

# Mountain Permafrost – A Valid Archive to Study Climate Change?

## Examples from the Rocky Mountains Front Range of Colorado, USA

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With 5 Figures

### *Abstract*

Mountain permafrost is highly sensitive to changing air temperatures because they affect the thawing depth of the annual active layer, as well as the time and speed of the refreezing process, mainly in the winter. The Long Term Ecological Research Site (LTER) Niwot Ridge and the Critical Zone Observatory Site (CZO) Green Lakes in Colorado, USA, with their high alpine tundra climate and vegetation, offer ideal conditions to study changes of mountain permafrost. The sites provide high quality climate data, together with studies on permafrost since the 1970's, which make these places rather unique in the US. We present data from our studies on permafrost distribution using different geophysical techniques to portray the shallow subsurface. The data on permafrost and soil temperature are compared with existing models of permafrost distribution and possible thermal degradation, as well as with older data on the existence and distribution of permafrost at these sites. At some locations, we find large differences when compared to the older data and the prognostic model. Sites formerly indicated as permafrost in the 1970's shifted towards sites with annual ice lenses today. We discuss the results and attempt to discern if the observed change is a direct consequence of the current rising air temperatures.

### *Zusammenfassung*

Alpiner Permafrost reagiert höchst sensibel auf Temperaturänderungen, da diese sowohl die oberflächennahe jährliche Auftautiefe als auch den Zeitpunkt und die Geschwindigkeit des Wiedergefrierens im Winter beeinflussen. Die ökologische Dauerbeobachtungsfläche der Niwot Ridge (LTER) sowie das Untersuchungsareal der Green Lakes des Critical-Zone-Observatoriums (CZO) in Colorado (USA), bieten durch ihr hochalpines Klima und die besondere Vegetation ideale Möglichkeiten, Permafrostveränderungen zu erfassen. Qualitativ hochwertige Klimadaten zusammen mit diversen Studien zur Permafrostverbreitung sind für die Untersuchungsflächen seit den 1970er Jahren vorhanden, was die Flächen ziemlich einzigartig in den USA macht. Wir stellen Daten unserer Arbeiten zur Permafrostverteilung vor, welche durch oberflächennah arbeitende geophysikalische Methoden gewonnen wurden. Daten zum aktuellen Permafrostvorkommen und zu Bodentemperaturen im Untersuchungsgebiet werden mit aktuellen Modellen zur Permafrostverbreitung und möglichen thermischen Degradation sowie mit älteren Daten zur Permafrostverteilung verglichen. An einigen Stellen sind große Unterschiede zwischen den aktuellen und den alten Daten sowie den prognostischen Modellen aufzuzeigen. So weisen Areale, welche ehemals als Permafrostgebiete klassifiziert waren, heute nur noch jährliche Eislinsensbildung in den kalten Monaten auf. Wir diskutieren die Ergebnisse und versuchen zu erkennen, ob die dargestellten Unterschiede die Folge beobachtbarer Temperaturerhöhungen sind?

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## **1. Introduction**

Permafrost is defined on the basis of temperature as sediments or rocks that remain below 0°C throughout the year. It forms when the ground cools during the winter to produce a frozen zone that persists throughout two following summers (e.g. WILLIAMS and SMITH 1989). Permafrost areas can be classified as continuous, non continuous or sporadic, and an overview of their world wide distribution is given by NELSON (2004). Mountain permafrost known from high altitude regions, such as the Himalaya in Asia (JIN et al. 2000), the Alps in Europe (HARRIS et al. 2003), the Rocky Mountains in North America (JANKE 2005) and other high altitude mountain ranges, composes only a small quota of the worldwide permafrost distribution. However, as climate is one of the main factors determining the existence of permafrost, its possible degradation is seen as a major challenge in the actual discussion of globally rising temperatures (LEMKE et al. 2007, HARRIS 2005). The spatial distribution, thickness and temperature of permafrost is highly dependent on the temperature of the ground surface and is influenced by several other environmental factors, such as vegetation type and density, snow cover, drainage, soil type and site-specific internal heat flow. HARRIS et al. (2003) give clear evidence of rising air temperatures and warming permafrost in European Mountains, and LI et al. (2008) reach similar conclusions for high altitude areas in China.

