1388	176.8	36.6	1	2157
U-200	1554	49.6	9.1	2	5689

[1] Total surveyed length of all passages.
[2] Difference between surveyed high and low points in cave.

Ice level is usually measured as the distance from a fixed point (monitoring datum) on the cave wall or ceiling above the ice floor, marked by a screw permanently inserted into the rock, to the surface of the ice floor (Smith, 2014). For simplicity and minimal resource impact to the cave wall or ceiling, each ice floor has only one or two monitoring sites. Shorter/longer distance trends between the datum and the ice deposit indicate increasing/decreasing ice level. Despite the spatially limited information and the inability of this method to differentiate between basal and surface melting, it is a proven technique for showing changes in ice levels over time (Fuhrmann, 2007, Thomas, 2010). In the case of Heppe IC, the prohibitively high ceilings prevented establishment of a similar reference level above the ice floor, so, as an exception to the standard methodology, horizontal dimensions of the ice deposit (i.e., width-length) are measured at each visit in this cave.

When multiple observations were available from a cave for a given year, the data offered the opportunity to sketch the cave ice phenology (i.e., the intrannual ice level fluctuation). Following a preliminary evaluation we have chosen four as a minimum required number of observations per year (ideally one from each season) to characterize the cave ice phenology.

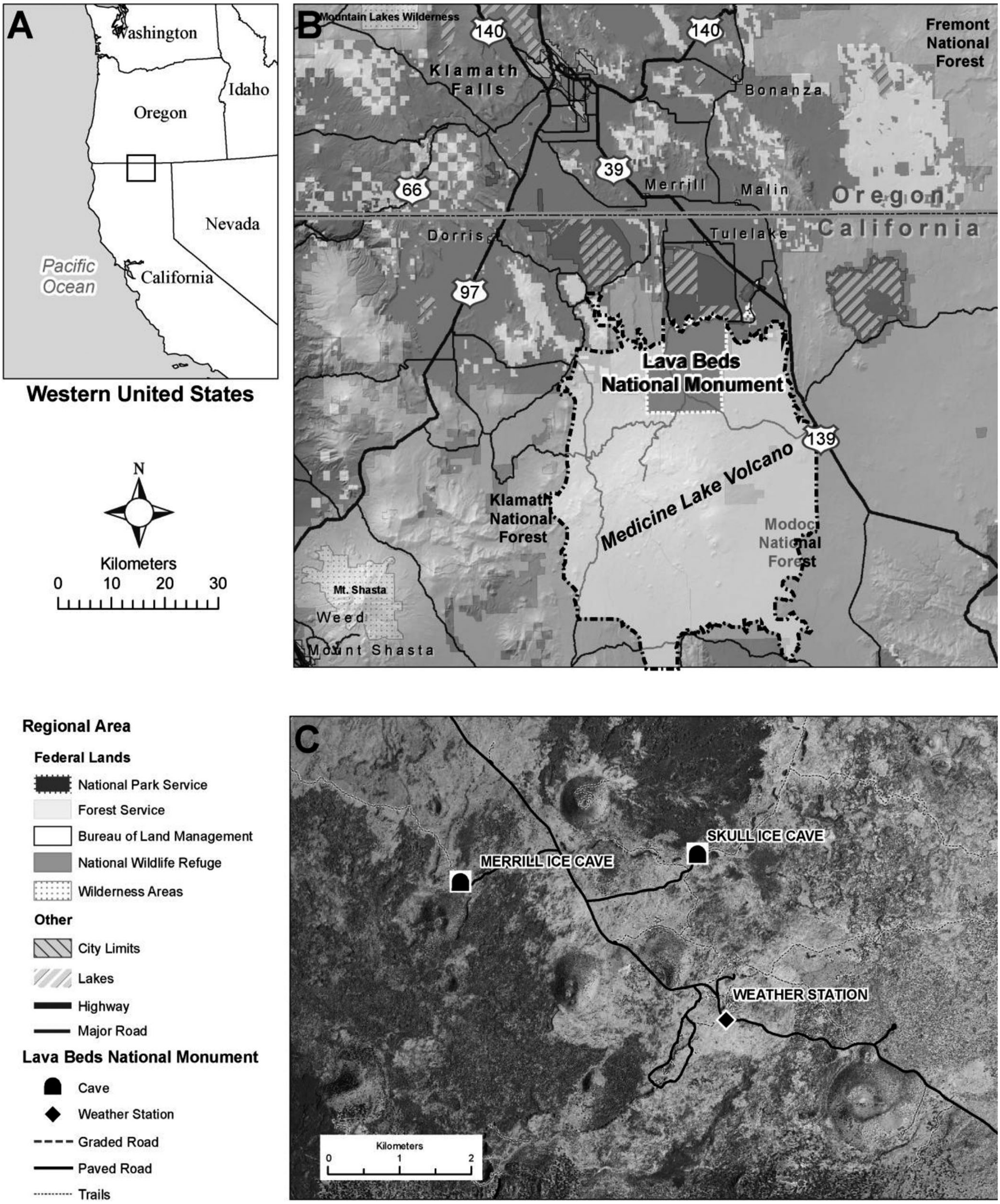

FIG. 1 - Geographical setting. A: The study site is located in NE California. The black box corresponds to the frame of the map of panel B. B: Lava Beds National Monument and its surroundings. The outline of Medicine Lake Volcano (shaded area) is retrieved from Donnelly-Nolan (2011). C: The weather station with the locations of two show caves are indicated in the aerial photo. (Note the other caves are protected hence it is not allowed to publish their location).

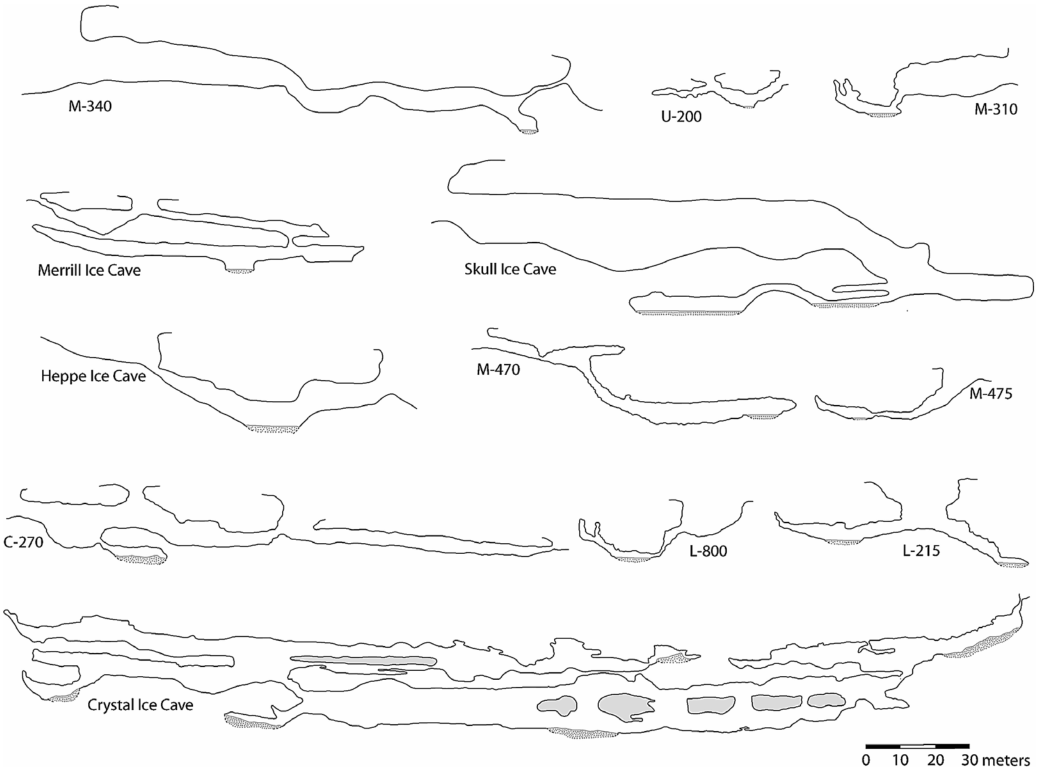

FIG. 2 - Profile views of the monitored lava tubes and locations of ice floors within the caves. Dotted areas show the major perennial ice deposits.

METEOROLOGICAL DATA

Air temperature and precipitation are recorded by the National Weather Service weather monitoring station at monument headquarters (fig. 1). The relative proximity of the weather station to the monitored ice caves (distance ranging from 0.7 to 5.7 km, table 1.) and the broad-scale similarity in terrain and elevation across LBNM suggests the station's instrumental records provide a relevant reference for the surface climate surrounding each cave. Monthly mean of daily maxima/minima, monthly precipitation totals, and total monthly snowfall data were available. These data have been collected since December of 1945; however, missing values were relatively frequent during the first several years of meteorological monitoring, so data only after 1960 were used when the records were complete. Although lava tube ice monitoring began in 1990, the longer records are invaluable because they provide a more robust picture of the natural climate variability to help evaluate potential anomalies during the ice level monitoring.

RESULTS AND DISCUSSION

The full dataset, either as direct ice level measurements (n=381) or related descriptive information (n=32), collected during the LBNM cave ice level monitoring is presented in the Appendix (tab. A1, A2). Five of the lava tubes with the most complete record were selected to graphically illustrate our major findings (fig. 3).