Mountain permafrost in the US is mainly located in Alaska, but there are also areas of frozen ground described in the Front Range of the Colorado Rocky Mountains above 3,300 m a. s. l. (JANKE 2005). Studies on the permafrost distribution and associated processes of the Front Range were started in the late 1960s and the early 1970s (BENEDICT 1966, 1970, IVES and FAHEY 1971). Today, two major US-NSF-funded research projects, the Niwot Ridge Long Term Ecological Research Site (LTER, <http://culter.colorado.edu/NWT/>) and the Boulder Creek Critical Zone Observatory (BC CZO, <http://czo.colorado.edu/>), deal with the genesis and the future development of the structure, the physical and the chemical parameters of the subsurface. These sites provide an ideal chance to link older data with modern techniques of permafrost detection and monitoring and to discuss the results in the context of changing temperatures.

## **2. Study Site**

The Niwot Ridge area, located at W105°36' and N40°03', is a set of upland surfaces and adjoining slopes near the US-continental divide within the Colorado Front Range, which forms the eastern flank of the Rocky Mountains (Fig. 1). The Range slopes from elevations over 4,000 m a. s. l. down to the Colorado Piedmont and High Plains at about 1,500 m with correspondingly strong temperature and moisture contrasts that control altitudinal zonation of vegetation and soil types (BIRKELAND et al. 2003). The study sites at Niwot Ridge (Fig. 1) are located in the alpine tundra zone where mean annual air temperature (MAAT) at 3,743 m is 3.8°C and annual mean precipitation is about 993 mm (BARRY 1973, WILLIAMS et al. 1996, GREENLAND and LOSLEBEN 2001, D1 in Fig. 1). MAAT at 3528 m a. s. l., 200 m from the study site (Fahey site), is slightly lower, -2.13°C based on a temperature record from 1982–2010 ('Saddle' in Fig. 1). Geomorphic, hydrologic, climatic and biogeochemical aspects of the local area have been studied in considerable detail over the past 50 years (c. f., <http://www.colorado.edu/mrs/mrspubs.html>). We present data from two sites: one is the Fahey site located at 3,500 m a. s. l. close to the saddle station and the other is a site west of the D1 station (Fig. 1).