INTRA-ANNUAL ICE LEVEL FLUCTUATIONS

Neglecting the really few exceptions, like L-800 in 1999, or C-270 in 1998, it is quite clear that ice level minima were recorded in late autumn (~November) and highest ice levels were reached in spring. Such a timing of the seasonal ice level low stand is usual in mid-latitude ice caves (e.g., Halliday, 1954; Serban & Racovita, 1991; Ohata & *alii*, 1994b; Kern & *alii*, 2007; Perşoiu & *alii*, 2011). It is interesting to note that the largest ice loss was recorded in 2003 in each cave (L-800, M-470, Merrill IC) where monitoring data are available from this year (fig. 3).

INTER-ANNUAL ICE LEVEL FLUCTUATIONS

In general, five distinct periods demarcated by four characteristic tipping points are discernible in the ice level evolution records of the selected lava tubes (fig. 3). Tipping points were determined when similar closely coinciding changes (increase or decrease) were detected in the ice level history in more than half of the lava tubes.

Period 1 (1990-95)

The ice levels for the caves remain stable for several years during the initial monitoring phase at Skull IC, C-270, and M-470. Moreover, L-800 and Merrill IC records show a slight ice accumulation during the first five years of the monitored period.

Period 2 (1996-97)

Positive mass balance was observed for four (Skull IC, L-800, C-270, Merrill IC) out of the five lava tubes until