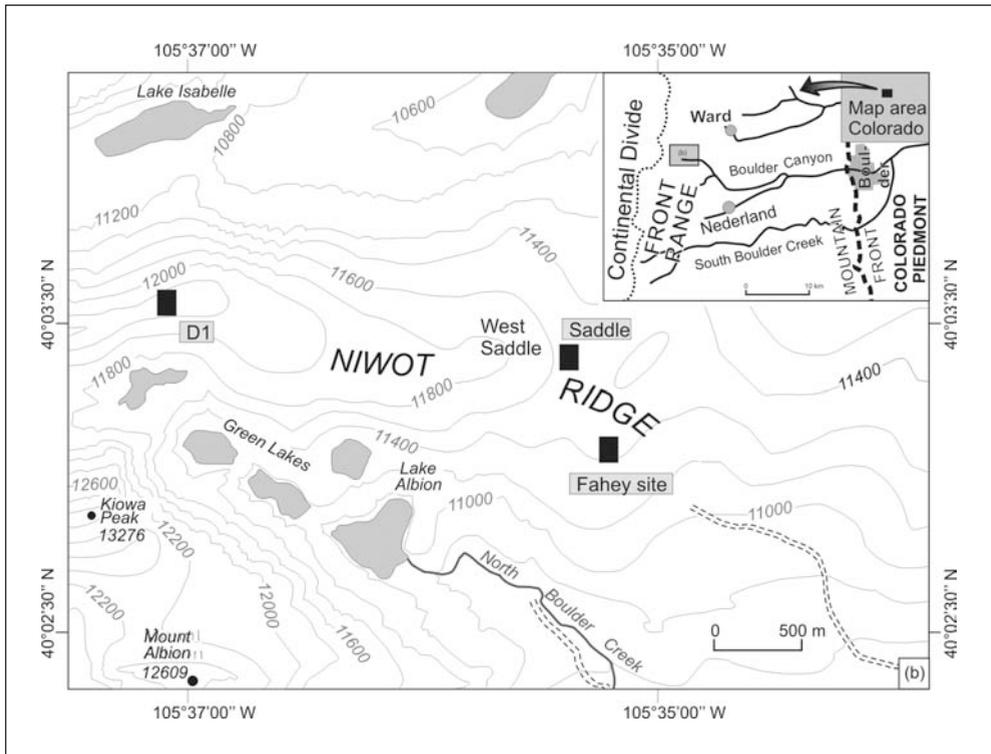


Fig. 1 Overview of the study sites in the Colorado Front Range of the Rocky Mountains, USA. Meteorological data has been sampled at D1 at 3,739 m a. s. l. since 1952 and at the Saddle station at 3,528 m a. s. l. since 1982. The Fahey site and the slope south of D1 were surveyed using geophysical methods.

### 3. Methods

As frozen materials have characteristic physical properties which differ from unfrozen materials and which are intensified under the presence of ice/water, permafrost can be successfully detected using geophysical methods (HAUCK and KNEISEL 2008). These methods, such as electric resistivity tomography (ERT), ground penetrating radar (GPR) and shallow seismic refraction (SSR), use electric current or electromagnetic and acoustic waves to measure the electric conductivity and density of the subsurface. These techniques have been successfully applied to portray the shallow subsurface of the study site (for site-specific details see LEOPOLD et al. 2008a, b). Additionally, two bore holes were drilled in 2006 to install temperature loggers on and beside an active solifluction lobe at 3,500 m a. s. l. Loggers were installed every 5, 20, 40, 80, 120, 200 and 280 cm on the lobe (named as east-loggers) and at the same depths, but continuing as deep as 500 and 700 cm, beside the lobe (named as west-loggers). Air temperatures were measured at the ‘LTER-Saddle station’ about 200 m west of the lobe and at the D1 station (Fig. 1).

#### 4. Results

MAAT at D1 in the period of 1953–2008 was calculated at  $-3.35^{\circ}\text{C}$  with a standard deviation 1.2 (comp. Fig. 2). The Saddle station yielded a MAAT of  $-2.13^{\circ}\text{C}$  with a standard deviation of 1.0. Summer air temperatures (SAT), determined by using the months with potential thaw-temperatures (here June to September), reach values of  $6.09^{\circ}\text{C}$  at D1 and  $7.14^{\circ}\text{C}$  at the saddle. Both stations show high annual variability, with a rise of SAT during the last decade. Differences in MAAT between D1 and the Saddle station are mainly caused by differences in the winter temperatures. At both stations MAAT was below the threshold value of permafrost of  $-1^{\circ}\text{C}$  (IVES 1974) except for the year 1956 at D1.