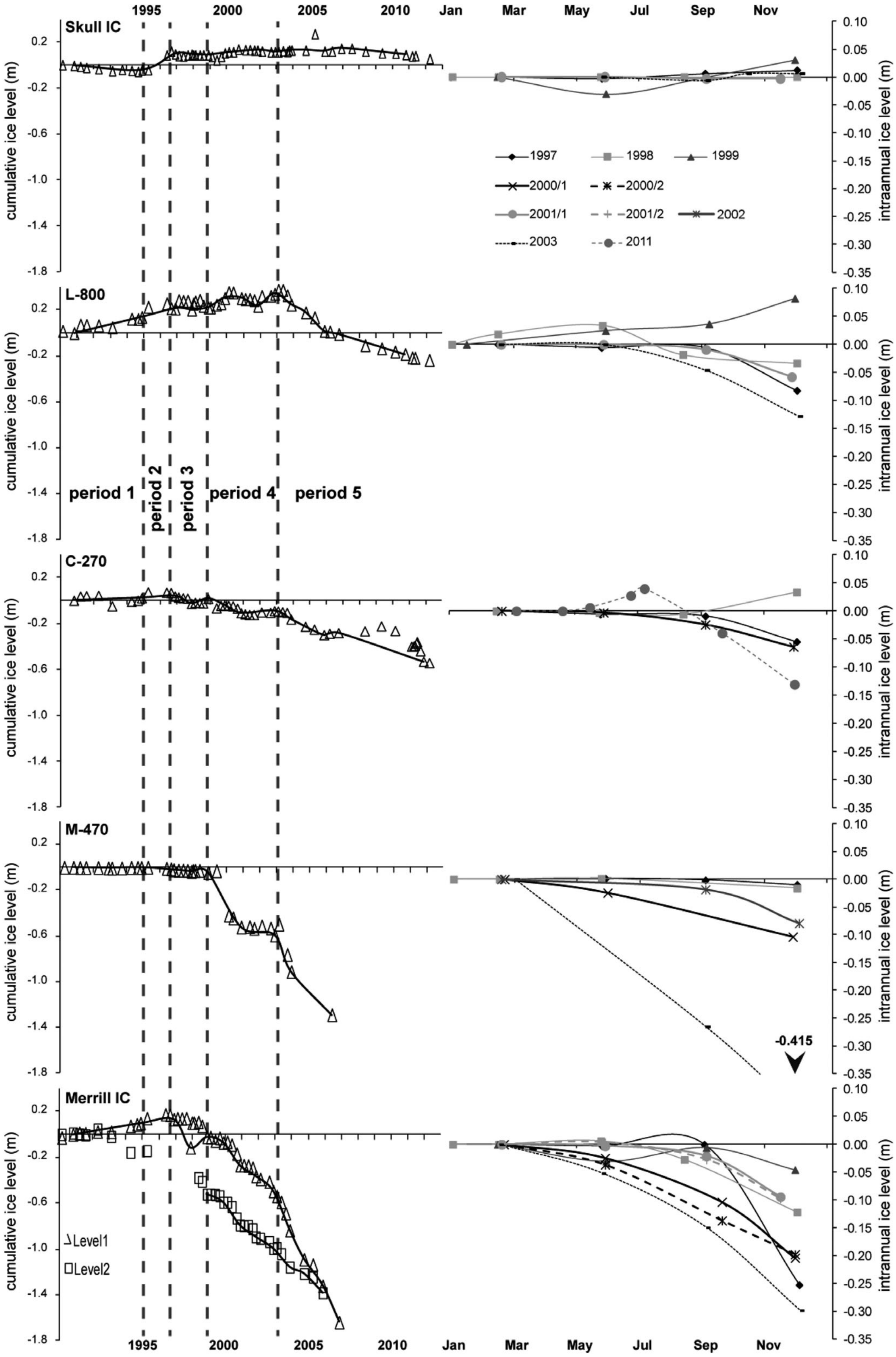

FIG. 3 - Ice level history of perennial ice deposits of five lava tubes from LBNM. Left panel: ice level observations relative to the ice level measured at the first survey, a curve (solid black) is fitted to late autumn (Oct-Nov) ice level data to emphasize the interannual evolution. Dashed vertical lines indicate characteristic tipping points observed in at least three ice level trends. Ascertained periods separated by the tipping points are given in the ice level history chart of L-800 with consecutive numbering. Right panel: Intrannual ice level changes relative to the ice level measured at the first survey of the given year. Only years with more than 4 observations were selected to sketch the cycles of ice phenology.

1997. The exception was M-470; however, the ice level did not decline in this cave, but rather remained stable.

Period 3 (1998-1999)

Stable conditions (no clear melting/ablation) were observed at four (Skull IC, L-800, C-270, M-470) of the five lava tubes.

Period 4 (2000-03)

A significant breakpoint appears in the records around the turn of 1999/2000. After that, ice level decline initiated in C-270, M-470, and Merrill IC. This declining trend persisted until recent times for these caves. L-800 and Skull IC were not affected, as relatively stable ice levels were reported from these caves.

Period 5 (2004-2012)

The next remarkable tipping point is 2003. Ice level decline intensified for the above mentioned three caves; in addition, this date became a major tipping point also for L-800 ice level history because mass balance turned to negative and resulted in net ice loss over the next decade. Accelerated ice loss finally resulted in the disappearance of perennial ice from M-470 and M-475 by 2005 and from Merrill IC by 2006 (tab. A1).

It is interesting to note that Skull IC has not been affected by net ice loss. Similarly, a stable glacial regime seems to prevail in U-200 (tab. A2), although its observation record has thus far been relatively short.

There is some correspondence between long-term and intrannual ice level changes for the studied caves. The ice level of Skull IC is stable not only at interannual but also at seasonal scale. The recorded variability at Skull IC is usually in the order of a couple cm (fig. 3), which may in some cases be attributed to tape reading uncertainty between different monitoring events/groups. Seasonal amplitudes of ice level change were smaller also for M-470 until 2000 (fig. 3). Afterwards, as long-term ice level evolution shifted to a recession phase, seasonal cave ice level change tended to present larger amplitudes. Perhaps M-470 provides the clearest picture to illustrate this tendency (fig. 3). This is an interesting characteristic and the correspondence between exaggerated intrannual ice loss and the long-term steady ice level decline suggests that enhanced ablation rather than reduced accumulation played a central role in the observed ice loss trend.

Ice level fluctuations - various explanations

The shared tipping points of the presented ice level records suggest that a regionally acting trigger drove the changes. The regionally homogenously acting trigger mechanism could, obviously, be the climate/weather conditions. The first opinion about the ice level changes of Lava Beds was that the rainfall of previous years is the chief factor in determining the volume of ice present in the caves (Swartzlow, 1935). Recently Fuhrmann (2007) hypothesized that the ice may have been melted due to warmer outside air temperatures. In addition, non-climatic factors such as unrestricted cave visitation, transformed cave passages due to a significant seismic event, and altered hydrological regimes due to vegetation changes above the caves were suggested as causes for the multiannual accelerating ice loss at Merrill IC (Fuhrmann, 2007). These factors are plausible but so far unsubstantiated, whereas most detailed monitoring studies conducted in mid-latitude ice caves at other sites suggested that the ice mass balance is primarily controlled by winter temperature and precipitation regimes and that summer climatic conditions contribute negligible effects on the annual ice mass balance of the cave (Ohata & *alii*, 1994a; Rachlewicz & Szczucinski, 2004; Luetscher & *alii*, 2005, 2008, Perşoiu & *alii*, 2011).

To test these above mentioned climate related theories for LBNM ice caves, the characteristic periods/tipping points ascertained for the ice level histories of the investigated lava tubes were compared to the regional climate records. Winter season thermal conditions were first compared to the cave ice level history, especially to the ascertained breaking/tipping points. Two seasonal windows were defined: Dec-Jan, the pair of coldest months, and Nov-March, as an extended winter (fig. 4a-d). One-sided triannual moving averages combining coinciding multimonthly means with previous two annual values were also calculated to emphasize the potential multiannual anomalies. Mean of daily low and high temperatures were both calculated to see any potential difference.

To test Swartzlow's (1935) hypothesis, previous 'year' precipitation was also calculated in two different seasonal windows. Both the previous calendar year, and the preceding hydrological year (i.e., from previous November to October) were screened (fig. 4e-f).