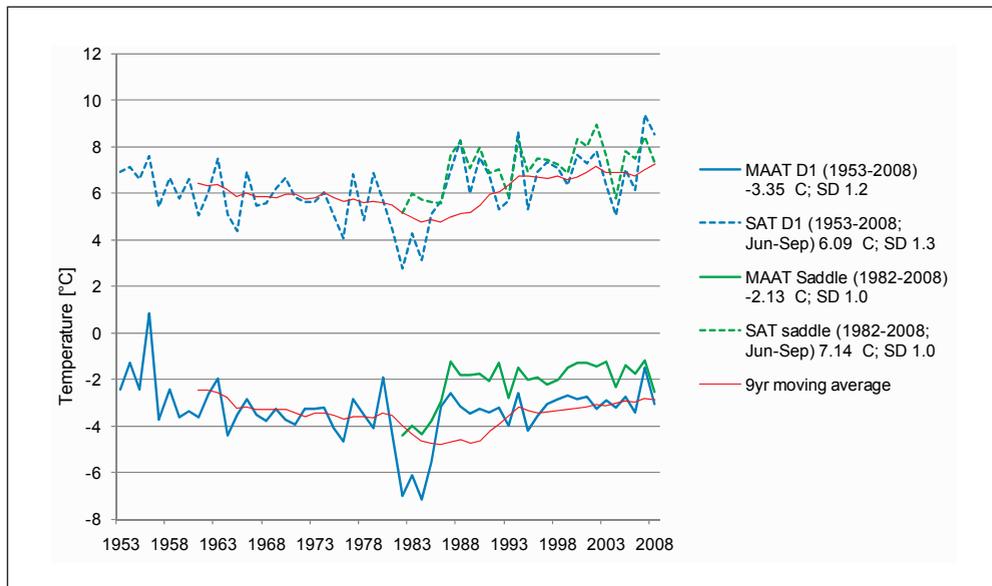


Fig. 2 Air temperature at the D1 and Saddle climate station are given as mean annual air temperatures (MAAT) and summer air temperatures (SAT, June – September) using months with possible ice melting conditions above  $0^{\circ}\text{C}$ . For the data at D1, a 9 year moving average trend line is given, thus, the lows of 1982–1984 is phase shifted for 4.5 years.

In July 2005 several GPR survey lines were conducted in order to get an initial overview of the subsurface of a solifluction lobe at the Fahey site (see LEOPOLD et al. 2008a). CMP-velocity analysis of the subsurface using GPR allows conclusions on the existence of ice because the electromagnetic signal sharply increases at the border of unfrozen to frozen material. The outcomes suggested the occurrence of ice lenses at a depth of 2 – 2.5 m, but not deeper, which most likely indicates that no permafrost exists at this site. This contradicts the results from IVES and FAHEY (1971) and GREENSTEIN (1983) who suggested permafrost below 2 m on wet sites and below 5 m on drier sites above 3,300 m a. s. l. Thus, several new GPR and ERT surveys have been conducted in order to provide more data. The outcomes from 2005 to 2009 document that during the summer month of August, all ice melts to an unfrozen subsoil present down to several meters. The same result was yielded during an ERT survey in August

2006 where unfrozen material was displayed by a high conductivity of the subsurface down to more than 15 m (Fig. 3A). Any remnants of ice would have caused low conductivity conditions and a subsequent increase of electric resistivity as indicated during a survey in late December 2009 (Fig. 3B). High resistivity values down to 1.1 m represent the winter refreezing zone in December above unfrozen material at greater depth (Fig 3B).

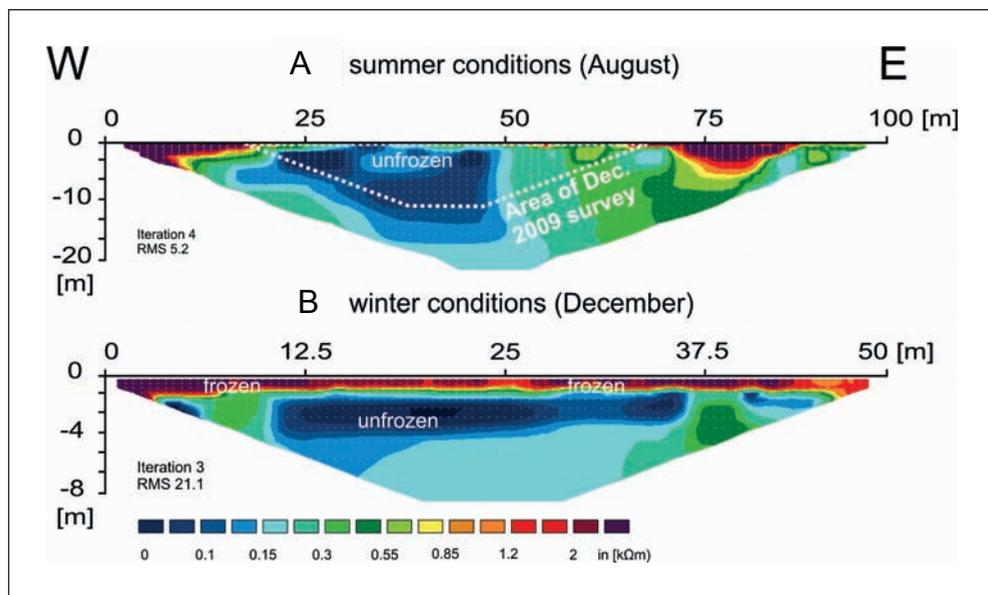


Fig. 3 Results of the electric resistivity tomography at the Fahey site under summer and winter conditions. Note the different horizontal meter scale. (A) ERT-results during summer show unfrozen, moist conditions throughout the solifluction lobe between 20–65 m as represented by low resistivity values, and dry conditions with corresponding higher values at two adjacent blocky crevasses. (B) ERT-results during winter conditions show a uniformly frozen layer of 1.1 m throughout the whole solifluction lobe and still unfrozen conditions in the deeper parts..

The outcomes of the geophysical survey correlate with data derived from two boreholes, which are equipped with temperature loggers down to 7 m (Fig. 4). While the west-loggers indicate dry conditions beside the solifluction lobe, the east-loggers record the subsurface temperature data from the solifluction lobe with moist conditions. Both sites show a high thermal variability in the upper 1.2 m, which is closely linked to air temperatures. Further below the surface, temperature variability is decreased, documenting the general ability of the subsoil to filter highs and lows of air temperatures, which makes it a valuable climate archive. The data shows that below 280 cm depth, the ground stays unfrozen all year round. Winter freezing reached depths of slightly over 2.5 m, but by the end of July, it had melted again, just as predicted by the geophysical survey. This temperature trend was generally the same from 2006–2009.

Since the results seen above document the general suitability of the geophysical techniques to precisely locate permafrost, we conducted surveys at a site with even higher elevation. Occurrence of permafrost at 3,739 m a. s. l. next to the D1 site was predicted by IVES

and FAHEY (1971) and GREENSTEIN (1983), and was modeled with a probability of 63 % by JANKE (2005). The results of our ERT survey along the south slope onto the Ridge close to the D1 are displayed in Figure 4. Even though a MAAT of  $-3.35^{\circ}\text{C}$  would suggest the occurrence of permafrost, there is no indication of ice in the subsurface down to about 10 m depth. Values do not exceed 30 k $\Omega\text{m}$  in general, and areas of highest values correspond with the distribution

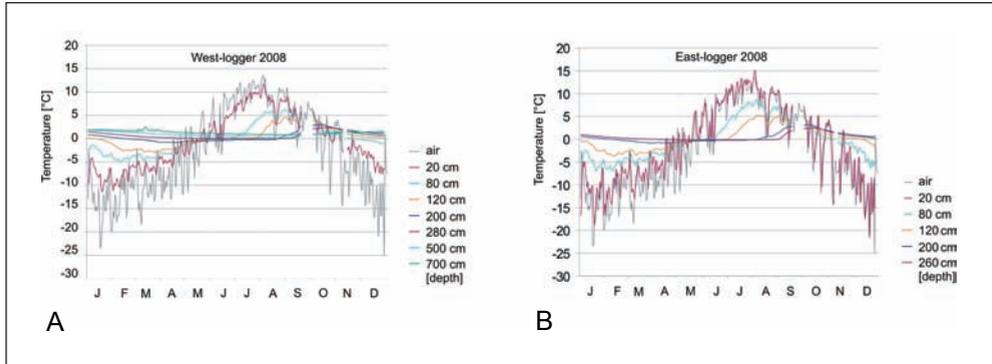


Fig. 4 Temperature profiles for the year 2008 at the (A) West- and (B) the East-loggers at the Fahey site. Note the high variability and close correlation with the air temperature down to about 120 cm. Ice melt was completed by mid August between 200 and 280 cm.