Comparing the ice level fluctuations to the time series of climatic factors thought to be important in explaining the variability of cave ice mass balance, such as winter temperature (e.g., Ohata & *alii*, 1994a; Racoviţa, 1994; Rachlewicz & Szczucinski, 2004; Luetscher, 2005; Morard & *alii*, 2010) or previous year's precipitation (Swartzlow, 1935), some extreme years seemed to coincide both with positive and negative mass balance years. Winter of 2002/2003 was extremely mild, for instance, corresponding to the severest summertime ablation, while the second mildest winter (1995/96) is close to the characteristic general positive mass balance event. Similarly, the wettest preceding year (both calendar or hydrological) was 1999, followed by the launch of the ice loss trend in three out of five caves (Period 4). Contrary, the second wettest year (1996) coincided with Period 2, a positive mass balance event.

Therefore, there is no obvious pattern in these candidate climate factors supporting any easy interpretation of the recent multiannual ice decline. A similar experience was reported by Ringeis & *alii* (2008), who failed to find any clear evidence in the local meteorological records to explain the long-term decline of the mid-20th century ice level records of the Schellenberg IC.

It is also interesting to note that despite the decreasing trend in winter low temperatures since 2000 (fig. 4a-d), suggesting that winter conditions became more favorable for ice accumulation during this period, the ice loss trend persisted in the lava tubes.