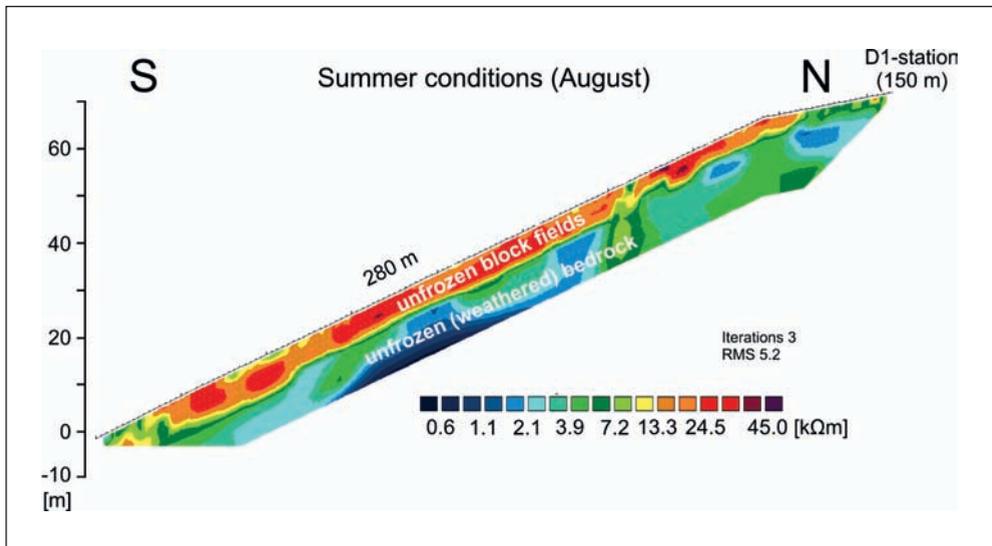


Fig. 5 Electric resistivity survey (Wenner configuration, 2 m spacing) along the south slope near the D1 climate station. A 4–5 m thick layer of blocky materials is portrayed by high electric resistivity values (20–30 k $\Omega\text{m}$ ) over weathered bedrock. No permafrost could be detected.

of block fields. Ice rich permafrost would yield much higher values of 100 kΩm or more, as documented on a nearby rock glacier (LEOPOLD et al. 2010) and by many other authors (see HAUCK and KNEISEL 2008).

## **5. Discussion and Conclusion**

Our data provide no indication on the existence of permafrost at selected sites at Niwot Ridge where, based on older data from the 1970s and 1980s (IVES and FAHEY 1971, IVES 1974, GREENSTEIN 1983), we would have expected permafrost. Even newer models calculate a probability of higher than 63 % for permafrost at these sites (JANKE 2005). As the selected sites are at the lower altitude of sporadic permafrost distribution, our results could result from permafrost degradation due to globally rising temperatures in the last 40 years, similar to what is known from other sites (LEMKE et al. 2007, HARRIS et al. 2003). However, careful evaluation of the older data presents some questions that must be answered before a final answer can be given for the study site. Since MAAT below  $-1^{\circ}\text{C}$  and bottom temperature of winter snow (BTS) below  $-3^{\circ}\text{C}$  seem to be closely linked with permafrost distribution (comp. HARRIS et al. 2003, JANKE 2005), one would expect permafrost on the Fahey site as well as on the D1 site today. MAAT temperature from 1953 to 2008 at D1 has slightly increased from  $-3.8^{\circ}\text{C}$  in 1996 (comp. WILLIAMS et al. 1996) to  $-3.35^{\circ}\text{C}$ . However, JANKE (2005) used data from 1988–2002 and calculated MAAT at D1 to be  $-2.9^{\circ}\text{C}$  and at the saddle to be  $-1.4^{\circ}\text{C}$ . If we extend the data from JANKE (2005) to 2008, we find a small temperature decrease to  $-3.0^{\circ}\text{C}$  at D1 and to  $-1.7^{\circ}\text{C}$  at the Saddle, values that seem to somehow reflect the known variability. Furthermore, it corroborates the statement from WILLIAMS et al. (1996) that ‘changes in climate on Niwot Ridge are not in synchrony with lowland warming in the Great Plains’ mainly caused by local conditions. On the other hand, ground surface temperatures show an increase of  $1^{\circ}\text{C}$  over the last decade, which is consistent with the glacial negative mass balance and potential loss of permafrost at the lower altitude sites (WILLIAMS et al. 2007). Slope aspect, albedo and winter snow cover also play a major role in the distribution of permafrost, as we found permanently frozen ground on and around a north facing rock glacier in the nearby Green Lake valley at 3,600 m a. s. l. (LEOPOLD et al. 2010) and it was also detected at a steep north facing slope at 3,750 m a. s. l. by IVES (1974).