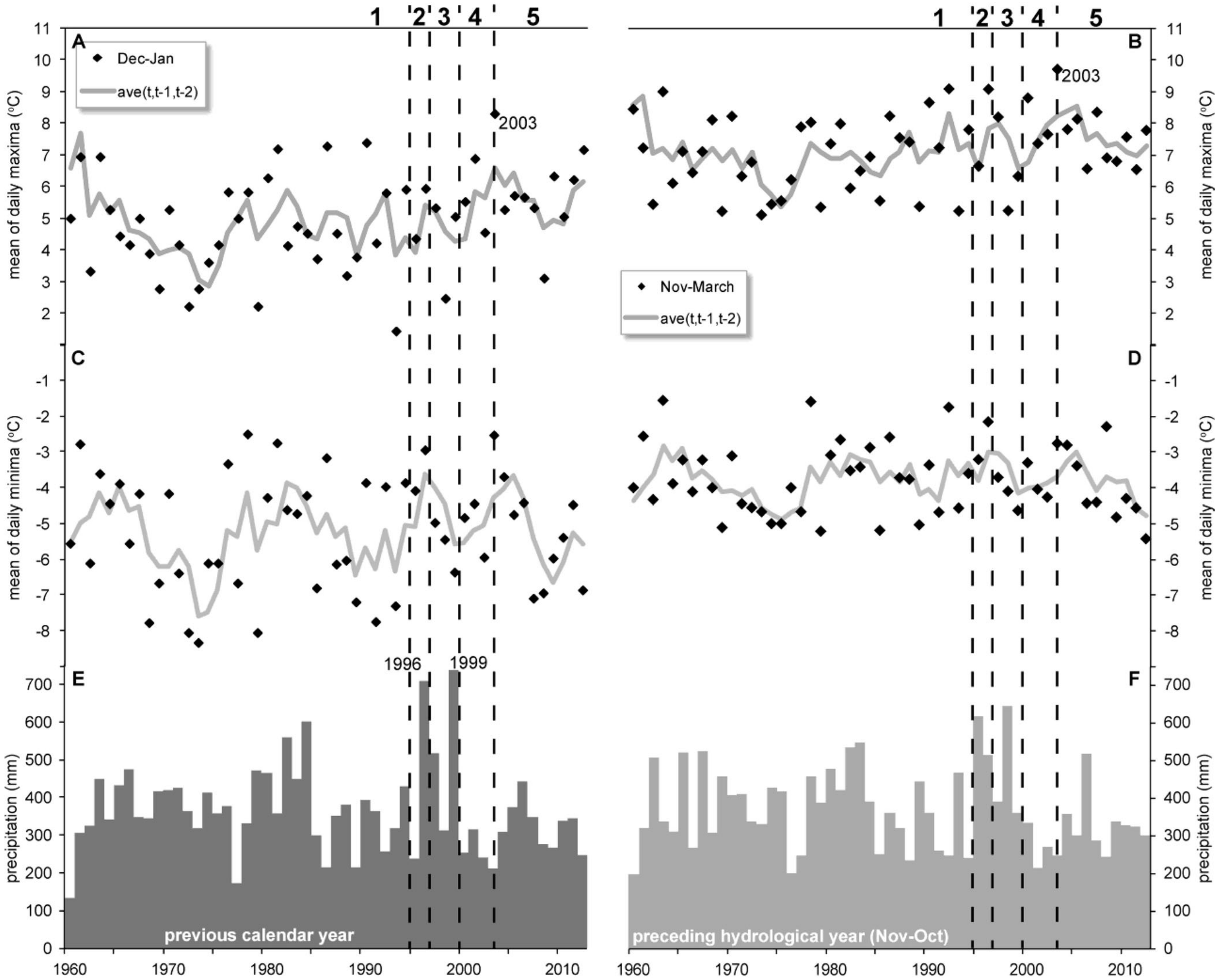

FIG. 4 - Selected meteorological parameters potentially affecting subterranean glaciation. Mean of daily maxima for December-January (A) and November-March (B) periods. Mean of daily minima for December-January (C) and November-March (D) periods. Thick gray line is the one-sided triannual moving average. Precipitation preceding the ice accumulation was also screened in two seasonal windows: previous calendar year (E) and preceding hydrological year (November-October) (F). Few extremes are given. Dashed vertical lines indicate characteristic tipping points and numbers at the top refer to the ascertained major periods of ice level history of the lava tubes (see fig. 3 and text for details).

Finally, however, we note that summer air temperature had steadily risen from the mid-1990s to 2008 in the region (fig. 5). Mean of daily maximum temperatures lined up in an unusually narrow and high range (min: 27.5°C in 2001; max: 29.2°C in 2006) from 2000 to 2009. The mean of this period is c. 2°C higher compared to the previous four decades. This suggests that heat flux to the lava tubes could have increased due to conductive processes and/or latently due to warmer infiltrating water. Luetscher & *alii* (2008) found in the Monlési IC (Swiss Jura Mts) that melting of cave ice is mostly controlled by conductive heat through cave walls. Keeping in mind that the studied lava tubes are relatively small caves, the exchange surface areas of the cave walls are proportionally larger to the cave volumes. Therefore the conductive heat flux could be a dominant component in their energy balance. As the host rock has large thermal inertia, the ground heat flux cannot be expected to change significantly at shorter (annual) timescales. The prolonged period of consecutive warm summers (2000-09), however, might have increased the regional ground heat flux.

However recently published field observations further emphasize the large difference in the importance of the heat flux through the host rock among the individual ice cave systems (Spötl & *alii*, 2014; Ribas & *alii*, 2014).

Detailed speleometeorological and speleoglaciological monitoring (Luetscher & *alii*, 2008; Perşoiu & *alii*, 2011; Obleitner & Spötl, 2011) could be needed to quantify the contribution of different processes (e.g., ground heat flux) to the energetic and mass balance of the different glaciated lava tube systems.

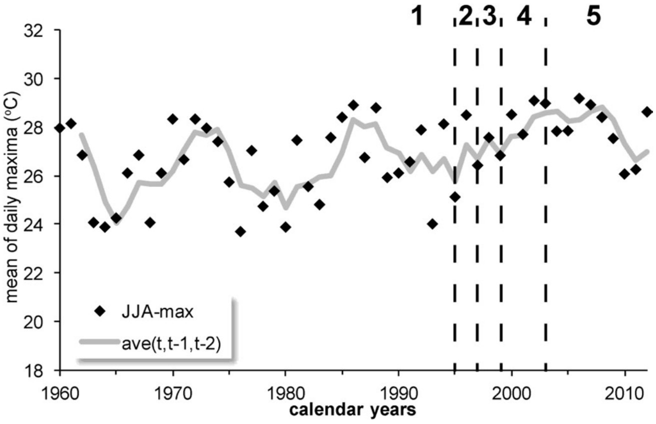

FIG. 5 - Mean of daily maximum temperatures for June-July-August. Thick gray line is the one-sided triannual moving average. Dashed vertical lines indicate characteristic tipping points and numbers at the top refer to the ascertained major periods of ice level history of the lava tubes (see fig. 3 and text for details).

CONCLUSION

Based on multiple observations available from 12 ice caves in Lava Beds National Monument (NE California), the usual ice phenology of the glaciated lava tubes can be characterized by March-May high stands and late autumn (usually November) low stands. Monitoring records reveal two characteristic types of cave glaciation conditions: i) balanced glaciation with hardly any seasonal ice level fluctuation and lack of ice loss trend, and ii) imbalanced glaciation with pronounced seasonal ice level fluctuations and decadal-scale declining ice levels. Although balanced glaciation characterized most of the caves until the end of the 1990s, an accelerating ice loss trend emerged over the past decade.

Drastic ice declines have already been reported for Merrill IC (Fuhrmann, 2007) and also for a couple of other caves for the LBNM region (Kern & Perşoiu, 2013).

It is important to note the exceptional behavior of Skull IC; intrannual ice level changes do not show any characteristic seasonal cycle in this cave, however, the really odd character is that this is the only one of the 12 monitored in the region in which the ice mass balance is positive at a multidecadal time scale.