It continues to astonish us that we cannot detect permafrost where it has been detected in the 1970s at 3,500 m a. s. l. Our explanation to this apparent discrepancy is site-specific conditions. While BENEDICT (1970) never described permafrost, but instead only seasonal ice lenses, IVES and FAHEY (1971) reported of two summers, where temperatures remained fractionally below  $0^{\circ}\text{C}$  at the Fahey site (3,500 m a. s. l.), and this was done by temperature logging down to 2 m and by digging a trench. Beside the Fahey site summer temperatures remained above  $0^{\circ}\text{C}$  down to 5 m depth (IVES 1974). The conclusion of widespread permafrost around D1 was produced by the extrapolation of temperature profiles. Deep drills and accurate temperature logger are missing for these sites up to present, except for the Fahey site (2006–2009), which is discussed in this paper. However, permafrost described by IVES and FAHEY (1971) at the Fahey site was at the ‘edge’ of permafrost definition on a south-facing slope. The degradation or the existence at this site could be the result of a freeze lasting a few days longer during the winter, deeper and more long lasting snow cover in the spring or a denser cloud cover during the summer months with a decrease of radiation. These param-

eters can vary from year to year, leading to conditions that allow ice to stay in the subsurface during the summer. Thus, disappearance of ice or ice lenses during the summer months as documented by our results must not necessarily be interpreted as result of global warming. Moreover, it shows that threshold values of MAAT, BST and permafrost that have been elaborated and proven many times in the European Alps, might not be valid for all parts of Niwot Ridge with its much more southern latitudinal position. This is corroborated by HOFFMAN et al. (2007), who give evidence that summer temperatures and not winter air temperatures or snow accumulation regulate glacial mass balance here. That suggests that permafrost loss might be driven by SAT at the area around Niwot Ridge, rather than BTS or MAATs. SAT (June – September) did rise at D1 to 7.9°C in the last decade compared to 6.3°C from 1965 to 1975, where IVES and FAHEY (1971) made their investigations. Higher summer temperatures in the last decade, in combination with less precipitation in the early 2000s as described by WILLIAMS et al. (2006) together with differences in snowdrift and albedo might be the reasons for permafrost loss on south slopes. At the least, these conditions anticipate the reformation of permafrost at our study sites. Degradation and reformation of permafrost in combination with increased solifluction have been proved for several periods throughout the Holocene (comp. BENEDICT 1970), and it seems to be a part of the site specific conditions at Niwot Ridge.

Global temperature variations undoubtedly influence alpine permafrost, as documented many times (e. g. HARRIS et al. 2003). However, each site needs to be carefully checked and monitored over a sufficient period of time in order to fully understand variation of the local conditions other than temperature that influence permafrost genesis before any climate relevant conclusion can be drawn. In our case the lack of permafrost at two sites at Niwot Ridge cannot be correlated exclusively with general global warming trends as shown above.

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