When winter thermal conditions and precipitation amounts observed at a local weather station were compared to ice level fluctuations, some extreme years seemed to coincide both with positive and negative mass balance years. Neither winter air temperature (the likely candidate factor affecting the accumulating coldness in the tubes) nor precipitation (the likely candidate factor affecting the hydrological surplus for ice formation) shows any pervasive trend to explain the observed gradual multiannual ice loss trend. However, the summer air temperature had steadily risen during the first decade of the 21th century. The mean of daily maximum temperatures from 2000 to 2009 is c. 2°C higher compared to the previous decades. It suggests that heat flux to the lava tubes could have increased due to conductive processes and/or latently due to warmer infiltrating water.

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APPENDIX

TABLE A1 - Monitoring record of Merrill Ice Cave, Skull Ice Cave, Crystal Ice Cave, C-270, M-310, L-800, M-470, M-475 and M-340. Values are in cm

	Merrill IC		Skull IC	Crystal IC			Red Room		C-270		M-310	L-800	M-470	M-475	M-340
Date	Ice Level #1	Ice Level #2		Rusty Pin: #1	BLEP: # 2	Steel Pin: #3	Pin 1	Pin 2	SW marker	NW marker					
18.02.1990	168.2	75.9	125.58									100.3			102.4
06.04.1990											86.0		2.0	71.6	
27.05.1990				116.7											
26.10.1990	165.5	74.7	126.19										2.1		
27.10.1990									77.7			102.1			
16.03.1991	164.3	75.6	127.10								69.5	94.8	2.2		
17.03.1991									74.1						
26.07.1991													2.2	67.1	
27.07.1991	164.6	76.2	128.02						73.8			95.1			
18.04.1992												95.4			
19.04.1992			128.93						73.5		66.8		2.2		
20.04.1992	163.1	71.3													
28.11.1992													2.6		
13.02.1993									82.6			97.2			
14.02.1993	163.4	77.7	130.76								135.6		2.7		
18.09.1993			129.54										2.6		
16.04.1994	158.2	91.4	130.45						78.6			89.6	2.1		
03.09.1994													2.1		
04.09.1994	157.0		131.37						77.7			89.9			
24.11.1994	155.8		130.15										2.2		
26.11.1994												88.1			
27.11.1994									75.6						
15.04.1995	151.5	89.9	129.84						70.4			79.2			
16.04.1995													2.0		
27.05.1996	148.1		117.04						70.7			76.2			
28.05.1996													2.9		
01.09.1996	148.7		113.69						71.0			80.5			
02.09.1996													3.4		
02.11.1996													4.2		
28.11.1996	152.4		116.13						74.1			80.8			
15.02.1997	151.5		117.65						75.0			73.5	4.6		
24.05.1997	151.8		117.96	128.0					75.6			74.1			
27.05.1997													4.5		
30.08.1997	151.5														
31.08.1997			117.04									74.1	4.8		
01.09.1997									75.9						
29.11.1997	176.8		116.43						80.5			81.7	5.6		
02.01.1998	155.4		117.04									76.5	4.9		
16.01.1998											172.2				
15.02.1998	155.4		117.04						79.6		153.9	74.7	4.9	-	
23.05.1998	154.8	113.4	117.04						79.9			73.2	4.8		
10.08.1998												78.3			
11.08.1998	158.2	116.7	117.04						80.2						
26.11.1998													6.5		
27.11.1998	167.6	128.0	117.04						76.2			79.9			
16.01.1999												79.9			
14.02.1999	167.9	128.0	118.26												
28.05.1999	171.0	128.3	121.31									77.4			
31.05.1999									84.4				5.0		
04.09.1999	168.6	129.2	118.26						82.3			76.2			
25.11.1999	172.5	135.0	115.21						82.0		199.3	71.6			
20.02.2000	171.9	135.0	114.30						82.3			66.4	43.9		
27.05.2000	174.3	138.7	114.30						82.6			66.8			
29.05.2000													46.3		
03.06.2000											170.7				
07.06.2000															138.1

	Merrill IC		Skull IC	Crystal IC			Red Room		C-270		M-310	L-800	M-470	M-475	M-340
Date	**Ice Level #1**	**Ice Level #2**		**Rusty Pin: #1**	**BLEP: # 2**	**Steel Pin: #3**	**Pin 1**	**Pin 2**	**SW marker**	**NW marker**					
02.09.2000									84.7						
16.09.2000	182.3	148.7	111.86												
23.11.2000													54.3		
24.11.2000									88.7			71.6			
25.11.2000	192.3	154.8													
15.12.2000											170.7				
18.02.2001	192.3	155.4	112.47						89.6			72.5			
26.05.2001									90.2		168.2	72.5	53.9	dry	
27.05.2001	192.6	155.1	112.47												
01.09.2001	194.5	158.2	112.78						90.2			73.5	55.5		
21.09.2001											187.1				
11.11.2001	201.8	165.2	112.78												
22.11.2001												78.3			
16.02.2002									88.1			69.8			
17.02.2002			113.69								173.7		53.3		144.8
18.02.2002	204.2	166.4													
21.03.2002				172.2	see new										
31.08.2002													55.2		
01.09.2002	206.7	169.2	114.30						88.4			69.6			
27.11.2002											215.8				
28.11.2002									86.9			68.0			
29.11.2002													61.3		148.4
30.11.2002	214.9	175.3	114.30												
16.02.2003	219.2	174.7	114.30						87.2			64.6			
01.03.2003													51.8		
02.03.2003											175.6				
24.05.2003	224.3	179.8	113.39						87.8						
26.05.2003												64.6			
31.08.2003									88.4			69.2	78.3		
01.09.2003	234.1		114.00												
27.09.2003											214.9				151.5
10.10.2003			112.78												
27.11.2003											187.5		93.3		
28.11.2003									94.2			77.4			
30.11.2003	249.0	191.4	112.78												
18.01.2004				182.9	190.5										
04.10.2004			112.78												
09.10.2004									100.6			84.1			
10.10.2004	274.3	197.2									231.3				
23.04.2005	278.9	200.3	98.45	182.9 (to rocks)	210.0	139.9			103.0			88.4	no ice at pin		
24.04.2005											222.2				
07.05.2005														no ice, moist	165.8
24.11.2005			113.69						107.9		253.0	100.3			
25.11.2005	297.5	214.0													165.2
25.03.2006	can't reach pin	204.5							106.7		214.6	100.9			
06.05.2006			113.69	–	228.6	157.6							131.1		
08.10.2006									106.1			103.0			
24.11.2006	329.2	no ice									198.7				171.0
26.11.2006			111.25												
19.05.2007													no ice		
14.07.2007			111.25												
28.07.2007				no ice	253.0	178.3									
09.05.2008									104.5			112.8	no ice	91.4	
10.05.2008	no ice	204.2, no ice	113.69								185.0				171.3
11.05.2008				182.9 (to rocks)	260.6	188.4	108.2	172.5							

	Merrill IC		Skull IC	Crystal IC			Red Room		C-270		M-310	L-800	M-470	M-475	M-340
Date	**Ice Level #1**	**Ice Level #2**		**Rusty Pin: #1**	**BLEP: # 2**	**Steel Pin: #3**	**Pin 1**	**Pin 2**	**SW marker**	**NW marker**					
08.05.2009	no ice	no ice	115.21						100.3			115.5			
10.05.2009				182.9 (to rocks)	268.5	198.1	107.9	171.6							
23.05.2009													no ice, some seasonal		
24.05.2009											176.8				171.9
26.02.2010												118.3			
02.03.2010			115.52								171.6				
05.03.2010				no ice		221.9	108.2								
09.03.2010									104.2						
07.10.2010												120.4			
10.10.2010			116.74												
28.02.2011			117.96								166.7				
10.03.2011												123.4			
18.04.2011									118.0	94.5					
03.05.2011						240.2	108.5		118.0	94.5					
12.05.2011												123.7			
13.05.2011	no ice	no ice	117.65												
14.05.2011									117.3		166.4				
22.06.2011									115.2	93.9					
05.07.2011									114.0	93.6					
17.09.2011									121.9	92.0					
25.11.2011									131.1	104.2					
19.02.2012				no ice at pin	297.2	254.2	108.2	111.7							
21.03.2012			120.09									125.6			
05.03.2012											166.4				
30.03.2012									132.3	104.5					

Table A2. Ice level below a datum of L-215 and U-200. Horizontal extent (width/length) of floor ice of Heppe IC. The values are in cm

	Heppe IC		L-215		U-200	
Date	**Width**	**Length**	**NE Pin**	**SE Pin**	**Ice Level # 1**	**Ice Level # 2**
28.05.1999	1197.9	944.9				
28.05.1999	1197.9	944.9				
25.11.1999	gone	gone				
27.05.2000	gone	gone				
16.02.2002	gone	gone				
24.04.2005	457.2	731.5				
07.05.2005					77.7	77.1
05.09.2005	609.6	883.9				
24.11.2005	682.8	891.2				80.8
25.03.2006	810.8	1005.8				
06.05.2006						54.3
26.11.2006	1335.0	1341.1				
08.05.2008	1298.4	1295.4				57.9
30.05.2008						62.2
27.03.2009			60.0	93.6		
09.05.2009	gone	gone				55.8
01.03.2010			58.5	93.3		
10.10.2010						80.8
01.03.2011			61.0	93.9		
03.05.2011	79.2	97.5				
13.05.2011						60.4
07.12.2011	did not measure ice floor, just noted its presence					
22.03.2012			65.5	91.4		